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Developing breakthrough innovation capabilities in university ecosystems: A case study from South Africa

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ABSTRACT

The emergence of the Fourth Industrial Revolution (4IR) paradigm, whilst posing challenges, also presents significant opportunities to bolster research capabilities and pioneer breakthrough innovations that can stimulate economic growth across various sectors. However, the realisation of these benefits relies heavily on the ability of countries and their constituents to innovate effectively in this new landscape. The purpose of this study is to explore how innovation mechanisms can be employed to foster stronger innovation capabilities within a university ecosystem, particularly in the African context. To do so a case study methodology is used, where cross-sectional data gathered over six months is assessed using the Diffusion of Innovation (DOI) as a theoretical lens. The findings reveal that such innovation mechanisms, like a makerspace within a university ecosystem, provide critical support for design phase innovation and collaboration. We illustrate this by employing a conceptual framework that explains the process by which innovations evolve from ideas into valuable outcomes.

1. Introduction

Emerging technologies of the Fourth Industrial Revolution (4IR) are effectuating significant transformation across various spheres. It is reshaping business strategies, pedagogical approaches in academia, social interactions and even the very future of work (Schwab, 2017; Xu et al., 2018). The implications of inadequate readiness for this paradigm could be consequential on several fronts (Botha, 2019). For example, societal costs, where higher unemployment rates could occur with expanding levels of automation (Rainnie and Dean, 2020). This is even more critical in African regions, as they are more susceptible to labour disruption (Adenle, 2017). Policymakers then across the continent must understand the complex array of variables and impact of emerging technologies brought on by the 4IR (Kamau and Wamuthenya, 2021).

This perspective though should not be construed as solely a narrative of impending adversity. The paradigm unveils several opportunities that can strengthen research capabilities and breakthrough innovations to drive economic growth across sectors (Dean et al., 2023). The actualisation of these outcomes hinges on a nation's innovation capability (Oztemel and Gursev, 2018). Effective innovation within this landscape is, however, complex, and multi-faceted, requiring a multi-disciplinary and coordinated approach (Ittipanuvat et al., 2014; Lu, 2021). Notwithstanding, innovation has seen extensive research across disciplines, supporting its role in improving existing processes or creating new business opportunities to deliver value for sustainable competitiveness (Audretsch and Caiazza, 2016; Etzkowitz, 2003). For example, Hiran and Henten (2020) showed how cloud computing has been instrumental in reshaping the technological landscape of Africa and supporting the regions' ability to innovate in the 4IR. However, the authors also noted that scalable platform that supports innovation and growth has been slow in the region due to a lack of higher education engagement and upskilling to use this technology.

Amidst the rapidly emerging technologies of the 4IR then, universities, as central hubs of knowledge and innovation, are well positioned to have a transformative role within the 4IR, shaping a workforce cohort that is adaptable and innovative (Guerrero et al., 2019). These institutions, by spearheading multidisciplinary research and fostering innovative ecosystems, can translate the potential of the 4IR into tangible progress and societal growth (Carayannis and Morawska-Jancelewicz, 2022). Furthermore, universities can play a vital role in advancing transformation by extending access and representation across various demographic boundaries, such as race, gender, and sexual orientation (Kamau and Wamuthenya, 2021). For instance, in South Africa, the percentage of black students' admission to higher education

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institutions has risen from 52 % in 1994 to 81 % in 2014 as a step towards redressing past inequalities (Stats SA, 2022). However, Sutherland (2020) notes that academic actors in the country struggle to drive innovation capability due to a lack of "basic" infrastructure such as Information and Communication Technology (ICT) and low levels of access to basic education.

To catalyse on innovation, academic institutions across the globe are actively engaging in various measures (Baena et al., 2017; Bloom and Faulkner, 2016; van Stijn et al., 2018). A trend to achieve this has been the further development of innovation ecosystems using key mechanisms such as accelerators, incubators, hacklabs, makerspaces, fablabs, launch labs and technology transfer offices (TTO) to name a few (Crupi et al., 2020; Kruger and Steyn, 2019). The dialogue surrounding the role of innovation mechanisms in university ecosystems is pivotal, particularly in the context of enhancing innovation in response to the demands of the 4IR. While a select body of research, such as that by Kruger and Steyn (2019), Lee, Wong, et al. (2020), Li et al. (2017) and Rainnie and Dean (2020) has started to unpack these complex interrelations, the full spectrum of innovation mechanisms within universities and their impact on fostering a 4IR-ready innovation society requires further investigation. The study by AlMalki and Durugbo (2022) further highlights the importance of supporting organisations in advancing education and underscores the imperative to investigate the supportive mechanisms within higher education that can cater to the nuances of the 4IR. This is even more prevalent in developing regions, who rely heavily on academic institutions and their ecosystems to support innovation development (Huang and Li, 2019; Sutherland, 2020) to engage in the 4IR paradigm (Coskun-Setirek and Tanrikulu, 2021).

Despite the potential and existing academic literature, there remains a gap in our understanding of how universities in developing contexts, such as South Africa that is positioned in the global south, can enhance their innovation capabilities to navigate and shape the 4IR landscape, creating radical innovation outcomes (Kamau and Wamuthenya, 2021; Solomon and van Klyton, 2020; Sutherland, 2020). Rainnie and Dean (2020), specifically allude to the lack of data on this topic. This underscores the need for further investigation into the context-specific strategies employed by academic institutions in developing regions such as South Africa (Baena et al., 2017; Lee et al., 2020b).

A resulting research question is: "*How can innovation mechanisms be employed to enhance the capabilities of university ecosystems in managing breakthrough innovations?*". To address this question, this study explores the function of an innovation mechanism - specifically a makerspace - embedded within an academic institution in South Africa, and how it enhances innovation outcomes.

The study brings novelty to this research area in several ways. Firstly, the research contributes to the literature by offering insights into the functions of innovation mechanisms within academic ecosystems particularly in the context of developing African economies. Secondly, it examines how such ecosystems can evolve to support and transition breakthrough innovations. In this way, initiatives can be aligned to strengthen university ecosystems based in emerging economies, improving their innovation capabilities and achieve the resulting cascading effects. Finally, by evaluating a locally successful university mechanism, the study identifies practical strategies for fostering collaboration and innovation despite resource limitations.

The remainder of the study is structured as follows. Firstly, existing literature on innovations role in creating long-term value in the 4IR is analysed to demonstrate the paradigms principles and consequential innovation opportunities. The role universities have in further driving innovation into the future is then noted, with the mechanisms they use reviewed. The resulting theoretical gap and limited focus on emerging economies is highlighted, with the South African context provided. The theoretical lens that underpins the resulting investigation is then reviewed. In Section 3, the study's methodology is presented, followed by findings from the case study in Section 4. The discussion is then presented alongside the conceptual framework. Finally, conclusions and limitations are noted.

2. Literature review

In the 4IR landscape, innovation emerges as more than a by-product, but rather as a vital instrument for leveraging the paradigms technological advances. Ciriello et al. (2019) and Lee et al., 2020a,Lee et al., 2020b align on the premise that innovation is essential in realising the long-term benefits offered by the 4IR. The fusion of emerging technology as detailed by Sousa and Rocha (2019), underpins the drive of the paradigm in product development and operational efficiency, with customer value points being created. Central to this transformation, including a digital one, is the integration of smart technologies to advance autonomous, sensor-based and self-regulating systems (Bendul and Blunck, 2019; Rajan and Saffiotti, 2017). Collectively, these propel businesses towards unprecedented levels of automation and sophistication (Lee et al., 2017; Li et al., 2017). For reference, automation uses several control systems to render a designated task, usually to a machine, be it virtual or physical (Fabris et al., 2015; Park, 2017). The benefit of automation is the ability to reduce human labour and the associated errors, costs, and downtime (Rainnie and Dean, 2020). The concept of automation is by no means new; however, with the 4IR, this could mean outperforming activities of even skilled tasks through Machine Learning (ML) and Artificial Intelligence (AI) (Goolsbee, 2018; Muhuri et al., 2019) that is already occurring across various industries (Xu et al., 2018). Additional technologies such as Big Data, Blockchain, Cloud Computing, Robotics, IoT and Additive Manufacturing (AM) also form part of the 4IR.

With this array of technology, several stakeholders are exploring innovative applications that transcend traditional boundaries (Castelo-Branco et al., 2019; Kruger and Steyn, 2019), underscoring the multidimensional nature of the 4IR as reviewed by Xu et al. (2018). It is within this context that universities are acknowledged as key agents of change, tasked with the analysis and adoption of these interconnected technologies, shaping the future trajectory of innovation across sectors (Bartoloni et al., 2021; Carayannis et al., 2018; Etzkowitz, 2003).

2.1. Universities as key role-players

As the 4IR offers several opportunities for innovation, the onus lies not with one, but multiple stakeholders to harness such potential (Bartoloni et al., 2021; Paredes-Frigolett, 2016). One key stakeholder is academic institutions, as they serve as the nexus of creation and innovation by providing robust knowledge ecosystems that foster skills development and engagement, catalysing innovation (Cobben et al., 2022). This transition is particularly pronounced in the 4IR era, where the integration of technology and talent becomes critical as specified by Guerrero et al. (2019).

Their role is significantly emphasised within the contexts of regional innovation systems, particularly when adopting strategic approaches such as the Quadruple Helix models (Bartoloni et al., 2021). This framework explains the dynamic interactions among academia, industry, government, and civil society to foster regional innovation. In this schema, as with this study, academic institutions are crucial actors in driving knowledge production and managing breakthrough innovations towards impactful outcomes for economic growth (Guerrero et al., 2019; Youtie and Shapira, 2008). These outcomes include patents, intellectual property (IP), copyright, and business spin-offs (Kruger and Steyn, 2019; Rasmussen et al., 2014). In this vein, the concept of developing innovation capabilities emerges as a powerful strategy (Sahin et al., 2019). Innovation capability within a university context refers to an institution's ability to generate, develop, and implement new knowledge, ideas, technologies, or processes that result in improved performance or value creation. This often manifests through the production of new research, the development of novel pedagogical strategies, the creation of innovative products or services and establishment of dynamic collaborations (Bartoloni et al., 2021). Resource allocation is another key determinant of a university's innovation capability. This encompasses not only financial resources, but also human resources (e.g., skills, expertise, creative potential of staff and students) as well as physical resources (e.g., infrastructure, technology, facilities) (Dixit et al., 2022).

Academic institutions, therefore, are not only adopting these technologies but are also shaping the trajectory of research and innovation. In such an ecosystem, universities accelerate multi-dimensional forms of innovation, evidenced by patent registrations and the rise of business spin-offs (European Commission, 2018), including breakthrough innovation (Paredes-Frigolett, 2016). Consequently, there has been a surge in investment and interest in establishing mechanisms capable of leveraging these technologies, thus fostering integrated concepts across disciplines and sectors to bolster innovation and its associated outcomes. This has been applicable in both advanced and developing regions such as South Africa (Botha, 2019; Olaitan et al., 2021).

2.2. Innovation mechanisms within university ecosystems

As universities continue to expand their roles as hubs of innovation within the 4IR landscape, the utilisation of innovation mechanisms has become increasingly crucial (Bartoloni et al., 2021). A key node that can channel these components to create new forms of value are innovation mechanisms (Kruger and Steyn, 2019). A particular mechanism noted from literature that supports design phase innovation is a makerspace (Niaros et al., 2017). Such spaces have gained traction internationally (Irie et al., 2019) and in emerging economies such as South Africa (Matthee and Turpin, 2019) due to their ability to act as a catalyst for access across disciplines and drive needed skills development. Historically, makerspaces have been known as environments that supported exploratory learning and experimentation. Core to this is the philosophy of Do-it-Yourself (DIY). There are various names and forms that share similarities, including hackerspaces, fab labs, tech labs or hubs. However, depending on scale and output as well as strategic alignment to an institution, they have evolved, bridging gaps in skills by providing access to not only hardware technologies but digital ones as well. Consequently, as highlighted by Cox (2016), one avenue of their evolution is Digital Scholarship Centres. Irrespective of the term, they aim to promote innovation and productivity (Niaros et al., 2017) to support users to ideate and test their ideas, allowing them to design solutions (Kruger and Steyn, 2022). Therefore, academic institutions bear a critical responsibility to foster such innovation mechanisms. The strategic implementation and support of these environments can significantly enhance the innovative capacity and strengthen a university's ecosystem, leading to meaningful contributions to knowledge production and regional development (Bartoloni et al., 2021).

In advanced regions such as Europe, Digital Innovation Hubs (DIHs) are employed to drive collaboration and technology adoption through a network of expertise across diverse businesses (European Commission, 2020). Core to which are activities such as linking partnerships, funding, and skills development (Castelo-Branco et al., 2019; European Commission, 2018). Unsurprisingly, first world countries remain at the forefront of producing breakthrough innovations (Asplund et al., 2021). Developing regions such as those on the African continent are making several efforts to replicate such initiatives due to their proven success (Coskun-Setirek and Tanrikulu, 2021). However, such regions face several barriers such as a large skills gap, rapid urbanisation, high inflations rates and disproportionate youth unemployment (Adenle, 2017). These factors are creating a complex situation, where initiatives that are being duplicated do fail due to certain barriers in the region, lowering innovative outcomes and exasperating existing employment challenges (Olaitan et al., 2021).

2.3. The theoretical gap and limited focus on developing economies

The exploration of innovation mechanisms within university ecosystems reveals a growing field of research, where substantial work has been conducted on the general functions and outcomes of incubators, accelerators, and makerspaces. These studies have laid the groundwork for understanding how such mechanisms operate and contribute to the entrepreneurial and innovative capacities of individuals and start-ups (Campbell and Carayannis, 2016; Guo et al., 2017). However, there remains a theoretical gap in the literature concerning the integration and operation of these mechanisms within the larger framework of university ecosystems, especially in managing and transitioning breakthrough innovations. While the existing literature provides snapshots of the impacts of innovation mechanisms, often these analyses examine the success of these entities in isolation or focusing on short-term impacts (Sisko Patana et al., 2013). For instance, studies may assess the number of start-ups incubated or the amount of funding secured through accelerators (European Commission, 2018), but there is less insight into how these mechanisms help achieve strategic objectives of universities (van Stijn et al., 2018). Moreover, the current body of research tends to overlook the role that these innovation mechanisms play in the critical phase of managing and transitioning breakthrough innovations from university labs to the market (Huang and Li, 2019).

This dialogue is crucial in the broader economic landscape, especially for countries caught in the middle-income trap, characterised by medium wages and educational levels (Barbosa et al., 2022). These nations often rely on labour-intensive industries, which are increasingly at risk due to the rise of (Autor, 2015; Lee et al., 2020b). University ecosystems can, therefore, play a critical role in mitigating these risks by upskilling the labour force, fostering entrepreneurial ventures, and facilitating the development of new industries less susceptible to automation (Carayannis et al., 2018). Moreover, they can collaborate with governments and industries to ensure that innovation mechanisms are not only designed to bolster advanced research and development but also to promote radical innovation outcomes (McDowall, 2012).

2.4. The South African context

In South Africa, the challenge of stimulating economic activity and creating work opportunities are multi-faceted (Botha, 2019), exacerbated by high unemployment rates that exceeded 29 % (Statistics South Africa, 2021). These challenges are rooted in complex political dynamics, slow-moving legal and policy frameworks, and ethical dilemmas that often stifle the adoption of emerging technologies and long-term innovation development (Sutherland, 2020). A further hindrance is an insufficient number of qualified graduates in science, technology, engineering, and mathematics (van Laar et al., 2017).

Despite these challenges, there exist significant opportunities for innovation within South African university ecosystems. One critical avenue is to leverage 4IR technology, with academia playing a pivotal role as demonstrated in the White Paper published by the Department of Science and Technology South Africa (2019). They have the capacity to influence and shape their surroundings, creating ripple effects that can boost the regional economy and ensure societal development. To achieve this, open science across diverse knowledge fields, novel pedogeological methods and transdisciplinary research is being supported (Olaitan et al., 2021).

The role of innovation mechanisms within South African universities, presents a concrete opportunity to translate theoretical knowledge into practical outcomes that can impact society at large (Kademeteme and Twinomurinzi, 2019). Kruger and Steyn (2019) underline the significance of these mechanisms; however, there remains a lack of detailed exploration into how they can specifically enhance the capabilities of university ecosystems in South Africa. Consequently, there exists a noticeable gap in the literature that addresses the nuanced interactions between innovation mechanisms and the larger university ecosystem. This study aims to bridge this gap by providing a focused examination of interactions and functions. In addressing these gaps, the study recognises the necessity for a theoretical lens to analyse and interpret findings effectively. Rogers' Diffusion of Innovations (DOI) theory is selected for its robust framework that explains how, why, and at what rate new ideas and technology spread through cultures (Rogers, 2003).

2.5. Theoretical lens: Diffusion of innovation (DOI)

The innovation mechanism under assessment is embedded within a university, incorporating various technologies that enhance innovation capability development across the academic ecosystem (Dixit et al., 2022; McDowall, 2012). Given this context, the Diffusion of Innovation (DOI) theory is adopted as it is particularly suitable for the South African context, as it provides a strong argument for understanding the adoption and diffusion process within a socio-economic landscape characterised by disparities. The DOI theory can also explain the pathways through which innovation can be cultivated and sustained within the university ecosystem, accounting for the socio-cultural and economic factors pertaining to South Africa. The DOI theory, inherently adaptable and inclusive, evaluates a spectrum of technologies and their impacts, rather than a single technology in isolation. This flexibility allows for a comprehensive analysis of multiple 4IR technologies that are used within a makerspace and identify their synergistic effects on innovation outcomes (Straub, 2009). Furthermore, the DOI theory has strong affiliations with other prominent theories like the Technology Acceptance Model (TAM), Theory of Planned Behaviour (TPB), and the Unified Theory of Acceptance and Use of Technology (UTAUT). It also acknowledges that individuals vary in their degrees of innovation adoption, postulating that the diffusion of innovation among a population normally distributes over time (Rogers, 2003).

Rogers' DOI theory outlines five key constructs that are instrumental in understanding and evaluating the adoption of innovation including (1) Relative Advantage (RA): The degree to which an innovation is perceived as better than the idea it supersedes. In the context of this study, RA can be used to assess the perceived benefits of makerspace technologies over traditional methods in South African universities. (2) Compatibility (CA): This refers to how consistent the innovation is with the values, experiences, and needs of potential adopters. Compatibility will be evaluated in terms of how makerspace technologies align with the existing educational and research practices within the institution. (3) Complexity (CE): The degree to which an innovation is perceived as difficult to understand and use. Investigating the complexity of new 4IR technologies can shed light on potential barriers to their full integration in creating new forms of value. (4) Trialability (TA): The extent to which an innovation can be experimented with on a limited basis. Trialability can influence the willingness of university stakeholders to engage with makerspace initiatives. Finally, (5) Observability (OA): The degree to which the results of an innovation are visible to others. The observability of the impacts of makerspace technologies can accelerate their adoption among the academic community.

These constructs not only help in understanding the adoption process but also in designing strategies to enhance the diffusion of innovative practices within the university ecosystem. The DOI theory is thus more than a backdrop; it offers a structured approach to assess the processes of emerging technological adoption within an innovation mechanism assessed in this study.

3. Methodology

This study explores the role innovation mechanisms have in fostering stronger innovation capabilities within a university ecosystem, particularly in the African context. To do so, a case study methodology was adopted as it pertains to a specific area of enquiry, aligning with Gregor and Gregor, 2006 (2006:613). The case was chosen based on multiple selection criteria. Firstly, the case had to demonstrate a track record of tangible innovation outcomes that adds value to a university ecosystem. Examples of such outcomes had to include patents resulting from ideas and projects developed within the mechanism, spin-off businesses that took root from entrepreneurial ventures in the space, and partnerships formed between the academic institution and external entities. Secondly, it was crucial that the case focused on the development of graduate skills considered essential for the 4IR, such as digital literacy, critical thinking, problem-solving, and creativity (Bai, 2018). Consequently, the case selected was an academic makerspace, the first of its kind in South Africa, that had proven examples in this regard. At the time of assessment, it was based in the administrative capital of South Africa at one of the top ten universities in the country. It offered conventional services for creation, exploration, and idea sharing through standard tools and space availability. It extended this by integrating emerging 4IR technologies, such as 3D printing, 3D modelling, and IoT devices directly into academic coursework which is similar to international initiatives (Ciriello et al., 2019).

3.1. Timeframe

The study was cross-sectional, spanning over six months, from June to December 2020. This was done to identify processes towards innovation outcomes during an academic year in the region. Although activities in certain instances produced outcomes quickly, research outcomes commonly take more time to materialise, hence the time frame.

3.2. Data collection

A purposeful approach was used to attain the needed data. To obtain the data and observe activities, one of the researchers were based in the makerspace itself during the study, facilitating a purposeful sampling approach. They were directly involved in tracking outcomes of such activities, in this capacity allowing for granular observations and access to outcomes from activities. Activities that facilitated innovation per Rogers (2003) were noted and tracked, producing qualitative data from multiple sources as shown in Table 1. The qualitative data encompassed (1) project activities, where for each project case, all relevant activities were logged, providing detailed descriptions and dates. (2) Tangible project outcomes such as news items, patent applications, business spin-offs, minimum viable products (MVP), research papers or curricula integration for skills development were also logged. (3) Partnerships used during the project that enabled outcomes were logged, detailing the nature, scope, and duration of the partnerships to understand the collaborative framework within the makerspace. Finally, observational data on (4) new skills acquired by participants through their involvement in makerspace projects were collected to assess capacity building. For effective tracking and analysis, a project management tool based on Kanban principles was utilised. This tool facilitated a visual and dynamic representation of the projects, enabling easy monitoring, updating, and analysis of the innovation process as it unfolded.

3.3. Data analysis procedures

Thematic analysis is a widely used method for qualitative data analysis and was employed in this study to organise and categorise the data in a coherent and relevant manner to produce meaningful themes, in this case, functions that support DOI constructs and associated innovation capabilities (Saunders et al., 2016). The initial stage required the researchers to familiarise themselves with the data through reviewing all data collected from the project reporting tool. Significant points were then coded, where descriptive information to the data points were articulated into categories. From this data, categories emerged, where they were noted until such a stage that all needed information per Fram (2013) was collected. This allowed for the identification of

Table 1
Category overview.

Data type	Collection method	DOI focus area	Target group	Frequency of collection	Analytical tool
Project activities	Direct observation	CE, TA	Makerspace users	Continuous	Kanban board
Project outcomes	Record analysis	RA, OA	Makerspace projects	End of project cycle	Content analysis
Partnerships	Interviews/Archives	CA, CE	Academic/Industry Partners	As Formed	Descriptive Analysis
Skills development	Observational notes	TA, CE	Students/faculty	Continuous	Skill assessment tools

patterns to organise them into logical sections. To achieve this, constant comparisons throughout the study was conducted until a saturation point could be reached.

In accordance with the DOI framework, constructs were defined as follows: (1) Relative advantage (RA) was gauged by the user's propensity to adopt smart technology or amalgamate various technologies to augment their design and enhance the overall outcome. This dimension further encompassed ideation. (2) Compatibility (CA) was where testing of a concept occurred using specific technologies, demonstrating integration with user needs and existing systems. The (3) complexity (CE) was considered where the level of perceived difficulty was reduced, enabling users to harness technology to foster solutions and synergies across various disciplines, without posing significant technical challenges. (4) Trialability (TA) revolved around the opportunities provided to users to access smart technologies or skills, thereby reducing barriers to testing and iterating innovative concepts. (5) Observability (OA) was where demonstrations of technology applications through case studies, tours, workshops, external expertise, digital displays, and training took place to facilitate prototyping and transition to tangible outcomes for the subsequent phase.

For data validity, "investigator triangulation" on the qualitative data collected from tracking activities was employed. This approach incorporated multiple researchers to interpret and validate the data, reducing potential biases. Each researcher brought unique insights, significantly enriching the interpretation through their varied experiences and perspectives. This process not only enhanced the validity of our findings but also allowed for a more comprehensive understanding of the data. Through healthy discussions and debates, the researchers were able to extract more nuanced insights, strengthening the overall outcomes of our study (Saunders et al., 2016). Implementing investigator triangulation necessitated careful planning and coordination, but resulted in data that can be deemed valid.

Accordingly, by using a purposeful approach to selecting relevant data and thematic analysis, core functions could be identified towards a conceptual framework (Saunders et al., 2016; Urban and Chantson, 2017). A flow of the process to create the conceptual framework based on a pragmatic philosophical standpoint could be developed, the outcome of which is presented in Fig. 1.

It must be noted that despite the apparent homogenous population in terms of users, such as researchers, lecturers, undergraduate and postgraduate students within a university, it is accepted that significant differences in users' family backgrounds, cultures, ethnicity, sexual orientations, age, interests and field of study exist that could influence the variables per DOI (Davison and Martinsons, 2016). These were not explicitly noted to protect the users and align with ethical guidelines obtained from the institution's ethics board.

4. Findings

The makerspace environment in question embodies this theoretical framework through its dual physical and digital presence. It has transitioned from a DIY setup to a centre for technological exploration and innovation. The array of services provided—including access to high-end computing, 3D printing, CAD, IoT development, training, and hardware tools—facilitates a collaborative and co-learning atmosphere. The availability of professionals for consultation, either on-demand or

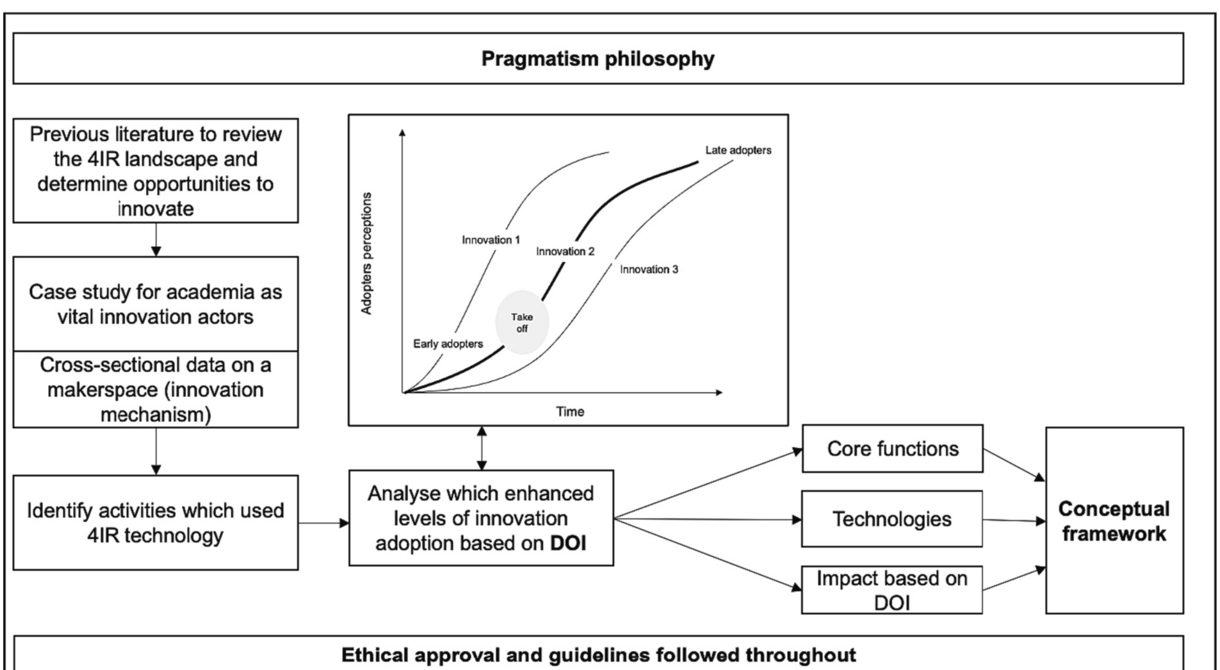

Fig. 1. Overview of research methodology
Source: Adapted from (Lyytinen and Rose, 2006; Saunders et al., 2016; Venkatesh et al., 2003; Yin, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

via appointments, serves to lower entry barriers and alleviate apprehension among technologically impeded users, fostering an inclusive and supportive learning environment. This approach not only aligns with but also enhances the principles of OA, TA, CE, and CA by making advanced technologies accessible and relatable to a broader audience, thereby catalysing innovative applications and solutions across diverse fields of expertise.

4.1. Project outcomes

349 outcomes were identified during the 2020 period of assessment that includes 12 high impact projects which required specific resources. High impact projects were considered to directly lead to research outputs, IP, copyright or patent. Table 2 provides a general description of the high impact projects, as well as key areas of development, with counts and categories assigned. Additionally, the primary discipline that it stemmed from is presented. During the period of assessment, 5 high schools and 3 universities consulted with the makerspace to replicate it within other regions of SA. The 5 schools would set such environments up as separate units, demonstrating a move beyond only higher education institutes.

From a theoretical narrative, several projects utilise theoretical constructs of the DOI, where some projects involved a deep interaction with technology, users appropriated digital and sensory technologies to address specific needs across disciplines. The makerspace environment, providing access to several 4IR technologies supported the creation of prototypes, thereby demonstrating constructs such as TA in a practical, high-impact scenario. The constructs are covered in more detail below.

4.2. Observability (OA) of 4IR technologies through the makerspace's physical and digital presence

The makerspace's dual presence, both physical and digital, created a conducive environment for the observability (OA) of 4IR technologies, a core principle within the DOI model which posits that the visibility of an innovation's results can stimulate peer-to-peer conversations and, subsequently, adoption (Rogers, 2003). The 170 instances of "*understanding 4IR technology*" from the data underscores this, reflecting the numerous opportunities for students and professionals to observe and subsequently engage with these technologies first-hand.

Table 2
Category overview.

Description	Count	Category	Discipline
Embargoed	1	Business spin-off	Engineering
Acoustic articulation for mammals	1	Research	Natural agricultural sciences
Dentistry enhancement	1	Research	Health sciences
Malaria research	1	Research	Natural agricultural sciences
Sensor development and deployment	1	Minimum viable product	Engineering
Bioreactor	1	Research	Engineering
Pressure sensing glove	1	Patent	Veterinary sciences
Sensor development and deployment	1	Research	Natural agricultural sciences
Biotechnical hand	1	Patent	Health sciences
Forensic pathology	1	Research	Health sciences
Radiographic tracking solution	1	Business spin-off	Health sciences
Business platform development	1	Business spin-off	Economic and management sciences
Understand 4IR technology	170	Curriculum engagement & skills development	Cross disciplinary
Collaboration	8	Research	Cross disciplinary
Innovate a product solution	69	Minimum viable product	Cross disciplinary
Test technology	87	Research	Cross disciplinary
Develop value outcome	3	Collaboration in ecosystem	Cross disciplinary

The digital presence of the makerspace, through virtual tours, digital exhibits, and online showcases, extended the reach of observability beyond the physical confines of the space. It provided a platform for external individuals to preview potential innovations, even radical innovations, amplifying the social influence paradigm and potentially accelerating the speed of adoption among diverse disciplines (Huang and Li, 2019). For example, the case studies and news items about innovations generated from the makerspace could have played a significant role in creating interest and conversations around the technologies showcased, thereby reinforcing the observability of their applications.

Within large academic institutions, the DOI with technology and place to observe the possibilities holds several benefits but also associated barriers. By creating and using a central place, such spaces appear to facilitate changes and encourage the positive observation (OA) of 4IR technology usage to support the speed of adoption in certain areas. In this instance the makerspace facilitated various experts across disciplines to note that despite resource limitations, usages and applications are possible. Students from all disciplines were granted access to the environment to explore possibilities, which was facilitated through various means such as tours, digital exhibits, workshops, case studies, and open collaboration groups. Thus, the space cultivated a positive social influence paradigm that allowed for the observation of innovation, and users were positively motivated to interact with smart technologies for their benefit and collective learning, thereby guiding the development and application of innovation. Core to which were competent leaders and engagement partners who appear to have created a culture of support and channel innovation for this paradigm that was present at the time of assessment. However, it should be noted that barriers were noted that could hinder projects identified such as existing ICT structures and resources.

4.3. Supportive conditions for Triability (TA)

Triability (TA) refers to the extent to which an innovation can be experimented with on a limited basis (Rogers, 2003). The makerspace facilitated this through access to resources like IoT integration projects, microcontroller kits, and 3D printing technologies. For example, unique animal surgeries on wildlife can be complex, with limited access to specific cases. By providing the tools to create a replica of a lion's tooth for surgical rehearsal, the makerspace enabled triability in a low-risk environment, ultimately leading to improved surgical outcomes. By allowing the surgical team to rehearse the operation on the replica, it helps to significantly reduce the time spent in actual surgery. Reducing surgery time minimizes the physical stress and potential complications for the patient - in this case, the lion - which is particularly significant for endangered or at-risk species. It also enhances the efficiency of the surgical procedure, allowing the surgical team to plan and predict potential challenges, thereby reducing risks and enhancing patient safety. Lastly, a shorter surgery time also translates to a more efficient use of operating room resources, which is an important consideration in healthcare settings where resources are often constrained. This is not only an instance of innovation but also an excellent example of how the makerspace's resources can be trialled for precise applications. This is in line with Hiran and Henten (2020) who note that access to expertise and technology in a safe space is crucial for fostering innovation. Such applications of 4IR technology in veterinary sciences demonstrate the practicality and immediate benefits of these technologies, likely encouraging further experimentation and adoption among users.

Furthermore, the case of thermal radiography for monitoring insect activity is another illustration of triability. The integration of IoT, ML, and cloud systems with existing ICT infrastructure facilitated the live-streaming and storage of data, pushing the boundaries of conventional research methods. The production of three research articles from this project highlights the substantial contribution of the makerspace to academic research and innovation. By offering access to 4IR technologies and allowing users to apply their concepts, negative perceptions and fear of users displaying lack of knowledge appear to have been reduced, especially where interaction was encouraged. This also shows that such spaces form part of the larger innovation ecosystems to show how value can be created from ideation through technology transfer per Kruger and Steyn (2019).

4.4. The role of the makerspace in simplifying complexity (CE) and enhancing compatibility (CA)

In environments like the one studied, it is common for users to be hesitant due to perceived complexities (CE) or fear of new technologies. The interactive nature of the makerspace, through workshops and open collaboration groups, appears to have mitigated such apprehensions. As suggested by Kruger and Steyn (2019), engagement with technology in a supportive ecosystem can lead to value creation from ideation to technology transfer. By translating 4IR technologies and fostering an atmosphere where trial and error are encouraged, the makerspace not only increased the observability (OA) of these technologies but also created a culture where their potential benefits and applications were tangibly demonstrated, aligned with the DOI model's theoretical underpinnings.

Academia in SA is held responsible for crucial skills development. However, as indicated by researchers like Jarrahi (2018) and Kaivo-Oja et al. (2017), this is a complex and multi-faceted problem as several future work skills are continually being researched. These vary but include creativity, critical thinking, complex problem solving, judgment, service orientation, emotional intelligence and technical computer skills (van Laar et al., 2017). The makerspace, by incorporating 4IR technologies into customised teaching and learning, lowers the barrier to understanding and using these technologies, thereby reducing perceived complexity for students and researchers. An example from the data that illustrates the reduction in perceived complexity is the engagement of students with AM, CAD and IoT. Through hands-on experience with these technologies, students were able to translate abstract concepts into practical applications. Turpin et al. (2020) observed that this practical engagement has led to a significant improvement in students' perceptions of these technologies, moving from seeing them as complex and intimidating too approachable and manageable. This was also later seen in a leadership course.

The compatibility (CA) of technology with the users' needs is fundamental for its adoption. The makerspace addresses this by allowing users to directly interact with the technology in a controlled environment. This interaction is critical for understanding how a technology can be applied to real-world scenarios. For instance, students in health sciences utilised 3D printing technology available in the makerspace to model human organs for surgical practice, directly linking their learning to practical medical applications. Engineering students developed IoT devices to monitor and improve campus energy efficiency, allowing them to translate concepts into environmental impact.

The multi-disciplinary nature of the makerspace's collaborations—ranging from health to economic and management sciences—facilitates a broad spectrum of knowledge exchange. Furthermore, the creation of a shared learning area where users can engage in cooperative learning and group-based experimentation fosters a conducive environment for nurturing innovation. Activities such as design thinking, brainstorming, technical skills development, complex problem-solving, collaboration, and critical thinking, are promoted through new media formats and assignments. The inclusion of emerging technologies like AM, CAD, IoT and cloud systems makes this a particularly exciting and stimulating space for undergraduate students.

By considering the specific context of the user, the space ensures that learning and innovation are tailored to the real-world applications of these technologies. The resultant effect is research that is both contextually applicable and practically relevant, positively influencing perceptions of complexity and compatibility. This approach, therefore, provides an excellent blueprint for university ecosystem drivers and multi-disciplinary research in a 21st-century academic setting.

4.5. Integration of services leads to enhanced perceptions around relative advantage (RA)

When investigating commercialisation potential, the Minimum Viable Products (MVP) concept was noted as a benchmarking tool (Guinan et al., 2019). The environment is uniquely positioned in the institutions ecosystem as it can identify potential research areas for technology transfer across disciplines or areas overlooked. Where they are identified, encouragement and support to develop an MVP relevant for this emerging paradigm are enabled through rapid prototyping. Where the space cannot assist, other mechanisms like the business accelerator or technology transfer office would be involved. The initiative ensures users are aware of channels to access various forms of capital in the region to strengthen entrepreneurial activities (Guinan et al., 2019; Urban and Chantson, 2017). Consequently, users could identity relative advantage (RA) and more importantly, channel the concept to actual outcome. The makerspace management aids in the practical assessment of this advantage by supporting the creation of MVPs. MVPs provide empirical evidence of the feasibility, viability, and desirability of new products or services before committing significant resources to full-scale development (McDowall, 2012).

For example, several different forms of MVPs were formed when the space collaborated with a business department. The space conducted design thinking on the role of innovation and application of emerging technologies. The outcome from this was a system that gathered new data to add insights into human movements—this combined IoT as physical devices to gather data and cloud systems to relay it. Users utilised CAD to design conceptual products containing IoT devices for needed data tracking. This solution was then conceptualised and put towards a business spin-off through the business accelerator at the time of writing. This demonstrates innovation space's role in supporting ideation. However, the scaling of commercial products or concepts remains a challenge, as noted by Sutherland (2020). This issue is especially prevalent in the developing world, where ecosystems to support scale-up activities may not be as mature or robust as in developed countries.

4.6. Transition and evolution of the makerspace

The transition of the makerspace from a DIY space to an innovation hub is substantiated by the diversity and impact of the projects it has supported. For instance, the development of the "radiographic tracking solution" indicates a shift towards sophisticated, market-ready solutions with a clear business application, moving beyond the realm of simple hobbyist DIY projects. This is despite resource constraints, where the entity's strategic revision towards a business model that could stimulate revenue generation showcases its adaptability. The 12 high impact projects necessitated specific resources, indicative of the space's ability to generate high-value outputs. This pragmatic approach to business modelling within an innovative space demonstrates an effective translation of theoretical constructs into sustainable practice. The sustainable business model pivot can be exemplified by the range of disciplines and categories that the high impact projects span. Revenue generation, as suggested by business spin-offs and patents, indicates a focus on commercial viability and entrepreneurship within the makerspace. This strategic shift facilitated by the makerspace aligns with the concept of managing ideas from conception to market-ready innovations, contributing to its sustainability.

In summary, the makerspace's hybrid structure, supported by competent leadership and a culture of innovation, facilitated the observability and triability of 4IR technologies. These supportive conditions enabled diverse users to move beyond mere observation, to engage with and apply these technologies innovatively, fostering a cycle of learning, application, and diffusion consistent with the principles of the DOI model. Table 3 encapsulates activities relevant to these influences, as per the DOI model, drawn from the examined reports and observations. Areas and associated functions that aided in the transition of the concept to break-out innovations were also explicitly noted. For the purposes of this investigation, the complexity and compatibility of a technology were synthesised into a single construct, as it was identified that the central function of the mechanism to facilitate this construct towards diffusion lay in skill capacity. It is noteworthy that these functions exhibit parallels with Digital Innovation Hubs (DIHs). Despite DIHs providing more comprehensive services than the DIY concepts of generic makerspace's, the findings suggest that the spaces themselves bear the potential to evolve and offer an extended range of pertinent and functions to bolster the design phase of innovation and transition areas within an ecosystem, particularly in the context of a developing world.

5. Discussion

The case study focuses on an academic makerspace functioning as an innovation mechanism within a university ecosystem addressing the question: "*How can innovation mechanisms be employed to enhance the capabilities of university ecosystems in managing breakthrough innovations?*"

The case study aligns with the constructs of DOI, such as Observability (OA) and Trialability (TA), as the makerspace's core functions not only facilitates social learning and iterative development but also uniquely reflects the interplay of technology and scarce resources. However, while literature suggests that resource constraints typically hinder innovation, our findings interestingly indicate that these constraints may also drive creativity and problem-solving, thus contributing a novel perspective to DOI (Ciriello et al., 2019; Dixit et al., 2022). Moreover, the technologies used span across the physical, connectivity, and digital layers of the 4IR, lending a needed perspective on how to harness the potential opportunities offered by this paradigm (Kademeteme and Twinomurinzi, 2019). To better connect these observations with DOI, each construct is represented through case study activities. For instance, the complexity and compatibility of new technologies are mitigated through tailored workshops that develop both hard and soft skills, thus fostering an innovation-ready mindset. This practical application enriches DOI by illustrating how innovation mechanisms can be structured to facilitate the diffusion process.

- Observability (OA): The makerspace facilitates social learning and co-creation, enabling users to learn from each other and collaboratively develop innovative solutions.
- Trialability (TA): It serves as a hub for rapid prototyping, encouraging experimentation across varied disciplines, echoing the necessity for cross-functional innovation as indicated by McDowall (2012); allowing innovative solutions to be developed and tested across a range of disciplines, including business, mining, health, energy, and art. This supports our research question pertaining to the capacity of makerspaces to enable the prototyping and refinement of interdisciplinary ideas.
- Complexity and Compatibility (CE and CA): The makerspace fosters the convergence of creative ideas, enhancing the creative capacity and technology literacy of its users, which ultimately results in the creation of tangible outcomes using technology. Data reveals the makerspace's role in amalgamating creativity with technological literacy, essential for tangible outcomes, aligning with the relationships between digital skills and needed 21st century skills aligning with van Laar et al. (2017). This addresses the research question on how makerspaces contribute to the technology competency within a university ecosystem.
- Relative Advantage (RA): The makerspace management's approach to MVP development directly contributes to identifying the relative advantages of new technologies and innovations. By providing the

Table 3
Summary of findings.

DOI Construct	Core functions that impacted construct	Outcomes	Primary 4IR technologies
Observability (OA)	Culture for transdisciplinary access and collaboration to identify and develop concepts while ensuring collaboration. Demonstration of technology usages through case studies, tours, workshops, digital displays, and news items. Applications are shown across industry sectors to demonstrate to various adopters the possibilities and help them understand a technology's usage.	Cross disciplinary engagements that encourage new avenues of research and uptake of new technologies. Social learning enablement and co-creation concepts. For example, in an informatics class of over 400 students who engaged with the makerspace space within the prototype phase of design thinking. The outcomes saw 42 student projects created, with three groups being recognised as success cases within the university.	Demonstration of AM, CAD, IoT allowing users to see what is occurring and observe the potential applications
Triability (TA)	Idea development (ideation) workshops, hackathons, and training to allow testing most viable technologies and developing ideas and solutions. Access to use a technology for academic or personal reasons. Hobbyist mindset encouraged allowing access to a larger community.	Rapid prototyping of innovative solutions towards needed outcomes across several disciplines, including business, mining, health, energy, and art. For example, integration with the biological field where animal surgery for small mammals was improved by reducing surgery time attributable to prebuilt solutions using 3D printing. Microcontroller kits were available on loan with dedicated training that saw 3 research outcomes a bioreactor design, a new data collection system in agriculture and enhanced tracking in malaria simulations.	Guidance and access to using technologies such as AI, AM, IoT, CAD and 3D scanning
Complexity (CE) and Compatibility (CA)	Skills development on 4IR technology usages, integration, development and application through dedicated training and hands on consultation. Leverage technology as a catalyst to create solutions and synergies across	Convergence of idea, creative capacity & literacy to create an actual outcome using technology. For example, the integration with veterinary students for practical engagements not	Design with CAD, rapid prototyping with AM (3D Printing), building IoT simulations for testing and data collection points. Solutions could be tested with cloud systems

(*continued on next page*)

Table 3 (*continued*)

DOI Construct	Core functions that impacted construct	Outcomes	Primary 4IR technologies
	disciplines by creating solutions that are not technically challenging.	before possible with IoT to collect and benchmark data on bovine palpations.	whilst incorporating ICT infrastructure.
	Customised teaching and learning integration for future of work skills development.	Support early technology adoption by relating technologies to users' contexts, where there was direct integration with 1 large scale course (over 1000 students).	
	Ideation and guidance for accessing various forms of capital in the region to strengthen entrepreneurial activities. Also, guidance to transition a concept once conceptual idea has been tested.	Cross-disciplinary and expert collaboration to incorporate new 4IR technologies and deploy solutions rapidly across fields of expertise. For example, introduction of client facing robot.	
Relative Advantage (RA)	Collaboration and partnership development to enable prototyping and deployment to tangible outcomes for next phase.	Channelling concepts to viable capital funding for commercialisation with collaborators internal structures or industry partners. The space also channels users to other mechanisms such as the business accelerator or technology transfer office would collaborate, forming a larger innovation ecosystem.	Usage and application demonstration of various 4IR technologies to extend adoption (AI, ML, IoT)
		Enhanced transition management within the university ecosystem to channel and support breakthrough innovations.	

means for rapid prototyping and fostering a multidisciplinary environment conducive to design thinking, makerspaces can significantly impact the successful commercialisation of innovations. The empirical example of the collaboration with the business school unit demonstrates this approach in action, leading to tangible outcomes and highlighting the potential of the makerspace as a cornerstone in the entrepreneurial ecosystem.

The findings underscore the role of stakeholders in enriching the makerspace's functionality, aligning with the works of Jain (2023), yet extend this discussion by showcasing how the same functions enable innovation despite the challenges prevalent in developing regions as noted by Huang and Li (2019) that includes South Africa. These insights provide practical implications for policymakers and educators in similar contexts, suggesting that innovation can be catalysed through strategic resource allocation and technological integration, as argued by Lee et al. (2018). Additionally, innovation mechanisms in research-rich areas like universities remain crucial. They support the diffusion of innovation through interdisciplinary collaboration, design thinking, and open access, fostering the design phase. These mechanisms also serve as channels for knowledge exchange and ideation within university ecosystems, bridging the gap between theoretical knowledge and practical implementation. They also facilitate experimentation (triability), iterative development (compatibility), and idea refinement using advanced technology, creating value (relative advantage) even in developing regions. This continuous cycle of learning through practice stimulates innovation and instils essential skills, thereby enhancing the ecosystem. Makerspaces and similar innovation mechanisms can serve as strategic tools within universities, holding transformative potential regardless of differing strategic objectives. The identified core functions can be integrated into various environments to foster innovation capabilities, even in the face of significant obstacles such as those present in South Africa, thereby building a stronger university ecosystem. Lastly, during the assessment, the pandemic emerged. Aligning with the perspectives of Wegmann and Schärrer (2020), the establishment and successful operation of such innovation mechanisms can generate value, even amidst crises as shown by Kruger and Steyn (2022).

Although the research focuses primarily on the South African academic context, the theoretical contributions offer insights into the operationalisation of academic innovation mechanisms in similar ecosystems. Firstly, it underscores the importance of academic institutions and their ecosystems in fostering innovation (Sutherland, 2020). It posits the makerspace as an essential intermediary, facilitating the transition from idea generation to commercialisation, in accordance with the university's strategic objectives (Castelo-Branco et al., 2019; European Commission, 2018). The study posits the critical role of internal structures or industry collaborators in turning ideas into viable commercial ventures. It highlights the function of the innovation space as a bridge, guiding users to other supportive mechanisms like business accelerators or TTOs, thereby fostering a more comprehensive innovation ecosystem. However, limitations such as a lack of infrastructure and expertise may hinder these mechanisms (Sutherland, 2020). Secondly, while not challenging existing theoretical foundations, the research emphasizes the importance of effective transition management within the university ecosystem, which is fundamental for channelling and supporting breakthrough innovations. These theoretical insights contribute to our comprehension of how collaborative internal dynamics and well-managed transitions can augment the performance of university innovation ecosystems. Within the African context, this is a large failure point. Lastly, by enabling triability and mitigating complexity, an innovative environment like a makerspace can aid faculties in expanding 4IR technology adoption, furthering innovations in research, and producing commercially viable outcomes. By doing so, it can strengthen the overall university ecosystem (Bartoloni et al., 2021). This supportive space thereby plays an instrumental role in accelerating the uptake of innovation, guiding the journey from concept to tangible innovation breakthroughs.

Based on these insights, a preliminary review of constructs and influential factors was formulated (Seo-Zindy and Heeks, 2017) from the theoretical lens of the DOI. The construct observability can ensure the understanding of users towards the 4IR, allowing them access to develop concepts and ideas to engage in the paradigm. From this user develop ideas, sometimes referred to as ideation, to stimulate new designs and products, where access to test the solution (triability) and integrate the new technologies is considered. Complexity and compatibility require certain skills to enable the creation of an actual outcome. Finally, relative advantage, where there is proof of concept and demonstration of value is critical (Marak et al., 2019; Matthews, 2017; Utterback et al., 2019). Based on these premises, and the existing literature reviewed, a draft conceptual model was developed shown in Fig. 2. This framework illustrates how academic makerspaces can catalyse the innovation process, offering a strategic tool for universities, especially in developing

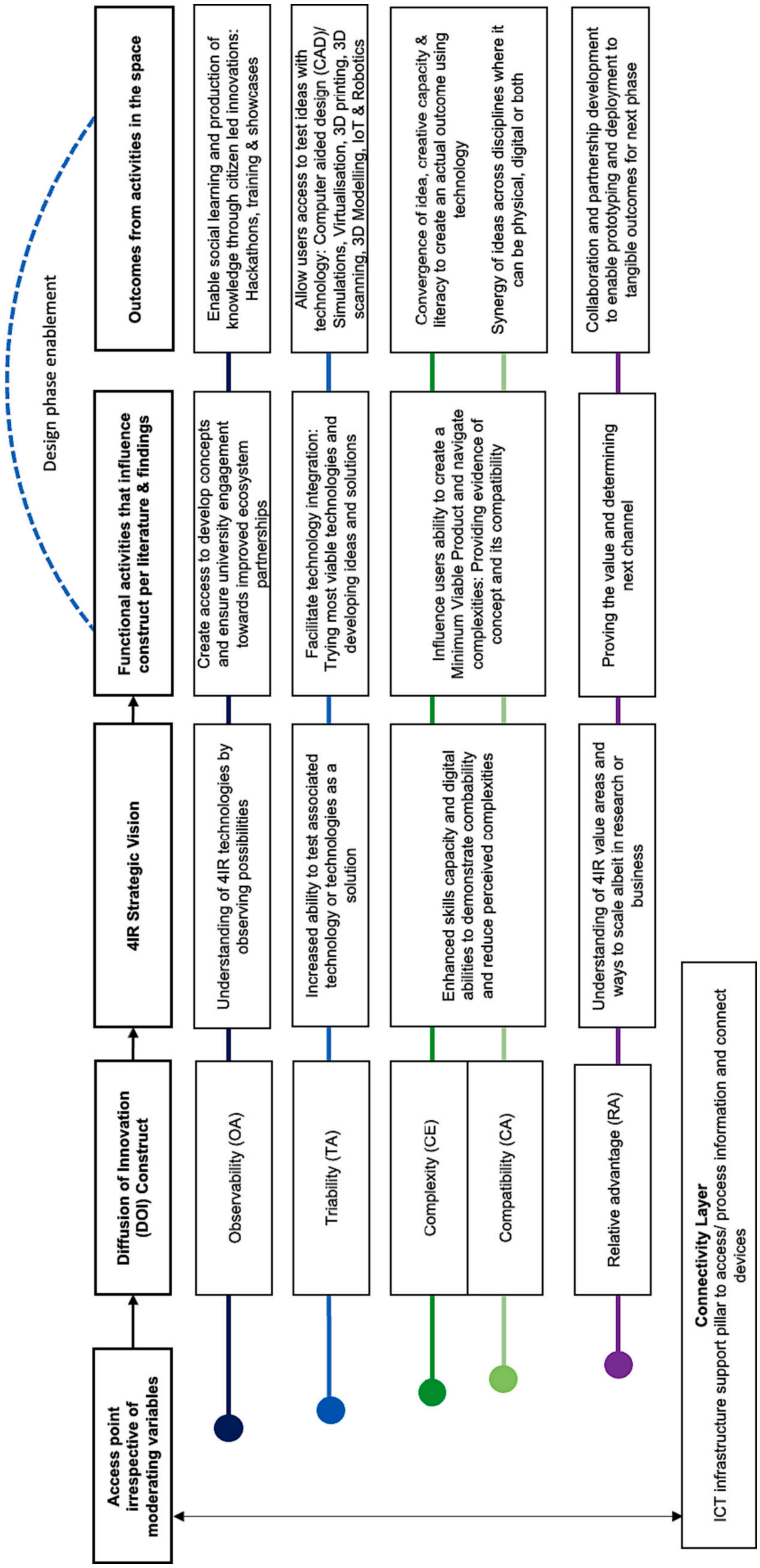

Fig. 2. Conceptual framework enhancing outcomes within the design phase of innovation.

regions. By bridging the practical case study with the theoretical frameworks of DOI, this research contributes to the understanding of innovation diffusion in unique socio-economic contexts, such as those found in South Africa, and highlights the strategic importance of academic makerspaces in nurturing innovation ecosystems.

6. Conclusion

This study presented a brief overview of the 4IR landscape, which has several potential benefits in developing economic activities through innovation. However, this advent paradigm has created a plethora of emerging technologies that actors need to consider, as it impacts societies in ways that are still being investigated. From a South African perspective, which is considered a developing world country, academia has been pressured to develop breakthrough innovations. From the findings, a conceptual framework was developed to note how makerspaces can act as innovation mechanisms to support adoption levels of 4IR technologies to develop needed innovation capabilities. To this end, the deliberate deployment and development of these innovation-centric environments can substantially boost a university's innovative potential, strengthening its broader ecosystem. This not only leads to substantial additions to the body of knowledge but also contributes meaningfully to the development of the region. Hence, academic institutions should embrace their pivotal role in fostering these innovation mechanisms, recognising the value they add in driving progress, developing knowledge, and stimulating regional growth.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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