The role of the Square Kilometre Array in South Africa's economic development strategy

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This study was undertaken to understand factors inhibiting and enabling the impact of the Square Kilometre Array South Africa (SKA SA) on the South African knowledge economy. A critical review of relevant literature revealed four themes, which are considered to be the main pillars crucial for engendering a knowledge economy: institutions, interrelationships, innovation and individuals. These pillars form the basis for the 4I model developed in this paper, the relevance of which in stimulating a knowledge economy was investigated. This study revealed no additional pillars, thus validating the 4I model in relation to SKA SA's contribution to the knowledge economy. SKA SA's success is underpinned by open and inclusive institutions, fostering and leveraging interrelationships, promoting innovation that may be commercialised, and attracting, retaining and training suitable individuals. Furthermore, this study provides a deeper insight into the 4I model by revealing new sub-themes that apply in a broader context, including the role of a nation's inherent competitive advantage in informing its competitive and innovation strategy, the nature of interrelationships that may be multidimensional, and politically astute leadership that is crucial for the ongoing support of a publicly funded project. This deeper understanding of the 4I model forms a basis for strengthening each pillar and its impact on the knowledge economy.

Significance:

- The 4I model, which is necessary for engendering a knowledge-based economy, is introduced.
- The role of a nation's inherent competitive advantage may inform its competitive and innovation strategy.
- A nation's institutions must be both inclusive and open for a knowledge-based economy to thrive.
- Interrelationships may be multidimensional in nature, including multidisciplinary, international and cross-sector collaboration.
- Politically astute leadership is crucial for the ongoing support of publicly funded projects.

Introduction

The main instrument and resource for economic development has evolved over time. Land was a key resource during a predominantly agrarian era.[1] Next, technological advances made way for the industrial revolution, which saw machinery as the key resource. More recently, further technological advances, mainly in information and communication technology (ICT), fostered the rise of an information age in which data and knowledge are the key resources.[1] Developed economies have turned to knowledge creation as an approach to realise competitive advantage and for sustained economic growth. Although South Africa has embarked on several initiatives to stimulate the economy, economic growth has steadily declined (refer to Supplementary figure 1 for South Africa's growth trend) and the economic outlook remains bleak.[2-4] In its search for sustained economic growth, South Africa is pursuing several knowledge-based initiatives.[5] The Square Kilometre Array South Africa (hereafter SKA SA or the project) is one such initiative.[6] The role and contribution of SKA SA to South Africa's knowledge economy is explored in this paper. The terms knowledge economy and knowledge-based economy (KBE) are used interchangeably hereafter.

Literature review

A KBE is an economy in which knowledge creation and its communication are the major engine for wealth generation and employment creation.[7] It results from the full recognition and exploitation of knowledge and technology as drivers for economic growth.[8] The creation of knowledge enables increased competitive advantage, not only for businesses but also for a national economy, which is difficult to imitate.[9-13] The concept of knowledge being linked to economic growth is not new, and the relationship has been acknowledged by Adam Smith, a pioneer of political economy.[8] However, knowledge remains directly linked to new economic growth theory[9], and must be converted, using innovation, and commercialised for economic growth[8]. For effective commercialisation, there must be close collaboration between industry, universities[1,8] and government: the role players in the triple helix model[14,15]. Although government may not be responsible for conducting research, innovation and commercialisation, it is responsible for establishing institutions with incentives such that a KBE may be fostered, such as fora for triple helix collaboration.

Government is the lynchpin in establishing and promoting a KBE. The determination of whether a nation has inclusive or extractive institutions, as described by Acemoglu and Robinson[16], refers to a nation's internal dynamics and is a direct consequence of policies adopted and implemented by its government[15,16]. In addition, nations need political and economic openness, which applies within a nation's borders as well as to its relationships with other nations.[1] Government is responsible for guiding the market system and thus economic growth.[17] A synchronised strategy is required, which accounts for institutions as well as policies required to enable the creation of a KBE. Importantly, the success of an institution hinges on the extent to which it is embedded in the economy. In addition, governments may adopt a structured ICT approach to support their synchronised strategy, thus closing

the gap between developed and developing economies by leveraging the learning of other nations, without following the same lengthy learning process.[1,18-20]

The role of individuals is another key factor influencing the creation of a KBE, as knowledge workers propel a KBE through their discoveries. Therefore, individuals must be supported and incentivised to innovate and discover new knowledge.[8] However, to support greater participation in the KBE, a broader set of incentives, in addition to the higher income earned, may be required. A diverse workforce or team promotes the convergence of different ideas, thus promoting creativity, and often yields commercially innovative solutions.[21,22] Diverse participation extends to the inclusion of women and the youth. A full and diverse workforce is required to optimise economic growth through innovation.[1] Although South Africa has some knowledge-based initiatives, such as SKA SA, transformation remains elusive. Income and wealth distribution continues to be inequitable and business structures remain non-representative.[23] Furthermore, the South African economy does not have full participation of its citizenry.[24] South Africa needs to identify sustainable initiatives, including those driven by innovation, to uplift those living below the poverty line and determine how to effect transformation such that broader citizenry contribution and participation takes place.

Science and technology (S&T) endeavours often result in innovation. The Organisation for Economic Co-operation and Development[8] considered that innovation might be either mission-oriented or diffusion-oriented. Typically, the benefits of fundamental research are realised in the long term.[8] Low-cost manufacturing and 'copy-cat innovation'[1(p.217)] may yield short-term benefits. However, fundamental research is essential for innovation, which yields competitive advantage, and thus sustained economic growth.[1,25-27] Innovation and development go hand in hand.[12] Global trends and technological advances have far-reaching consequences,[9,28,29] and their significance should influence national strategies and policies. Technological advances are disrupting existing markets and industries, thus fundamentally influencing how firms compete[10] and how national economies remain relevant. Mainly as a result of pressure from investors for short-term gains, the responsibility to drive fundamental research has shifted from corporations to government.[20] Fundamental research is extremely risky and by government funding fundamental research, market risk is reduced.[26,27] Skilled individuals and corporations will be attracted through government fostering of a collaborative climate in which innovation is pursued.[1,30] Moreover, S&T and innovation create the potential for developing nations to leapfrog or close the economic divide that exists between developed and developing economies, because developing economies do not have to follow the same innovation path previously followed by developed economies.[1,18,19] Seemingly, a paradox exists: sustained economic growth often depends on cutting-edge innovation, and the scale of cutting-edge innovation demands collaboration or sharing, which compromises competitive advantage. Indeed, sustained competitive advantage demands sustained and novel innovation. One leading scientific research area, which arguably rests at the pinnacle of innovation, is astronomy.

Astronomy – which refers collectively to astronomy, astrophysics and cosmology hereafter – stirs the imagination and spirit, and 'enjoys broad public appeal', from people of all ages[31(p.103)], by inducing awe and wonder[31]. It is the oldest science[31,32], and arguably has had the greatest enduring impact on civilization[31]. The human intrigue with the heavens has existed from time immemorial and inspired great feats.[32] Among its earliest uses, astronomy shaped the progress of agriculture and navigation.[32,33] Lunar and solar cycles underpinned the recording of time, and continue to do so even in modern time.[32] Arguably, the greatest technology-led breakthrough for astronomy was in 1609, when Galileo Galilei first used a telescope to view the night sky.[31] Since then telescopes have steadily improved.[31] Spurred by technological advances, astronomy has made unprecedented progress in recent decades.[31,34] Innovation resulting from astronomy has had far-reaching commercial spin-offs[35-37] (refer to Supplementary table 1 for a list of commercial spin-offs from astronomy-led initiatives). Astronomy embarks on fundamental research endeavours.[35,37] Although the fruit of these endeavours is often only realised in the long term[31], investment in astronomy fosters innovation, enhances educational opportunities in science, technology, engineering and mathematics (STEM) and contributes to developing the workforce[31,35,37]. Importantly, the high-quality feeder from both primary and secondary education significantly influences the success of universities to attract and develop good students.[20,31] Training must be supported by 'significant investments in world-class and innovative research infrastructure, [which enables a nation] to attract and retain excellent researchers'[37(p.7)].

The scale of modern day astronomical projects demands international collaboration[31], because partner countries may leverage cutting-edge data and technologies, as well as scientific funding[37]. Notably, these partnerships are not limited to partnerships between different nations, but may include triple helix collaborations[31,37], which are promoted by nations' institutions[36]. In order for commercialisation to be fast-tracked, researchers require incentives to promptly share findings with the public and industry.[37] Astronomy may underpin a nation's innovation plan.[31,37] A coherent strategy for astronomy is necessary to optimise the impact of available resources and may be an asset in negotiating international partnerships.[31] Astronomy is heavily reliant on government for funding. During periods of sluggish economic growth, governments may opt for short-term prioritisation, thus limiting or foregoing initiatives with benefits that are realised in the long term, such as astronomy-related fundamental research endeavours. Astronomy in South Africa lacks a comprehensive strategy and has faced budget reductions.[38] South African astronomy requires sustained funding and a comprehensive and coherent strategy, commencing with primary and secondary education, which is the feeder into universities. The quality of education, especially that of mathematics and science, is of great concern in South Africa.[39] Furthermore, the plan should ensure that institutions are established in which triple helix collaborations thrive and knowledge is diffused. The plan should identify astronomy projects, such as SKA SA, that will be pursued so that resources appropriated for astronomy in South Africa may be focused.

Arguably, as South Africa's largest science project and one of 18 Special Infrastructure Projects,[38,40] SKA SA plays a major role in the endeavour to build the world's largest radio telescope. Co-located in South Africa and Australia, the telescope is expected to have a total collecting area of approximately one square kilometre.[41] Significant technological advances are required to complete the telescope's construction, which will result in image resolution superior to that of the Hubble Space Telescope by a factor of 50.[42] The SKA telescope will observe stars and galaxies up to billions of light years away to better understand the formation and evolution of celestial bodies.[41] It will be constructed in phases to manage risk and to allow technological advancement.[43] Notably, as more dishes are added to the telescope, more data will be generated (refer to Supplementary figure 2 for the anticipated data volume of SKA SA). This iconic project has been attracting the best scientific talent from around the world. SKA will pioneer advances in high-performance and big data computing, provide a platform to create skills for KBEs, and stimulate interest in mathematics-related careers. In addition, the new infrastructure development will create opportunity for innovation, which will yield commercial spin-offs.[41]

The preceding literature suggests that South Africa can improve its competitive position as well as the World Economic Forum's ranking regarding the quality of its scientific research institutions, and its capacity for innovation,[39] by adopting a synchronised plan, which includes open and inclusive institutions. The plan should promote collaboration among individuals, and incentivise innovation so that a KBE may flourish, and competitive advantage is achieved. The Department of Science and Technology – the organ of state responsible for promoting scientific research in South Africa – has identified SKA SA as its flagship project.[38,44] This paper considers the requirements for creating a KBE, and focuses on the relevance of SKA SA as a knowledge engine and its contribution to economic growth.

Theoretical model

Four main themes crucial for creating and sustaining a KBE emerged from the literature review: institutions, interrelationships, innovation

and individuals. These themes may be considered as the pillars crucial for a knowledge economy. The interplay of these pillars is referred to here as the 4I model. Notably, these pillars do not exist in isolation. To successfully promote any one, depends on the strength of the remaining pillars. Each of these pillars must be strengthened to strengthen a knowledge economy. The relationships among the pillars may be likened to that of gears. The speed, size, and strength of any of the pillars will influence the remaining gears, as illustrated in Figure 1. There is a complex interaction and inter-dependence among the four pillars. *Individuals* exist, operate and influence each of the other three themes. *Institutions* must be open and inclusive to attract and retain individuals who innovate. Open and inclusive institutions foster an environment in which ideas may be transformed, by individuals, into *innovations* for commercialisation. Institutions establish the platforms on which triple helix *interrelationships* may flourish. Arguably, the greater the number of symbiotic interrelationships, the greater the prospect of sharing, and the greater the prospect of success. The 4I model is the basis of this research study.

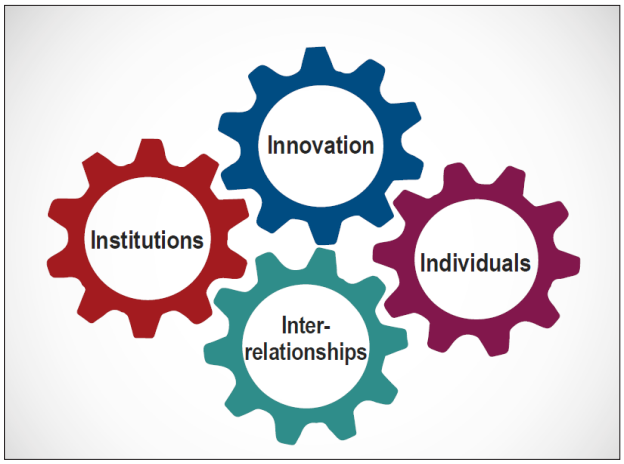

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Figure 1: The gear-like nature of the 4I model.

Methodology

A qualitative research approach was adopted because it supports constructing a detailed description of a participant's social construct or perceptions. This study is inductive in nature and employed interpretivist epistemology. A cross-sectional research design, rather than a longitudinal design, was employed because the SKA project is in its infancy and it will take many years before its impact as a knowledge engine in the South African economy can be measured more meaningfully. Although this study is cross-sectional in nature, it is replicable. A future study might provide more clarity on SKA SA's impact on the South African economy, as more information may then be available. However, the same themes are expected to emerge. This study was segmented into five steps, which are described briefly below.

Firstly, the literature was reviewed to broadly determine the factors that contribute to economic growth and development. The literature review was then focused on S&T, particularly on astronomy, to determine the role of S&T and astronomy on economic growth. The literature review was interrogated to identify themes, which formed the basis for the research questions devised. Secondly, data were gathered through a process of semi-structured interviews. The interview questions were formulated to investigate the themes that emerged from the literature review, as encapsulated in the 4I model – that is, the role of institutions, interrelationships, innovation and individuals in creating a KBE. A question was included to investigate impediments and enablers for SKA SA's success that were not already proposed by the respondent. This additional question was important because it investigated gaps in the literature review, and could have highlighted additional findings. Thirdly, the findings were formulated, drawing on themes that emerged from the interviews. Fourthly, recommendations are made on how the 4Is should be strengthened to augment SKA SA's impact in promoting a knowledge economy in South Africa, and, lastly, the conclusions drawn from this study are discussed.

Primary data were collected over a 7-week period through interviews. Interviews were conducted via Skype™ as the most convenient method to access participants in the available time frame. One-on-one interviews were chosen over focus groups, for greater control, and allowed respondents greater freedom to express themselves.[45] In addition, one-on-one interviews were more practical to schedule and allowed for a more in-depth investigation. The interviews were recorded to preserve the data for subsequent review.[45] Homogenous and purposeful sampling was adopted, and senior officials associated with SKA SA were selected as respondents for this study, as they have the specialist expertise and knowledge regarding SKA SA. In collaboration with the business manager of SKA SA, 11 suitable candidates to participate in this study were identified. Interviews were audio recorded, and supported by field notes[46,47], to determine themes that emerged.

Ethical clearance for the study was obtained from the Graduate School of Business, University of Cape Town (ref. GSB/MBA/2016/101). The respondents were informed that their participation was voluntary and that they could withdraw at any time. The respondents were also informed that their identities would be protected; all references to the respondents ensure anonymity.

The results of the study may be limited by participant bias and the small sample size. Participants may have shown a bias to support SKA SA, because the project's success is key to their continued employment. In addition, the sample size was by necessity small, as the number of senior officials associated with SKA SA is small.

Results and discussion

The results confirm that the SKA SA project contributes to promoting South Africa's knowledge economy. The study verified that the four main themes identified in the literature review (institutions, individuals, interrelationships and innovations), as encapsulated in the 4I model, are crucial for creating a knowledge economy, as demonstrated in the context of SKA SA. No additional themes were identified. In addition, four new sub-themes emerged that were not identified in the initial literature review. However, each of these new sub-themes is directly linked to one of the main themes. The sub-themes relate to the role of inherent competitive advantage in formulating a nation's strategic policies, the introduction of the concept of multidimensional interrelationships, the significance of leadership being politically astute, and the significance of developing and commercialising value chain products. The main findings relevant to each pillar, including the new sub-themes, are discussed in further detail below.

Institutions

This study has revealed that stable and consistent policies and funding strengthen the institutions pillar, especially for long-term projects.[20,48,49] Astronomy and SKA SA, a long-term project, have both benefitted from stable and consistent policies and funding.[50-53] The respondents noted that while there is significant engagement with other government departments to maximise support for the telescope, and to maximise the economic benefit that the telescope may yield, there remains scope for improvement. Six respondents noted that SKA SA is adequately funded. State investment in fundamental research, which is extremely risky, reduces the overall market risk.[26,27] As a business unit of the National Research Foundation, SKA SA is subject to standardised processes, some of which are ill-suited for a development project such as SKA SA. For example, the onerous procurement requirements of the *Public Finance and Management Act* promote governance, but occasionally slow the rapid progress of the SKA SA. The respondents expressed the view that there is a national focus on quantity rather than quality: for example, there is a drive to produce an increasing number of students and publish an increasing number of papers. Respondent 6 conjectured that South African scientists will be ill-equipped to lead the big science endeavours in years to come, if quality continued to be ignored.

Although SKA SA enjoys widespread support from government, certain regulations, structures and policies slow SKA SA's progress.

A new sub-theme was revealed – namely that a nation's competitive and innovation strategy may be informed by its inherent competitive advantage. Inherent competitive advantage may be leveraged to strengthen the key pillar of institutions, thereby fostering a knowledge economy. South Africa's geographical advantage was considered when determining fields in which the country's fundamental research endeavours should be promoted.[54] Importantly, the geo-location advantage is latent unless it is coupled with sound institutions, which is an argument overlooked by Landes[55], but appreciated by Acemoglu and Robinson[16]. Moreover, government efforts must focus on a subset of industries.[1,17,56] Arguably, the same is being done in South Africa, where focus is directed at areas with inherent competitive advantage, such as radio astronomy.

Interrelationships

All respondents noted SKA SA's interrelationships with universities, government and local businesses. The interview data revealed that SKA SA has impacted and maintained interrelationships with universities. Seven respondents noted that SKA SA enjoys widespread support from government, and that SKA SA engages with external companies to pursue research and development opportunities. The respondents further noted that developing these local industry partners during the design phase would strengthen the likelihood of these industry partners being awarded tenders for international contracts during the SKA construction phase. These data demonstrate that SKA SA's interrelationships are consistent with the triple helix model as described by Etzkowitz and Leydesdorff[15] and Etzkowitz[14].

However, the astronomy landscape is evolving, which heightens the need for collaboration and knowledge sharing. Respondent 10 noted that the scale and complexity of modern projects transforms the sociology of astronomy. This respondent further noted that astronomy today calls for multidisciplinary, as well as cross-sector collaboration, which is founded on knowledge sharing. Evidently, knowledge sharing underpins the success of astronomical projects, such as SKA SA. Moreover, knowledge sharing is underpinned by interrelationships, that is, both SKA SA's relationships with other partner countries as well as cross-sector collaboration. Six respondents mentioned that the astronomy domain has had a culture of knowledge sharing. Respondent 11 contrasted astronomy with the military, noting that confidentiality is imperative in the military. However, the respondent highlighted that the collaborative culture that exists during the design and construction phase will not apply to fundamental scientific discoveries. The respondent noted that knowledge gained from fundamental research studies will be guarded, and shared through academic publications.

The nature and complexity of modern astronomy demands cross-sector, multinational, and multidisciplinary collaborations, hereafter referred to as multidimensional interrelationships, which is a new concept introduced here. Respondents provided examples that highlighted the multidimensional nature of interrelationships at SKA SA. Eight respondents mentioned that SKA SA works in conjunction with partner countries in multinational teams and that SKA SA has representation on SKA International's board of directors. All respondents noted that SKA SA had initiatives across the full spectrum of knowledge generators (knowledge generators refers to high schools, universities and further education and training colleges) and that project initiatives were not limited to universities. In addition, five respondents noted that collaboration was not limited to local businesses, but included collaboration with multinational enterprises, such as IBM.[57] Based on these responses, it may be inferred that triple helix interrelationships are less comprehensive than multidimensional interrelationships. The former is limited to cross-sector interrelationships, while the latter includes cross-sector, multinational and multidisciplinary interrelationships, and should be promoted for their more comprehensive role in developing the knowledge economy. Additionally, multidimensional relationships incorporate the full spectrum of knowledge generators. This study confirmed the conjecture made by Kose and Ozturk[58] that technological advances spur interrelationships and inter-dependencies.

Innovation

This study revealed that SKA SA is fuelling innovation through its big data and commercialisation initiatives. Innovation presents the opportunity for developing economies to leapfrog, and to close the divide between developed and developing economies.[1,18,19] Respondents 3 and 10 described big data[59,60] management as the greatest challenge that SKA SA is expected to face. Respondent 10 explained that the challenge will increase as more antennae are added to the telescope (refer to Supplementary figure 2 for SKA SA's anticipated data volume)[43]; however, the Inter-University Centre for Data Intensive Astronomy has been established in response to the big data challenge presented by MeerKAT, which is expected to be exacerbated by the SKA telescope. The Inter-University Centre for Data Intensive Astronomy recently became the first African institute to launch a cloud data centre, that is the African Research Cloud.[61]

SKA SA collaborates with local industry partners to increase the likelihood of local business winning tenders during the construction phase, developing local capacity in once declining technical areas, and to exploit commercialisation opportunities.[62] A strengthened innovation pillar increases SKA SA's chances of being awarded the post-construction operations contract. The respondents noted that the ongoing support and maintenance of the telescope's post-construction operations, with an expected duration of 50 years, presents a significant opportunity to contribute to the South African economy. In addition, all 11 respondents noted that SKA SA has developed several products suitable for commercialisation. Interestingly, several products developed may be used in various permutations with other products that are also developed by SKA SA, thus creating product value chains, which further strengthens the innovation pillar. Therefore, product value chains are considered a new sub-theme for fostering a knowledge economy, as they were not identified in the literature review. Importantly, creating such value chains promotes market sustainability of the products developed. However, Respondents 1 and 3 noted that SKA SA lacked a coherent policy for commercialising innovation, and Respondent 9 noted that there was no dedicated budget available for promoting commercialisation. A coherent plan is crucial to ensure that resources are optimised.[31] Notably, the respondents also mentioned that a commercialisation manager had recently been appointed by SKA SA, and was likely to address these gaps. Armed with fruitful symbiotic collaborations with industry partners, SKA SA appears poised to enable the transformation from innovation to commercialisation.

Individuals

This study revealed that upgrading human capital and attracting and retaining suitable individuals are essential sub-themes for strengthening the 'individuals' pillar. Suitable individuals refers to individuals representative of the diversity of South Africa who have the desired skill set. Diversity includes gender, age and racial considerations. In addition, a new sub-theme was revealed – that is, the significance of politically astute leadership on publicly funded projects, such as SKA SA. The responsibility for upgrading human capital in the astronomy pipeline, and attracting and retaining suitable individuals, rests mainly with the Human Capital Development (HCD) Programme and is discussed below. Notably, upgrading the skills of SKA SA's staff is the responsibility of the project's human resources function, while upgrading the skills of local industry partners is the responsibility of the design consortia.

The HCD initiatives are primarily directed at the youth, considered by Ross[1] to be more adept in using technology proficiently. Respondents 3 and 7 explained that the initiatives target the full spectrum of knowledge generators (universities, further education and training colleges, and schools) and includes a young professional development programme. Respondent 7 explained that by adopting a responsive and evolutionary approach, the programme has flourished and has become increasingly structured and focused. Ten respondents noted the impact that the HCD programme continues to have in universities in South Africa through

funding bursaries, grants and research chairs for the study of STEM subjects (refer to Supplementary figures 3 and 4 for the number of bursaries, fellowships and grants awarded). Five respondents mentioned that students created by the astronomy pipeline who are not absorbed by the astronomy community, will be absorbed by other sectors of the economy. SKA SA's initiatives are aligned with recommendations in the literature, in that universities contribute by training astronomers and attracting good students to study STEM subjects.[31,35] Astronomy-trained graduates assume senior roles in industry, thus further boosting the knowledge economy.[37] The upgrading of human capital is an essential requirement of a knowledge economy.[8] In a knowledge economy, highly skilled individuals are trained for highly skilled jobs.[9]

The respondents identified key enablers and inhibitors for attracting and retaining suitable individuals. All 11 respondents noted that the interesting and exciting nature of the SKA project has contributed significantly to attracting and retaining suitably skilled individuals within the project. Other factors credited for attracting individuals to SKA SA were the vision underpinning the organisation's goals, the professional management of the organisation, good leadership, healthy team dynamics, and working among high-quality peers. However, respondents also noted several challenges to attracting and retaining suitable individuals, which include the lengthy duration to obtain work permits for foreign nationals, and keen competition for the best skilled individuals who have scarce skills. Therefore, SKA SA places emphasis on the HCD programme to develop the skills of targeted groups of individuals. A significant investment in world-class infrastructure and innovation attracts and retains excellent researchers[37], and the visa processes should facilitate attracting individuals with desired skills, so that interrelationships and innovation can be promoted[20]. There was no consensus regarding the influence of remuneration in attracting and retaining individuals; three respondents considered SKA SA's remuneration to be market-related, while another three considered that it was not market-related.

A new finding that emerged from the primary data collected is that the political astuteness of leaders is crucial for ensuring sustained support for publicly funded projects. The political astuteness of leaders strengthens the key pillar of individuals. Therefore, the role of political astuteness of leaders is considered a sub-theme for fostering a knowledge economy. Four respondents noted the importance of SKA SA's leaderships' political astuteness in obtaining and retaining government support and funding. The respondents mentioned that the SKA SA leadership had strong professional relationships with government leaders, but also understood that delivering on commitments was essential for ongoing support.

Additional pillars and the 4I model

To test the robustness of the 4I model, respondents were asked if there were any factors, other than the four themes under investigation, which either impede or enable SKA SA's success. Six respondents noted that they were not aware of any additional factors or pillars, other than the four themes being investigated. Two respondents repeated their earlier contention that bureaucracy impeded SKA SA's progress. The importance of stable funding, the challenge of big data, and the challenge of South Africa having a limited pool of science graduates available for recruitment, are factors that were raised by each of three respondents. All the additional factors suggested by the respondents may be mapped into one of the four main themes that were already identified. Bureaucracy and stable funding are associated with institutions. The limited pool of science graduates is associated with individuals, and the big data challenge is associated with innovation. Therefore, this study did not reveal any additional pillars that enabled or inhibited SKA SA's contribution to a knowledge economy, thereby providing evidence for the robustness of the 4I model.

Recommendations and conclusion

Institutions, interrelationships, innovation and individuals were identified, through a literature review, as the four main pillars for a knowledge economy and investigated further. The findings of this study corroborate the validity of the proposed 4I model and no new pillars relevant to SKA SA were identified. Furthermore, this study revealed that the four pillars of the 4I model have indeed supported SKA SA's contribution to the knowledge economy. Although additional pillars were not identified, new sub-themes were identified from the interview data, which were not identified in the literature review. These sub-themes strengthened the 4I model, as each of the sub-themes is associated with one of the main themes. Furthermore, this study highlights that by strengthening each of the pillars through interventions identified below, SKA SA's impact on the knowledge economy will be further boosted. For each of the pillars, the main themes, sub-themes, limitations and recommendations, in relation to SKA SA's contribution to a knowledge economy, are summarised below.

It was found that open and inclusive institutions – one of the four main themes – are critical for engendering a knowledge economy. In the case of SKA SA, open and inclusive institutions were represented by protective legislation, and stable and consistent policies and funding. These institutions provide the foundation for SKA SA to flourish. Furthermore, SKA SA complies with institutional requirements, such as employment equity and broad-based black economic empowerment, that promote broad participation of South Africa's citizenry. However, this study also found limitations of institutions that hinder SKA SA from promoting a knowledge economy. Stringent and ill-suited processes, policies and key performance indicators can impede the project's progress. It was recommended that the structures, policies, procedures and key performance indicators for development projects such as SKA SA should be reformulated to optimise the impact of such projects. This study revealed a new sub-theme relevant to institutions: South Africa's inherent competitive advantage, that is, its geo-location was considered when determining the strategic direction of fundamental research that the country should pursue.

This study highlights that the nature and sociology of modern astronomy demands multidimensional interrelationships, rendering open institutions crucial for SKA SA's success. Multidimensional interrelationships are more complex than triple helix relationships. Knowledge is shared through multidimensional collaborations to find innovative solutions to complex problems. SKA SA's collaborations extend to SKA partner countries, government departments, industry partners and knowledge generators. Although not optimised, the project enjoys widespread support from all tiers of government. Furthermore, SKA SA's collaboration with industry ranges from small, medium and micro-sized enterprises to multinationals. Through collaboration with industry partners, SKA SA not only upgrades local human capital, but also places itself at the cutting-edge of technological breakthroughs. It was recommended that SKA SA involve additional industry partners, who already have a need for big data technology, during the early stages of product innovation so that commercialisation opportunities may be fast-tracked. This study also revealed another sub-theme – that is, product innovations may also be inter-related, thus creating product value chains. Product value chains improve the likelihood of market sustainability of products in value chains. The project successfully creates and leverages multidimensional interrelationships, which favourably impact South Africa's endeavours for fostering a knowledge economy.

It was found that the multidimensional collaborations often yield innovations, which may have commercial impact. Innovative products that are commercialised are also critical for a thriving knowledge economy. SKA SA has established and participates in numerous multidimensional collaborations, which promote knowledge sharing and joint problem solving. Local industry partners have been upskilled and are poised to commercialise product innovations resulting from the collaboration. However, SKA SA's commercialisation strategy remains outstanding, and is crucial for maximising economic benefit. It was recommended that SKA SA implement a commercialisation strategy. Overall, SKA SA has been successful with innovation, and once armed with a coherent commercialisation strategy, the project may have a greater impact.

It was also found that prestigious science projects, such as SKA SA, not only attract and retain suitably skilled individuals, but that these individuals are often amongst the best in their field globally. Furthermore, the professional management of the organisation, good

leadership, and healthy team dynamics contribute to the project's low attrition rate. Additionally, the HCD programme has fostered the astronomy pipeline, growing the astronomy community in South Africa. Students upskilled through the astronomy pipeline initiatives and not absorbed by the astronomy community could be absorbed by other sectors in the economy, thus further boosting the knowledge economy. Although diversity challenges persist, SKA SA has made progress with transformation. It was recommended that SKA SA continue to focus on transformation. Importantly, this study revealed the significance of politically astute leaders. These leaders are instrumental in ensuring ongoing support for the publicly funded project.

Overall, the results of this study show that SKA SA is contributing to growing the South African knowledge economy. The project is in its infancy and its full impact is not yet known. Future studies may include longitudinal studies of SKA SA, testing the validity of the 4I model on other fundamental research initiatives, and formulating the underlying economic theory for knowledge as a resource. Longitudinal studies may involve tracking the progress of SKA SA's bursars. Such studies may investigate the industries in which the bursars are employed, or the percentage of bursars retained in the South African economy. Another key subject to investigate is the extent and impact of fundamental research conducted on data from the MeerKAT and SKA telescopes. Here it would be important to determine how many of the big science research initiatives are being led by South African based scientists, which would provide a measure of the success of the HCD programme.

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