Transversality and innovation capability-based catch-up for sustainable mining in South Africa

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ABSTRACT

The study examines a cross-cutting innovation system, centred around the precious metals mining sector of South Africa which experiences unique challenges, requiring effort to improve the level of capability for catch-up. It explores the possibility of transversality across the mining and Information and Communication Technology (ICT) sectors for enabling catch-up and attempts to uncover promising windows of opportunity for leapfrogging in the mining sector.

The theoretical concept of transversality examines the possibility of synthesis and cross-fertilisation from knowledge spillovers of firms, clusters, industries and sectors in a regional innovation system (RIS) that leads to innovation. The type of knowledge interaction and the variety inherent in the system is studied to determine the possibility of path interdependent knowledge recombination.

Technological capability as well as the firm environment play a significant role in the catch-up process, and the study examines the role of Public Research Organisations (PRO) and other research institutions in building capability to embrace advanced technologies for that purpose.

A qualitative methodology is adopted to analyse data collected from mines, PROs, research institutions, and a start-up in the regional innovation system. This is contrasted with existing literature to postulate the possible path to catch-up.

If was found that mining in South Africa experiences unique challenges that will require a new path to catch-up, especially for deep level mining. Fourth Industrial Revolution (4IR) technologies represent a new technological paradigm and are being embraced, largely through direct adoption, though the technologies are also applied to solve the unique challenges the sector experiences. Several challenges pose barriers for the adoption of 4IR technologies, especially in deep level mining. However, these are the subject of ongoing research. Technological capability is built through research at universities and research institutions as well as in a doing, using, interacting model (DUI) through adoption at mines. However, the firm environment poses several challenges that must be solved at country level. Opportunities for leapfrogging have also been identified.

DECLARATION

I, Mahendren Thorulsley, declare that this dissertation is my own unaided work. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in Innovation Studies at the Wits Business School in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other University

21 day of November 2021

Mahendren Thorulsley

DEDICATION

To Vebashini and Kairaav

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LIST OF ABBREVIATIONS AND ACRONYMS

3IR	The third industrial revolution, also referred to as the Digital Revolution
4IR	The fourth industrial revolution
AI	Artificial Intelligence, simulating human intelligence
ASM	Artisanal and small-scale mining
ICT	Information and Communication Technology
IOT	Internet of Things, devices fitted with sensors and actuators connected to the internet
LSM	Large scale mining
M2M	Machine to machine, interconnected devices
NIS	National Innovation System
PRO	Public Research Organisation
RIS	Regional Innovation System
SMME	Small and Medium Enterprise
TRL	Technology Readiness Level, measurement to determine maturity of technology from Basic Research (TRL 1) to Proven and Ready for Commercialisation (TRL 9)

CHAPTER 1. INTRODUCTION

1.1 PURPOSE OF THE STUDY

The purpose of this study is to determine the opportunities and capabilities required for transversality in the ICT and mining sectors of South Africa, towards catch-up and sustainable mining.

The mining sector is in general decline, but there is potential to benefit from emerging technologies, as evidenced in other countries. The goals of the study are to establish policy or practice, required to rejuvenate the industry.

The study examines a cross-cutting regional innovation system that includes two sectors, mining and ICT. Actors include mining and ICT firms, government, Public Research Organisations (PRO), universities, labour organisations, and mining supply and consulting firms. The study proposes that the Fourth Industrial Revolution (4IR) offers cross-fertilisation opportunities with mining that promote complementary outcomes that neither industry could have achieved solely. The search for such complementarity in knowledge intensive industries, where networks are often selective, and focussed on solving specific problems, is complex (Bailey, Pitelis, & Tomlinson, 2020). The study considers the entire mining value chain and considers outcomes that could lead to new clusters and industries, which offer opportunity for catch-up with advanced countries, and for sustainable mining.

The study explores the role of PROs, such as Mintek, in capability building to enhance the sector in adopting 4IR technologies. It begins with a review of ICT penetration in South Africa, to determine readiness for 4IR technologies, and to identify potential gaps when compared to advanced countries. The study then performs a similar review of the technological state of mining and minerals processing, again to identify potential gaps. The review focuses on the value chain of the precious metals sector within South Africa, with emphasis on gold and platinum group metals (PGM's).

1.2 CONTEXT OF THE STUDY

The role of the state and intermediary organisations is vital in stimulating capability development at industry and firm level (Lee, Wong, Intarakumnerd, & Limapornvanich, 2019). Philip Cooke (2012a) adds that "related variety" of independent industries at a regional level stimulates innovation to create new clusters and industries, but that social collisions, either formal or informal, stimulate the cross-fertilisation of ideas and concepts. Often, intermediaries and state organisations create platforms for the formal interactions that drive these innovations.

The research was carried out in the precious metals industry South Africa. Mintek is a PRO mandated to stimulate mining and minerals processing to establish and expand industries in this field (Mintek, 1989). Mintek, having extensive capability in mineral technology is well positioned to support mines with the transfer of emerging ICT technologies to mining. The mines participating in this study have begun work to improve productivity to remain internationally competitive, as well as focus on the environment, health and safety. Incremental innovations, such as through the application of IOT and AI have seen some penetration in the industry (Odendaal, 2020). However, opportunities for transversality are postulated and investigated.

The optimistic view that 4IR technologies would help solve mining challenges must be contrasted with potential negative social implications for the mining industry, such as job losses, particular for low and semi-skilled workers and there is a subsequent plea for upskilling in 4IR technologies to mitigate that impact. It is envisaged that PROs have a significant role in facilitating such conditional capability enhancement.

1.3 RESEARCH PROBLEM STATEMENT

Mining output in South Africa is on the decline due to a number of factors, including high operating costs, unreliable and costly electricity supply, complexity of the ore bodies, increasing depths required with certain resources such as gold, ever-decreasing ore grades, illegal mining activity, safety and environmental issues, and fluctuating commodity prices (Neingo & Tholana, 2016). The gold industry in particular has come under the spotlight in recent times due to a multitude of challenges, which has subsequently seen some miners sell off their local assets (Arnoldi, 2020). However, South African gold reserves remain one of the richest in the world, but the industry lacks the favourable investment conditions necessary to stimulate and revive interest in gold mining (MacRae, 2020).

To bolster the mining sector in Canada, the government places importance on interdepartmental coordination, on developing local, technologically intensive expertise with a goal of becoming a world leader in Science and Technology (S&T),

backed by significant stimulus, including the Mineral Exploration Tax Credit (Gstraunthaler & Proskuryakova, 2012). Canada also trains and attracts foreign talent to strengthen research capacity, already strengthened by a high number of researchers and high outputs such as papers and patents (Gstraunthaler & Proskuryakova, 2012).

In contrast, while South Africa can be lauded for its National Innovation System (NIS), private research, as well as policies and programmes aimed at improving productivity in mining and the number of PROs that contribute to mining research, its R&D density and the number of patents is low, as well as the levels of research conducted at universities (Gstraunthaler & Proskuryakova, 2012). Many initiatives have failed to be implemented effectively, PRO's lack specialisation, policies lack integration between departments, and the number of researchers, particularly post-docs, was also a concern (Gstraunthaler & Proskuryakova, 2012). Mining firms focus on core activities, relying on specialist suppliers for other services (Kaplan, 2012). These suppliers employ sophisticated technologies and have attracted considerable foreign investment, often undertaking applied research for product development, some of which are world leading, including expertise in deep-level mining, but is weaker where large-scale economies are required (Kaplan, 2012). Government support, particularly in education and training, played an important role, through Public Research Organisations (PRO) and universities; however, the support has decreased significantly since the early 1990's (Kaplan, 2012). The study highlights a few constraints for future growth, such as skills shortage and lack of technological capacity, deteriorating public research and linkages to industry, as well as limited access to finance, for example, the CSIR's mining research capacity has been diminished, as well as Mintek and the Council for Geoscience, each struggling to retain skilled workers.

Fourth Industrial Revolution technologies enable countries such as Canada and Australia to provide safe working conditions on mines, and improve productivity through the use of robotics and autonomous vehicles, but such technology has yet to be adopted in South Africa (Sutherland, 2020). The development and implementation of policy has proven difficult for the South African government, but they are crucial to help ensure equitable distribution of wealth if, for example, jobs were to be redefined or transferred.

Scholars suggest that Fourth Industrial Revolution technologies may offer a window of opportunity for catch-up in other countries, and it is questionable whether this would also apply to South Africa (Lee et al., 2019). Similarly, a number of alternative paths for catch-up have been discussed in the literature (Lee, 2013b, 2019). This includes focussing on absorptive capacity through imitative innovation, then gradually improving to explorative innovation, capability in short-cycle before long-cycle technologies, focussing on domestic value-addition with later participation in global value chains, as well as stage-skipping, and leapfrogging,

The next step for South African mining is uncertain, with no clear indication of the best path for catch-up (Deloitte, 2015). Local conditions such as labour intensity in the sector, and cost and quality of inputs, may serve as further extenuating factors. However, Fourth Industrial Revolution (4IR) technologies may offer opportunities that help solve challenges unique to South Africa. This study hopes to uncover which path would be appropriate, what capabilities would be required, and how this opportunity could be exploited.

1.4 SIGNIFICANCE OF THE STUDY

Scholars have studied technological advances that could be applied to mining, as well as the potential impact on jobs in this labour-intensive industry. However, the concept of transversality applied to a regional innovation system encapsulating mining industries and emerging ICT technologies has not had much attention, especially in the context of capability building.

Fourth Industrial Revolution technologies have seen applications in mining, particularly in advanced countries; however, the adoption in South Africa has been slow. The study will generate insights for mining and minerals processing industries for sustainable mining in South Africa, with guidance for policy and practice that mining firms and PROs within the sector should adopt.

1.5 DELIMINATIONS OF THE STUDY

The study will be limited to the mining and minerals processing industries in South Africa, particular to the precious metals sector, with analysis of impact of PROs, and mining companies. A regional innovation system (RIS) approach is followed, focussing on the north eastern parts of South Africa covering the Bushveld Complex and Witwatersrand Basin.

1.6 ASSUMPTIONS

It is assumed that mining will remain a key contributor to the economy in South Africa, and that stakeholders are willing to overcome the challenges in the industry, and to reinvigorate the industry.

One also assumes that 4IR technologies are transferrable to the mining and minerals processing industries, and that the industries and firms are amenable to such technologies. Moreover, it is assumed that there is scope for sustainable mining, given the constraints of complexity and cost.

It is further assumed that PROs have sufficient input in the industry and that they are able to drive capability building with a view to catch-up, and that these organisations have sufficient capabilities to do so, or are willing to build additional capabilities.

Primary data collection entails conducting interviews with participants in the mining industry. It is assumed that the participants have relevant knowledge, being actively involved in improvement efforts in mining related operations, and will remain honest about the information conveyed, and that the information supplied will be a valid data source for the study.

1.7 DEFINITION OF KEY TERMS

Industry 4.0	A German government initiative for “smart factory” and “smart production”. Intelligent, interconnected processes in manufacturing
Additive Manufacturing	3D Printing. The process of manufacturing that constructs objects in a layered approach (additive as compared to moulded or subtractive)
Innovation	The process of improving or creating a useful product, process or service, including organisational processes.

1.8 RESEARCH QUESTIONS

Research Q1: What is the level of capability relative to 4IR and Mining technologies in the Regional Innovation System

Research Q2: How can transversality help achieve catch-up in the mining sector?

Research Q2, sub question: What is the level of knowledge interaction between ICT firms and mining firms in the region?

Research Q2, sub question: What capabilities will this require, and what is the role of PROs in facilitating capability building and in stimulating transversality

Research Q3: What are the promising windows of opportunity for leapfrogging in the mining sector?

1.9 OUTLINE AND STRUCTURE OF THE REPORT

This report comprises six chapters, described as follows:

- Chapter 1
  Introduction to the problem, including delimitations, significance and assumptions
- Chapter 2
  Literature review, theoretical frameworks and conceptual model
- Chapter 3
  Presents the research methodology employed in the study, a qualitative exploratory study
- Chapter 4
  Presentation of data, including summary of interviews and secondary data.
- Chapter 5
  Analysis of the data in the context of existing literature
- Chapter 6
  Summary of major findings, key conclusions and recommendations

1.10 CONCLUSION

This study is primarily concerned with upgrading capability in the mining sector of South Africa, to leverage the envisaged opportunities offered by Fourth Industrial Revolution technologies. It seeks to understand the capabilities required for catch-up while simultaneously pursuing sustainable mining, and the role of PROs in building capability.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

South Africa is classified as an upper middle-income country according to the World Bank (Fantom & Serajuddin, 2016), but an increase in economic growth tends to be positively correlated with unemployment, implying non-inclusive growth (Abraham & Nosa, 2018). Increase in productivity as well as labour inclusive development is recommended for economic catch-up, and for balancing the inequality in the country (Nattrass & Seekings, 2015).

The mining industry has been a major contributor to economic growth since the discovery of gold, diamonds and other minerals in the 19^{th} century, but the contribution to GDP has been on the decline due to, for example, ore complexity, rising costs in operations and employment, decreasing ore grades, and the challenge of deeper mines (Sorensen, 2011).

Investment from mining companies has also been on the decline, and the role of technology in productivity gain has been limited to automation, as is characteristic of the Third Industrial Revolution (3IR). Technologies of the Fourth Industrial Revolution (4IR) offer opportunities for further productivity gain, and have yet to penetrate the industry.

Sustainable development goals to ensure environmental integrity, social advancement and economic growth, as encapsulated in the Mining Charter of 2018 (SAGOV, 2018), offer challenges for the adoption of 4IR technologies. Further, social advancement targets have traditionally focused on community and infrastructure development such as schooling, housing and clinics, while upskilling and transfer of capability from Multinational Corporations (MNCs) has not been a priority (Sorensen, 2011).

This section begins with a capability assessment in ICT and mining and minerals processing in South Africa, and an introduction to the Fourth Industrial Revolution, providing a definition for the study. It then focusses on capability building, and the role of Public Research Organisations (PROs) in capability building before defining sustainable mining. The two theoretical concepts, capability based catch-up and transversality are introduced before presenting the conceptual model for the study.

2.2 BACKGROUND

2.2.1 CAPABILITY ASSESSMENT: ICT

ICT technologies are at the heart of the 4IR, which offers a convergence of various fields through digital technologies. Adoption of 4IR is reliant on ICT penetration, including access to the internet, fixed and mobile broadband, and the speed, cost and, quality of internet access. South Africa is fortunate in that over 99% of the population had 3G coverage and over 92% 4G/LTE coverage in 2019, while about 90% of the population have access to smart phones for internet access (ICASA, 2020). However, the costs of data limits accessibility to the internet. According to the ICASA article, South Africa ranked 60th in the world in terms of mobile internet speed, and 96th for fixed broadband speed (average of 27 Mbps download compared to 202 Mbps for the world's number one), revealing a gap that may potentially inhibit the volume and variety of data that is synonymous with 4IR.

Technologies such as cloud computing are also available through either local or foreign providers. Kshetri (2010) shows that telecommunications and business related functions such as e-commerce, e-business and supply chain management are the primary use of cloud computing in South Africa. However, foreign technology giants such as Microsoft and Amazon offer infrastructure-as-a-service, platform-as-a-service and software-as-a-service products, which can be thought of as increasing in complexity (Mohlameane & Ruxwana, 2014), while only a few local providers offer software-as-a-service for IOT and Big Data, classified as 4IR technologies (Ridge, Johnston, & O'Donovan, 2015). Most MNCs have created local data centres reducing reliance on international bandwidth. However, the long-term prospects for South Africa as a provider of such technologies are bleak.

The ICT sector has been plagued with a lack of adequate skills, particularly software skills for almost a decade (Calitz, Greyling, & Cullen, 2014). The problem is difficult to solve as highly skilled employees are in demand and are often headhunted by international firms.

The problem of skills will be exacerbated with the rise in demand for artificial intelligence (AI) and other ICT skills. A report released in 2019 shows that AI has not seen much penetration in business, with only 13% of corporate South Africa using AI, citing cost as a barrier (Goldstuck, 2020). Only a small set of companies offer AI services in the country (Bradshaw, 2020). Universities and educational institutions are gearing up to provide training in AI (Bradshaw, 2020).

The general finding is that South Africa has a strong base for advanced ICT technology, but much work is required to improve capability to match that of advanced countries. For now, the country can afford to leverage foreign technology products and services such as cloud computing, but longer-term strategies must include plans for localisation.

2.2.2 CAPABILITY ASSESSMENT: MINING AND MINERALS PROCESSING

Mining contributed about 7% to GDP in the 2018, with approximately 80% of production exported, and a major contribution from platinum group metal (PGM), gold, coal and iron ore ("Investing in South Africa's Mining and Mineral Beneficiation Sector," 2020). This study is limited to the precious metals sector, focussing on two major contributors to GDP, gold and PGM mining in South Africa.

South Africa was the number one gold producer in 2009 but has fallen in rank in recent years even though gold reserves are still abundant. The industry has experienced a number of challenges that have contributed to the decline in production. Neingo and Tholana (2016) discuss some of the challenges, which include deep mines, with some of the deepest mines in the world located in the country, comprising ore bodies that are narrow and discontinuous, making mechanisation and automation difficult. The study further elaborates that underground temperatures average 60° Celsius requiring extensive cooling to maintain a safe working environment. Neingo and Tholana (2016) further point out that ore grades have been decreasing, requiring extensive processing of larger tonnage of ore to maintain production output. The study goes on to examine the costs of production that have increased for the processing of the higher tonnages, further compounded by higher energy tariffs imposed by Eskom and frequent load shedding and interrupted power supply. Labour costs and interruptions further impact production with ever decreasing productivity (Neingo & Tholana, 2016). Gold mining currently employs roughly 95 000 workers, mostly unskilled or semi-skilled ("Gold - Minerals Council South Africa," 2020). Criminal activity, particularly in gold mining is a another challenge, with illegal miners contributing to increasing financial loss (Nhlengetwa & Hein, 2015). Gold supply is supplemented by recycling, mainly from jewellery and electronic circuit boards, although most recycling occurs internationally. Gold demand is driven by jewellery, followed by investments, central banks and electronics, yet surprisingly, South Africa imports a significant proportion of jewellery. Local jewellery production methods are largely antiquated, unable to compete with advanced manufacturing employed internationally.

South Africa hosts 70% of the worlds platinum group metal (PGM) reserves and is the world-leading producer, but rising costs of production and falling commodity prices have led to a number of mine closures and fall in production ("World's top five producers of platinum group metals profiled," 2020). PGM supplies are supplemented by recycling from auto catalysts, and jewellery, which cumulatively constitute roughly 25% of total supply. Demand is driven from auto catalysts, jewellery and for hydrogen fuel cells in electric vehicles ("WPIC Platinum Quarterly Q4 2019," 2020). South Africa, through the HySA venture is building capability in fuel cell technology, and has recently joined Anglo American Platinum in a project to retrofit mine haul trucks with fuel cell technology (Creamer, 2020).

The last commodity upswing ended in 2011, and since then commodity prices have not recovered, except for the price of gold, which has spiked recently as the COVID-19 pandemic saw more safe haven investment (Gallagher, 2021). The commodity “bust” is usually associated with a decline in investment in new technologies. The general decline of the mining industry was a key discussion point for the Operation Mining Phakisa, held in 2015, which sought to improve investment in South African mining (Hermanus, 2017). Multiple stakeholders in the mining sector discussed strategies and plans for improving technological excellence through innovation, improving mine ownership distribution to include the previously disadvantaged, and ensuring job creation. The Phakisa contains a number of processes that are crucial for revitalising mining, and these include intensified R&D in hydrogen fuel cell technologies, development of technologies for the mechanisation of narrow tabular seam mining, stimulating local manufacture of mining equipment, developing technologies for rehabilitation of mining land and mining waste, beneficiation of specific minerals, including platinum, and support of those industries, supporting self-generation of electricity, and commitment to renew exploration activities (Hermanus, 2017). This later led to the formation of the Mandela Mining Precinct.

A number of changes to policy have negatively affected the industry, for example, numerous changes to the Mining Charter have resulted in ongoing uncertainties (Bulbulia, 2020). A recent development is the delay in policy amendment for power self-generation for mines, as promised by the minister of the Department of Mineral Resources and Energy (DMRE) (Liedtke, 2021).

Advancements in mining internationally have yet to be implemented in South Africa. Mining technology in the advanced mines in South Africa is characteristic of the Third Industrial Revolution (3IR), relying on automation to some degree, but being mostly manual in nature. Minerals processing facilities, however, usually employ more automation. A number of international mines have been fully automated, and the Samaya gold mine in Mali will be the first fully automated, underground robotic gold mine in Africa (Lucas, 2018). The mine, owned by an Australian firm, will see some job losses, but the firm argues that this will mostly result in foreign job loss.

In a study of the adoption of technology in the mining industry, Macfarlane (2001) presents a number of factors that influence the failure of new technology in mining operations. A thorough assessment of the new technology includes assessment of alignment to strategy, investigation and management of technical and financial risk, change management to prepare the workforce and systems, and a mechanism to measure impact (Macfarlane, 2001). The manager, ideally a senior line manager, should champion the technology, have sufficient authority to overcome challenges in the implementation, and have sufficient influence to make the change to the new technology. Macfarlane (2001) also goes on to indicate the importance of a shared vision for the new technology such that all workers understand the reasons and benefits to the mine, and how it will impact them. Managers must be able to create this vision, communicate it, and empower others to act towards it (Macfarlane, 2001).

Large-scale mining (LSM) firms dominate South African mining, with a share greater than 90% compared with junior mining and artisanal and small-scale mining (ASM). This is largely as a legacy of the apartheid government and continued high entry barriers for ASM firms (Ledwaba & Mutemeri, 2018). Even with LSM firms, MNCs have failed to transfer technologies and enable local capability in mining. Mkhize (2018) argues that MNCs create oligopolies that diminish the effectiveness of local mines. The lack of support for ASM firms has led to the proliferation of illegal miners in South

Africa, although the numbers are unknown, it is estimated that illegal miners contributed approximately seven billion rand in value of precious metals and diamonds in 2017 (Brown, 2017). Ledwaba and Mutemeri (2018) believe that ASM firms have the potential to become legal contributors to the economy, with the support of the state, for example through localisation of the African Mining Vision.

South Africa has a higher GDP/capita than most neighbouring states and the economy also has input from agriculture, industry and services. However, Elbra (2013) believes that South Africa also experiences the "resource curse", a term usually reserved for lower income countries that fail to benefit economically from their natural resource endowment. Elbra (2013) references the continued unequal distribution of wealth in the country, high levels of poverty, corruption, and a number of Millennium Development Goals that South Africa will not be able to achieve. While he does not specifically reference the value chain and the high exports of raw material, it is also evident that the country misses the opportunity to capture value from its natural resources. Lessons can be learned from Botswana's approach where capability was systematically improved from the mining and export of unprocessed diamonds, to processing and export of high quality end-products (Iimi, 2006). Norway's approach to escaping the resource curse, in contrast, can be attributed to industrial policy which stimulated adoption of existing technology, in learning-by-doing activities as well as diversifying industrial activities (Larsen, 2006). Cultural and societal aspects such as a transparent democracy, social norms, as well as a unique wage negotiation system which controlled increases in wage across sectors, limited opportunity for purely rent seeking activities as offered by resource export, crude oil in this case (Larsen, 2006)

2.2.3 THE FOURTH INDUSTRIAL REVOLUTION

Culot, Nassimbeni, Orzes, and Sartor (2020) point out that there are numerous definitions of the term 4IR, with no common definition. For the purpose of this study, 4IR is the set of emerging technologies, loosely captured in the nine Industry 4.0 components, enabling new solutions for the world's challenges.

The key technologies employed in the 4IR are artificial intelligence (AI), the Internet of Things (IOT), advanced robotics, additive manufacturing (3-D printing), autonomous vehicles, nanotechnology, biotechnology, materials science, energy storage and quantum computing (Schwab, 2017). Industry 4.0 (or the German Industrie 4.0), is a

German initiative that focusses narrowly on the concept of “smart production” enabled by “smart factory” ("What is Industrie 4.0?," 2020). It is composed of nine components including big data, autonomous robots, simulation, system integration, the Internet of Things, cloud computing, additive manufacturing, augmented reality and cyber security (Erboz, 2017). Industry 4.0 can be thought of as a subset of 4IR directed at improving productivity in manufacturing. The components envisaged in Industry 4.0 may offer a narrower framing for opportunities in the mining sector.

Perez (2009) discusses the cyclical nature of technological revolutions, which represent major changes in economic potential, offering innovation opportunities through a set of new generic technologies, or structures for significant productivity improvements. Perez (2009) identifies two main traits of a technological revolution as the “strong interconnectedness and interdependence of the participating systems in their technologies and markets” and the “capacity to transform profoundly the rest of the economy”. In the context of the Fourth Industrial Revolution (4IR), general-purpose technologies such as artificial intelligence (AI) become accessible through low cost associated technologies; there is also a belief that 4IR will have a major impact on society (Liu, 2017).

While the Third Industrial Revolution (3IR) introduced digitalisation and automation, 4IR builds on that platform by combining technologies in a hyper-connected environment, further characterised by the merging of systems, velocity, and breadth and depth (Schwab, 2017). In his book, Schwab (2017) explains how the merging of physical, digital and biological systems, with ever increasing computing power and communications technologies allows detailed modelling, simulation and interaction with physical and biological systems. He goes on to describe the velocity of change, which is now exponential rather than linear, and the breadth and depth referring to the transformation of entire systems.

Studies on which types of jobs are automatable and could be impacted negatively by 4IR paints a bleak picture for South Africa, with up to sixty percent being susceptible to automation (Millington, 2017). Employment rates in mining have already been in a general decline, due to a variety of factors, but new types of jobs could be created, for example, in the creative and services industries (Naudé, 2017). Some analysts are pessimistic and foresee massive job loss with the adoption of 4IR technologies, and those who are optimistic that new types of jobs will be created. In this study, the evidence has been in favour of the latter, where 4IR technologies augment existing jobs, making them simpler or safer, or new types of jobs such as installation and maintenance of new equipment, or in data analytics, are created. This is in line with the advice of Juma (2016), who recognised that new technology disrupts the status quo, which may bring “losses in employment, income, power and identity”. Juma (2016) advises that one should include all stakeholders in the innovation process, and ensure that those who might be impacted negatively are given the opportunity to participate and benefit from the new technology.

Another challenge is the quantification of benefit that 4IR technologies offer. Dos Santos (1991), thirty years ago, discussed the challenges in traditional budgeting processes such as NPV or cash-flow analysis in determining the value of new Information Technology (IT) projects, where benefit might present itself in aspects such as new investment opportunities or crucial experience gained, which improves the ability to develop new solutions based on the technology. Much more recently, Bai, Dallasega, Orzes, and Sarkis (2020) have concurred that the decision for adoption and evaluation of 4IR technologies is not simple, but could offer benefits such as profitable business models, improved efficiency and quality as well as better workplace conditions. According to Bai et al. (2020), a number of multiple attribute decision making (MAKM) methods exist, but would not adequately apply to 4IR technologies. The authors explain that not much is known about the real impact and contribution of the technologies, as well as the performance of such technologies in various contexts. The element of retrofit poses further challenges (Bai et al., 2020). The authors introduce a new technique to evaluate 4IR technologies against Triple Bottom Line (TBL) objectives for social, environmental as well as financial aspects and utilises a multi-context method using HFE, CPT and VIKOR methodologies. A tool such as this enables the evaluation of non-monetary aspects, such as work conditions.

Malicious attack is a concern for 4IR implementation. Malicious attacks employ resources, capabilities, processes and practices for the theft or control of computer systems, networks, data and related systems (Craigen, Diakun-Thibault, & Purse, 2014). Cybersecurity is then the art of defending such systems against malicious attack (Craigen et al., 2014). 4IR technologies merge physical and digital systems, resulting in a possible compromise of connected physical assets and traditional safeguards such as corporate firewalls, malware protection systems and intrusion detection systems would prove inadequate given the size of new systems (Culot, Fattori, Podrecca, & Sartor, 2019). Systems are growing through multiple WIFI connections and a preponderance of IOT devices, data sharing with multiple vendors and contractors, the multitude of personal mobile devices being connected, and the embrace of cloud computing (Culot et al., 2019). As the surface area for attacks increases, it becomes impossible to protect against all possible threats (Culot et al., 2019). However, it is increasingly important to implement robust risk prioritisation and mitigation, while at the same time ensuring cybersecurity tools evolve and that cybersecurity becomes a cross-functional agenda item on the corporate strategy (Culot et al., 2019).

For middle-income countries such as South Africa, a relevant question would be whether the 4IR offers a window of opportunity for escaping the middle-income trap or will 4IR reinforce the country's status, and is a similar concern for middle-income countries such as Malaysia and Thailand (Lee et al., 2019). Lee et al. (2019) delved into economic clusters in Malaysia and Thailand to determine their readiness for 4IR, and to determine the requirements for leveraging the technologies for economic growth. Support for well-functioning education systems was identified as a requirement for improving capabilities in certain technologies necessary for stimulating industries in those sectors. This includes tertiary education, for science and engineering, bolstered by state entities.

2.3 THE ROLE OF PUBLIC RESEARCH ORGANISATIONS IN CAPABILITY BUILDING

Mazzoleni and Nelson (2007) discuss the role of universities and Public Research Organisations (PROs) in economic catch-up. This is through learning and mastery of foreign technologies beneficial to the local economy. This may involve a model, where foreign technology may be imported and used, following a doing, using and interacting (DUI) based learning approach; however, this imitative approach is limited, and often the approach is to deliberately modify or tailor the technology for local conditions (Mazzoleni & Nelson, 2007).

Learning and building capability, is not limited to technological capability. It extends to creating and nurturing supporting environments for policy, law, finance, education and training systems and so on, which Mazzoleni and Nelson (2007) term, institutions. The study argues that building capability in these technologies and institutions requires effective system of education and public research.

A number of mechanisms facilitate the transfer of technological capability, such as cross border flows of people, knowledge transfer in joint research activities or applied knowledge transfer in firms through MNCs or international recruits (Mazzoleni & Nelson, 2007). Examples of cross border flows includes researchers studying abroad or foreign experts recruited to teach at universities. Póvoa (2008) discusses the role of universities in catch-up, and finds that both PROs and universities have a role to play in imparting skills to new employees, and to serve as sources of scientific knowledge for technological development. Financial constraints may, however, force universities into an entrepreneurial mode of operation, searching for cooperation with industry. Póvoa (2008) states that the main difference is that PROs do not teach, and have a few areas of specialisation. Velho and Saenz (2002) add that PROs have the ability to build long lasting relationships with industry, contrasted with university interaction, which is mainly through isolated projects. Mazzoleni and Nelson (2007) note that if the demand for skills is low, educated people may leave the country, resulting in a brain drain.

Foreign direct investment also plays a significant role in aiding catch-up. Another mechanism includes policies and subsidies that protect and encourage local industries; however, these policies are discouraged in the global arena in international treaties (Mazzoleni & Nelson, 2007). Weak intellectual property rights (IPR) regimes have in the past also encouraged reverse engineering, but are now grounds for prosecution after the promulgation of the Trade Related Aspects of Intellectual Property Rights (TRIPS) of the World Trade Organisation (WTO) (Mazzoleni & Nelson, 2007).

In light of these restrictions, Mazzoleni and Nelson (2007) call for the development of sectoral training and research infrastructure. The government’s role should be to create the infrastructure and then enable firms, PROs and universities to support each other to overcome obstacles in the absorbing and tailoring of foreign technologies for local environments.

Problems may require combinations of technology that are outside of the capability of the firm, but which is within the capability of PRO (Arza & Vazquez, 2010). PROs improve industries ability to solve problems, promote incremental innovation, and develop new instruments and methods required by industry and may also provide new sources of funding for industries' research (Arza & Vazquez, 2010). New technologies that a country absorbs requires tolerance of risk, and PROs can play a part in building capability and de-risking technologies; here R&D will be required to understand the technologies and customise them for local firms (Mazzoleni & Nelson, 2007).

Wu, Ma, Shi, and Rong (2009) propose a taxonomy of the problem-solving process that encompasses knowledge utilisation and knowledge creation. Knowledge utilisation features in imitation, seeks to understand and then build on existing technology, while knowledge creation falls into the domain of innovation; building and extending existing competencies in exploitative innovation; and search, experimentation and discovery in explorative innovation (Wu et al., 2009). Capability must be built first to understand existing technology, then to exploit and finally for exploration, each requiring different sets of competencies, but that can be built upon each other.

Mazzoleni and Nelson (2007) advocate for more applied research where PROs interact closely with industry to determine challenges and strive to solve them. They caution against research that is irrelevant to industry, referred to as research conducted in ivory towers, especially in early stages of catch-up. Often this type of interaction forms naturally in regional sectors, for example, universities located near technology hubs develop capability in that particular technology. Engineers, technicians and hands-on workers involved with learning by doing are important for new technologies early on. However, for latter stages of catch-up, an understanding of the fundamental scientific concepts and principles is required, calling for more scientists and basic research (Mazzoleni & Nelson, 2007). PROs demonstrate the importance of R&D activities, and in so doing, create demand for scientists and engineers in the country. PROs also play a role in mastering the technology, which may then be transferred to spin-off firms, and sometimes act as accelerators, providing venture capital, spaces and training.

Mission-oriented innovation offers an alternative approach for catch-up, where solving a country's challenges inspire opportunities to develop technology and expertise, possibly also for export (Mazzucato, 2018). Ethiopian Airlines offers a good example of the need for an airline that stems from the inherent difficulties of land travel due to treacherous mountain regions in Ethiopia (Oqubay & Ohno, 2019, pp. 235-261). Oqubay and Ohno (2019) describe the systematic progression from learning by doing, creating technical training centres for pilots to improve capability of their people, instilling in the employees a vision that would enable them to remain resilient and make decisions for the continued survival of the company, as well as then improving technology, expanding internationally, and eventually becoming one of the largest airlines in Africa. Mazzucato (2018) offers advice for public organisations engaging with technological and scientific priorities, for nurturing risk and experimentation and building dynamic capabilities internally.

4IR offers a unique leapfrogging opportunity to leverage emerging technology to try to reach levels of productivity in advanced countries and this will require capability in those relevant technologies that will aid in stage skipping (Póvoa, 2008). Scientific research helps identify the foreign technologies that would offer the best opportunities.

2.4 SUSTAINABLE MINING

Sustainable development is about working towards a prosperous life in the present without compromising life for future generations, thus it is the challenge of simultaneously pursuing economic, social, and environmental goals. For example, how might one stimulate economic growth while simultaneously reducing environmental impact, or how might one promote social wellbeing with limited resources (Imaz & Sheinbaum, 2017). The United Nations (UN) facilitated the setting of such sustainable development goals, encapsulated in the Millennium Development Goals (MDG) and more recently the Sustainable Development Goals (SDG) of the 2030 agenda (Imaz & Sheinbaum, 2017). The seventeen SDG's as laid out in the 2030 agenda can be summed as preservation of the environment, to promote social inclusivity and equality, and economic growth and poverty elimination (Ramachandran, 2019).

Sustainable mining was originally concerned with the rate of use of minerals compared with exploration and recycling or substitutes, and with minimal environmental impact, but this has evolved to include economic growth irrespective of resource depletion, and to include social considerations (Laurence, 2011). Kirsch (2010) describes the concepts of strong and weak sustainability, where weak sustainability overlooks some damage to the ecology offset by capital gains from the proceeds of mining, whereas strong sustainability refers to the total preservation of the environment. For the purpose of this study, sustainable mining is economic viability, while having minimal impact on the environment and ensuring social benefit.

The Mining Charter 2018 makes provisions for environmental conservation and rehabilitation as well as social benefit (SAGOV, 2018). However, economic viability remains a challenge for mines given rising operating costs and lack of investment for modernisation. Grossman and Helpman (1994) describe the case of a country with an abundance of natural resources and a high ratio of unskilled to skilled labour where manufacturing grows more slowly, skewed toward activities to meet demand for such resources as opposed to devoting resources toward new technologies and innovation. Their advice is to pursue production that does not require the latest technology in order to catch-up, before pursuing R&D in new technologies. The exploitation of 4IR technologies, rather than R&D in 4IR may present an opportunity for such catch-up.

The relation between sustainable development and science, technology and innovation (STI) has been dissonant. The pursuit of science for economic growth leads to the devastation of the environment, evidenced for example, by fossil fuel dependence and emissions contributing to global warming (Imaz & Sheinbaum, 2017). However, STI can also lead to environmentally friendly growth. Imaz and Sheinbaum (2017) argue that science has been largely viewed as an external object for the pursuit of knowledge; however, this disregards limits of technology in overcoming ecological challenges, and neglects other sources of knowledge and “eco-technological” approaches. They recommend viewing science as a social construct, one that is flawed but may offer opportunities once connected with society, culture and traditional knowledge.

Imaz and Sheinbaum (2017) make five recommendations to orient STI towards the SDGs including ensuring accessibility of STI developments; the use of technology for ecosystem management based on deep understanding of the ecological systems; an interdisciplinary approach; socio-economic policies not necessarily related to STI; and promoting debate on the approach to SDGs. This study calls for a careful re-evaluation of the role of STI in sustainable mining, especially in the context of South Africa where environmental sustainability, economic growth and social benefit have long been objectives in the national development agenda.

2.5 THEORETICAL FRAMEWORK

2.5.1 CAPABILITY BASED CATCH-UP

The concept of economic catch-up has been around since the First Industrial Revolution where Germany aspired to catch-up to the UK, and has been debated and theorised for a number of decades (Chandra, Lin, & Wang, 2013). A number of empirical investigations have led to postulates around the drivers of catch-up, such as by Rogers (2004) and Fagerberg and Srholec (2017). Transferable lessons arise from South Korea's ascent in economic status. Recent theorising and empirical evidence suggest that the focal driver of economic catch-up is capability, in the traditional technological capability sense, but also including aspects of education, firm capability and the firm environment.

In the last few decades, a few countries, such as South Korea, have achieved economic catch-up and have become role models for countries in similar circumstances seeking to upgrade their status (Chandra et al., 2013). However, the process of catch-up has proven difficult to emulate. The path to development usually begins with industrialisation, requiring manufacturing capability for exports, enabling participation in the global arena and thus increasing the rate of growth. South Korea is a role model for catch-up for countries in Southeast Asia, having achieved catch-up in only a few decades. However, the role played by the state in South Korea's development is questionable, and critics argue that the degree of state activism, especially in cultivating and protecting fledgling industries, would not be tolerable in the global environment (Lee, 2013a). Lee (2013a) argues that technological capability building was the main driver of South Korea's success, the state's role being secondary. The intention was to strengthen the capability of firms such that industries could be cultivated to participate in the global value chain. More recently, Lee (2019, pp. 35-55) advocates for detours in catch-up and technological leapfrogging instead of following directly in the path of forerunner countries, he also indicates that large local firms help with participation in the global value chain (GVC), but that technological capability remains the underlying facilitator for each of these approaches. Fagerberg and Srholec (2017) also emphasise the importance of the capability of firms in contributing to country-level technological capability.

Low-income countries could theoretically assimilate and adapt existing obsolete technologies from advanced countries, and this should result in higher growth rates, except that the level of technological capabilities of those countries is not sufficient to exploit such technologies (Fagerberg & Srholec, 2017). Fagerberg and Srholec (2017) show that capability building is complex, involving practical and context specific knowledge, or codified knowledge that is not easily transferable, and often the only approach is through immersive exploration involving teams of researchers in the pursuit of rediscovery of phenomena. Only then can the process of exploitation begin.

A possible exception is that of catch-up in emerging industries when output capability can be attained without the requisite innovation based capability (Awate, Larsen, & Mudambi, 2012). The authors argue that for an emerging industry, the path to catch-up is relatively short, and a firm with relatively shallow technological knowledge could follow an imitative approach to produce output that rivals that of the incumbent. However, the firm would not possess the breadth and depth of technological knowledge required for innovation, and may struggle to become dominant in that industry. In the long run, the exploitative experiential learning increases the depth of knowledge which may then enable exploration (Awate et al., 2012).

Lee (2013a) points out that traditional growth mechanisms, such as those captured in the Washington Consensus, are flawed. Mainstream economics emphasises the efficient use of resources, and concentrates on macroeconomic stabilisation and trade liberalisation, often leading to short-lived growth. For sustaining growth, the country must participate in the global value chain (GVC), which is possible through targeted technological capability building. Lee (2013a) advocates for a staged approach, beginning with technology and industry targeting for import-substitution, then gradually moving to export-oriented growth once firms have gained capabilities. Further, mature technologies should be the starting point for capability upgrading as these are well understood. Fagerberg and Srholec (2017) adopt a broader view, and suggest that catch-up must also consider the wider economic, social, institutional and political factors, closely corresponding to a broader National Innovation System (NIS) view.

Fagerberg and Srholec (2017) argue that in addition to firm capabilities, the firm's environment, including education and technical competence, are of equal importance. Empirical factor analysis of 114 countries over an 18-year period identifies three different inherent capabilities, technology, education and governance, upon which catch-up is dependent (Fagerberg & Srholec, 2017). Technological capability is the ability to absorb, exploit and create knowledge; while the educational environment includes primary, secondary, tertiary education as well as technological skills development aligned to critical (or targeted industries and technologies) and PROs which conduct R&D and technology transfer (Fagerberg & Srholec, 2017). Governance relates to the broader firm environment such as the commercial, industrial and financial environment that enables firms to conduct business; and the political and social environment that balances the risk and reward of conducting business (Fagerberg & Srholec, 2017). However, technological capability is emphasised as the most important explanatory variable. This corresponds to a science, technology and innovation (STI) dependence where R&D at tertiary institutions and at PROs is vital.

The roles of the political and social environment are underemphasised, and this may be a gross oversight, especially in low-income countries, or countries which have a disproportionate distribution of wealth. The barriers to growth due to corruption, weak rule of law, and lack of stable supply of basic inputs such as electricity has been shown to have significant impact on economic growth (Malikane, 2015). There is an assumption that economic growth-targeting will eventually lead to an upgrade of the socioeconomic situation of the people of the country. Fagerberg and Srholec (2017) also admit that variables such as financial institutions, managerial capacity as well informal institutions have been omitted from the analysis, due to lack of data. Again, these variables may have a large impact in low-income countries where, for example, alternative finance is beginning to play a role in venture creation (Ojah & Kodongo, 2015).

Nübler (2014) distinguishes between dynamic capacities and a knowledge-based concept of capabilities required for the process of catch-up. The author argues that a country has developed a set of capabilities that allows it to produce a set of products and technologies and those capabilities determine the potential for expanding to the global product and technology space. The knowledge-based concept argues that capabilities reside in the knowledge contained in the "labour force, economies and societies”. The ability to learn and create high-performing learning systems is then also a capability. With this view, a country can determine the best options for productive transformation, leveraging existing capacity and capability. However, to develop new economic activities and products requires entry into different knowledge communities and transformation of existing knowledge systems (Nübler, 2014). This view is in line with that of Lee (2013a) and goes further to highlight the importance of policy to shape transformational change, especially those that promote manufacturing in more advanced knowledge communities as it allows firms to build capability for diversification.

The theory presents a causal link between capability and economic growth. Catch-up requires capability building in a nurturing environment. Growth from rents of natural resources is an obvious exception; however, such resources are finite, and the authors caution on relying solely on resource rents for growth. Technological capability requires supporting and enhancing the capability of private firms, Lee (2013a) points out that even state-firms should eventually become private. The argument is for education as the primary contributor, through government initiatives to strengthen the education system. However, that is not sufficient, as Lee (2013a) adds that public research and technology agencies and even MNCs must be leveraged to encourage learning and building requisite capability for each industry being targeted. In the case of South Korea, the output of R&D was shared amongst government and local firms. Chandra et al. (2013) show that industries, which build on the inherent capabilities of the country, should be targeted initially for greater chance of success. An NIS model, in the broader sense, is encouraged as it is these interactions amongst government, private firms, education institutions, PROs and MNCs that promote learning and the spill-overs required for capability upgrading.

Lee (2013a) asserts that South Korea’s success is transferable to other countries, and that increases in R&D spend and improvements in the education system will see marked improvement in the economic situation; however, a caveat is the effectiveness of government and the implementation of policy that seek to create new rents rather than extracting more rents from existing local firms. Fagerberg and Srholec (2017) concur that improving social welfare and sustainability contribute towards improving technological capability, which leads to growth and the empirical evidence presented supports this argument. Governments often implement policy to promote the growth of firms, while overlooking the importance of the environment in which firms operate.

2.5.2 TRANSVERSALITY

Transversality is the economic development conceived from the interactions of different industries or clusters in a region, usually geographically located, through knowledge interaction facilitated either by the firm or by an intermediary governance organisation, the latter also being responsible for regional policy (Philip Cooke, 2012b). Firms involved in the development of one particular technology may interact with other firms involved with other technology due to geographic proximity, and aspects of “related variety” between the technologies may lead to new clusters or sectors that are a recombination of the technologies (Philip Cooke, 2012b). Social interactions, either organised or random, facilitate these knowledge spillovers. In informal settings, proximity plays a vital role, and in contrast isolated clusters and sectors remain economically static. An intermediary governance organisation such as state organisation or council may facilitate formal interactions to create knowledge flow. These organisations may also take conscious policy action to exploit transversality (Philip Cooke, 2012b).

National Innovation Systems (NIS) often overlook the details of the mechanics of innovation within regions or sectors, leading researchers to describe Regional Innovation Systems (RIS), which complement the NIS approach, as offering insight into issues around complexity and scale (Philip Cooke, Uranga, & Etxebarria, 1997). RIS offer rich descriptions of the actors and their interactions in the system.

Philip Cooke (2012b) discusses the concepts of “related variety” and regional innovation. Knowledge spillovers from firms and clusters lead to innovation through geographical proximity. This is better understood through the concept of preadaptation, which takes pre-existing ideas and applies them out of context to form other innovation, and the concept of the “adjacent possible” where the more variety the system displays, the easier it is create more novelty (Kauffman, 2008 as cited by Cooke). Preadaptation and the “adjacent possible” bring about path interdependent knowledge recombination in these regions.

In the theory, some concepts are not explicitly operationalised, although these may depend on the type of innovation present. Philip Cooke (2012b) also mentions that certain concepts such as preadaptation and the “adjacent possible” are usually observed *ex post*, and are difficult to predict.

There seems to be a strong correlation between the regional intersection of firms and knowledge spillovers leading to new clusters, industries and technologies. The creation of new clusters and industries leads to path interdependence and is likened to Schumpeterian “creative destruction”. Philip Cooke (2012b) categorises regional innovation against variety, to relate degrees of path dependent economic development, for example, low innovation and low variety may lead to user-driven innovation or incremental innovation, while high innovation and high variety may lead to transversality.

Later work has revealed some limitations of the STI approach and the need for inclusion of a DUI approach in regional innovation systems, extending the concept of transversality to include modular policy elements, where modules are parts of a sector or cluster that must be integrated (Phillip Cooke, 2016). Phillip Cooke (2016) gives an example of a core SME such as ICT, which would be augmented by user-driven firms such as tourism to broaden knowledge and innovation in the region. Another shortcoming is the lack of inclusion of informal knowledge sources and their role in innovation; this may be of particular importance to South Africa.

The theoretical framework is useful for examining regional innovation systems to maximise innovation through “related variety”. The role of governance and intermediary organisations in facilitating intersections and in moulding policy also stands out.

2.6 CONCEPTUAL MODEL

The mining sector faces many socioeconomic and technical challenges, yet remains a major contributor to South Africa’s economy, both directly and indirectly. Challenges include diminishing labour productivity, labour relations, deeper mines with lower grade ores, high input costs such as energy (also intermittent supply), and participation on the lower end of the GVC as most production output is exported, then reimporting goods, such as jewellery, higher up the value chain. Post-apartheid issues such as mining benefitting a few LSM firms, which are mostly MNCs, is another issue, forcing ASM firms to operate illegally due to high entry barriers and insufficient support from the state.

ICT technologies and 4IR promise to enhance productivity through the merging of physical and digital systems; for example, 4IR has encouraged productivity enhancements in manufacturing through IOT, digital twins, AI, augmented reality and robotics. South Africa faces deficiencies in skills required for 4IR, compounded by pre-existing ICT skills shortages, and the lack of adequate education systems. Nevertheless, South Africa must adopt the technologies to leverage the opportunities 4IR offers. The presidential commission, as well as the CSIR, has been leading the discourse on 4IR in the country, but attention to mining has been lacking. State organisations in the mining sector, such as Mintek, have a significant role to play to ensure that 4IR is also beneficial to the sector.

At the same time, 4IR brings the possibility of job losses, especially if South Africa follows the path of leading countries in foreign implementations. The Samaya mine case is an interesting development that perpetuates the imbalance that mining MNCs impose on the country. Countries such as Malaysia and Thailand welcome the relief from labour intensive activities as they typically experience labour shortages. South Africa faces surplus labour issues, which are not favourable for direct implementation of 4IR. South Africa is a middle-income country with large inequality and unequal distribution of wealth and issues of sustainable mining are paramount to rectify these imbalances, possibly repurposing technologies and exploiting opportunities offered by 4IR.

From the catch-up theory, it is important to understand the current state of mining in South Africa, particularly concerning the exploitation of the 4IR technologies, in comparison with advanced countries. An understanding of the capability of the workforce and of the organisation is important for the analysis, including strategies and plans for improving capability and the requisite supporting structures. The type and use of technologies, including advanced foreign technologies, must be understood, in order to determine if these are being adopted and exploited, as well as to explore innovative opportunities. The link between research and technology must be understood, particularly if research output is easily exploited for the benefit of the sector, or if research is conducted in ivory towers. Similarly, from the transversality theory, it is important to understand the nature of innovation in the mining sector, whether vibrant including large variety, or stagnant, and then to determine the possibility for cross fertilisation with the ICT sector. This must be distinguished from the mere implementation of existing technologies, focussing on novel opportunities, unique to mining and ICT. The nature of the knowledge interactions between the two sectors must be understood, whether co-development initiatives exist, encounters at technology discussion platforms, round table discussions or debates, and even coffee shop interactions. Governance orchestration, as well as facilitation of interactions, and formulation of policy to stimulate economic growth must be understood. This analysis will help determine the path to catch-up, whether in the path of forerunners, using detours, stage skipping, leapfrogging, a given combination, or none at all.

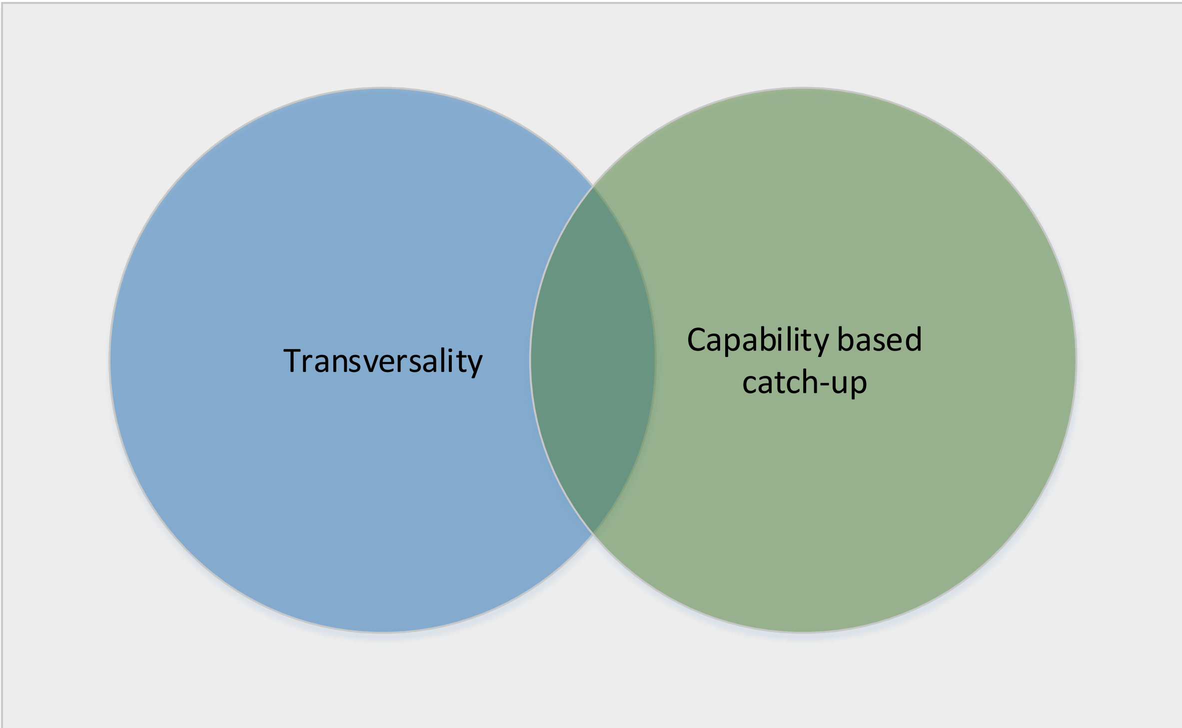

Figure 1. Conceptual model

The conceptual model, shown in Figure 1, merges the theoretical concept of transversality with capability based economic catch-up. In the context of the precious metals mining sector, geographically located in the north eastern parts of South Africa, mines, minerals processing plants, refineries and a host of suppliers, vendors, recruitment agencies and mining specialist firms participate in a regional sector. Gauteng is also the country's economic and financial hub, home to major ICT firms which traditionally serve commercial industries. The concept of transversality can be applied to ICT and mining. There is an opportunity for a synthesis of the emerging technologies of 4IR with mining related technologies using the “related variety” concept. Ideally, these would be limited to high-tech mining related technologies; however, this study is also concerned with sustainable mining. It is postulated that the capability in these sectors is inadequate for successful cross-fertilisation leading to innovation. A systematic capability upgrading will be required in both sectors. These areas are in geographical proximity to PROs such as the CSIR, CGS and Mintek, and it is postulated that these organisations have a major role in building capability in this sector.

The capability based catch-up literature advocates for the exploitation of technology in the early stages, and intensified R&D for exploration in the latter stages. 4IR technologies are readily available for exploitation; however, some work, often facilitated by PROs and other state institutions, is required to absorb the technologies. Initial implementation gives rise to opportunities to solve new problems, as the technology becomes understood, further increasing the variety of implementation scenarios. Thus, the potential for innovation improves; however, key here, often also facilitated by PROs, is the knowledge interaction between mining and 4IR workers, and favourable policy that encourages demand for innovation, in line with the transversality literature.

2.7 STATEMENT OF HYPOTHESIS OR PROPOSITIONS

Based on the literature review, the following questions and propositions arise:

2.7.1 WHAT IS THE LEVEL OF CAPABILITY RELATIVE TO 4IR AND MINING TECHNOLOGIES IN THE REGIONAL INNOVATION SYSTEM

Proposition: South Africa does not yet have sufficient capacity to acquire, absorb, transform and exploit 4IR technologies. At the policy level, the Commission for the Fourth Industrial Revolution has recently released their recommendations to the state, which includes an emphasis on capability building and workforce relevance (SAGOV, 2020). Countries such as Germany, have already embarked on their policy formulation as early as 2011, and have a significant head start in terms of capability (Kuo, Shyu, & Ding, 2019).

South African mining has been at the forefront of technology, often developing world-leading technologies to overcome complex problems. However, global mining productivity has been decreasing over the last few decades with decreased investment in R&D, and South Africa is no exception (Bartos, 2007; Hermanus, 2017).

Capability in both 4IR and mining technologies would be apparent through scientific and intellectual property rights output, such as journal papers and patents, as well as policy and strategic documents containing intent to exploit such technology.

2.7.2 HOW CAN TRANSVERSALITY HELP ACHIEVE CATCH-UP IN THE MINING SECTOR?

What is the level of knowledge interaction between ICT firms and mining firms in the region?

What capabilities will this require, and what is the role of public research organisations in facilitating capability building and in stimulating transversality

Proposition: It is uncertain which of the recommended paths for catch-up could be relevant for South African mining (Lee, 2013b, 2019). For the early stages, well-known technology could be adapted to improve productivity, and this could include acquiring or imitating foreign technology. Options such as leapfrogging require ability to exploit technology and explore new opportunities for innovation.

Mining firms do not have capability in 4IR technologies, and require support to upgrade operations for catch-up (Kaplan, 2012). ICT firms promote digitalisation of mining systems without in-depth understanding of their operations, often resulting in transactional interactions. PROs thus have a part to play in proving new technologies and novel concepts and building supplier capability towards solving mining-related problems.

PROs could also have a part to play to stimulate knowledge interaction, increase related variety, influence regional policy and enable capability enhancement to facilitate the creation of new clusters and industries in the RIS.

2.7.3 WHAT ARE THE PROMISING WINDOWS OF OPPORTUNITY FOR LEAPFROGGING IN THE MINING SECTOR?

Proposition: There exist opportunities for leapfrogging in the mining value chain. Based on the existing development trajectories in the ICT and mining sectors, potential for new opportunities may become evident. Downstream opportunities would be more likely, as 4IR primarily benefits manufacturing (Dalenogare, Benitez, Ayala, & Frank, 2018).

For example, from the demand side, 3D printing can utilise metal powders for jewellery manufacture, thus leapfrogging advanced manufacturing of other countries. This may create new industries to support the new structure of the industry, but must be cultivated through favourable policy and regulation.

CHAPTER 3. RESEARCH STRATEGY AND METHODOLOGY

3.1 INTRODUCTION

The research follows an interpretive qualitative approach aimed at uncovering the experience, struggles and hopes of individuals in organisations (Merriam, 2009). This study focusses on those individuals tasked with adopting Fourth Industrial Revolution (4IR) technologies for the mining sector. The chapter discusses the research strategy and design, selection of participants, methodology, data analysis and limitations and ethical considerations.

3.2 RESEARCH STRATEGY AND DESIGN

The research follows an interpretive qualitative approach focussing on selected case studies in the mining sector. Qualitative inquiry aims to understand the experiences of individuals uncovering what they sense, the meanings attached, their motives, actions and emotions (Merriam, 2009).

An interpretivist approach is relevant for this study since there is no single truth or answer to the study question. Rather, the study aims to uncover the range of possible strategies and outcomes that will be employed, seeking to find a common thread. Thus the study is explorative in nature and Rossman and Rallis (2011) categorise this as "analytic descriptive studies". Analytic descriptive studies concern describing and then analysing social phenomena for purposes of improved understanding.

A number of actors play a role in capability enhancement for the mining sector in South Africa, such as primary and secondary education, tertiary education institutions and technical training centres and training institutes. However, the actors of relevance are involved in upgrading firm capability with expertise in emerging technologies, being able to use, exploit and possibly create innovations. To understand the activities of such actors, interviews with selected employees were conducted. The unit of analysis is thus organisations, those involved in mining and in exploring opportunities offered by 4IR technologies for the mining sector.

3.3 RESEARCH METHODS

The research follows a qualitative case study approach, which is appropriate for an exploratory study for understanding the experiences and thoughts of the organisations under analysis (Merriam, 2009).

The study employs a case study protocol as recommended by Yin (2017). This document constitutes a partial fulfilment of the protocol, particularly the overview of the case study, data collection procedures, and tentative outline for the case study. The questionnaires for the protocol questions are appended to this document.

To improve validity and credibility, Noble and Heale (2019) recommend triangulation, which in this case includes interviews with other actors in the mining value chain. The mining value chain is complex with many stages, and each actor may only understand stages within their sphere of expertise. Additional interviews would help minimise assumptions and improve overall understanding.

3.3.1 DATA COLLECTION AND INSTRUMENT

3.3.1.1 PRIMARY DATA: INTERVIEWS

The inquiry employed guided conversation or in-depth interviews (Yin, 2017). A basic set of questions has been configured according to the case study protocol, and “how” questions were used to delve further into an area of interest. Yin (2017) advises on the use of “how” questions even for elucidating “why” responses since the latter may lead to defensiveness.

The case questions were trialled in the interviewer’s home organisation, with a set of mock participants, to test for weaknesses, ambiguities, and the use of unclear language, and to prepare and train the interviewer, having no prior experience.

3.3.1.2 SECONDARY DATA: DOCUMENTS

The organisations’ websites, as well as publicly available policies, roadmaps, annual statements and media statements were collected. Where possible internal strategy documents, policy documents, and project portfolio data for any projects pertaining to 4IR were also requested. However, these were sometimes confidential in nature and the organisations were not willing to share them. The data relating to projects required elicitation in the interviews.

3.3.2 SELECTION OF PARTICIPANTS

A Public Research Organisation (PRO) involved in mining and 4IR research, as well as mining firms searching for solutions that leverage 4IR, have been selected. Mintek is a suitable representative of a PRO, having extensive capability in mineral technology and mandated to support the sector. Two large scale mining (LSM) firms serve as suitable candidates for mining firms. The LSM firms own a number of platinum and gold mines in South Africa with centralised engineering and development teams, and are able to invest in new technology for productivity, environment and safety improvement.

An in-depth case study has been conducted with each of these organisations. Five individuals represented Mintek, while three individuals represented each mine, constituting a sample size sufficient for an exploratory case study design (Yin, 2017).

For triangulation, further interviews were conducted with a number of other organisations participating or influencing the mining sector. This includes individuals in the HySA consortium, Gold Ore, a start-up in the gold industry, as well as the Mandela Mining Precinct, and researchers at the Wits Mining Institute. Policies and documents from the Department of Mineral Resources and Energy (DMRE) were studied. The objective was to determine if there was cohesion in terms of improved mining, as well as strategies for leveraging 4IR for downstream activities such as manufacturing.

These participants had a working understanding of 4IR and the realistic benefits and challenges for the mining sector in the country. The selection could have resulted in an elitist participant set, as 4IR is high on the agenda of these organisations, with upper management leading the charge to develop programmes and roadmaps for the implementation, thus a certain level of judgement was required to ensure that the questions were relevant and did not undermine the status of the individual.

Policies, annual reports, media statements and other publicly available documents were collected to enhance the understanding of the approach to the problem. These form secondary data to corroborate the interview data, and were studied beforehand such that the interviewee had sufficient background knowledge to steer the conversation.

3.4 DATA ANALYSIS

3.4.1 INTERVIEWS

The interviews were in-depth guided conversations, which were recorded with consent from the participants. The first step in the analysis was to transcribe the recordings into electronic text formats. This raw data was input into a database.

Each interview was analysed to extract themes, assumptions and deviations from theory leading to interpretive content analysis (Erlingsson & Brysiewicz, 2017). Erlingsson and Brysiewicz (2017) recommend a reflective, non-linear process of extracting meaning units, condensing the units, coding, categorisation and theming.

3.4.2 DOCUMENTS

Documents were collected prior to the interviews and scoured for information related to the research topic. This supported the interview process initially.

For data analysis, additional internal documents added to the narrative and the content analysis. Each document was input into the database, along with reference source, history and circumstances that led to the creation of the document, or further revisions.

3.4.3 THEMES OF INTEREST

The interviews were constructed to understand the participants understanding of 4IR and the benefits and challenges for their organisation and the sector.

It was important to understand what technology would be implemented, how the technology would be implemented, and how the challenges would be overcome.

An understanding of interactions between organisations in the Regional Innovation System (RIS) was also of relevance, with insight into possible opportunities that might arise from these interactions.

The themes relate to the concepts of catch-up and transversality, which are key to this study.

3.5 LIMITATIONS OF THE STUDY

The unit of analysis was mines extracting precious metals and PROs in the mining sector. An extension of this study, in a cross-sectional perspective, might include mines extracting other commodities, artisanal and small-scale mining (ASM) firms, and other actors engaged with 4IR activities.

The researcher is an employee of Mintek, and this may have had a negative effect on the responsiveness in the interviews, perhaps resulting in non-responsiveness. However, this was disclosed and the scope of the study explained, that being research intended for a post-graduate degree.

3.6 ETHICAL CONSIDERATIONS

Ethical standards as per the Wits code of ethics was strictly adhered to. This proposal was also approved by the Wits Ethics Committee before fieldwork could commence.

Each potential interviewee was introduced to the scope of the study and requested to participate, pending willing consent. Interviewees remain anonymous, including title and designation within the organisation.

The researcher wished to record all interviews, requiring further consent be requested, and this was granted in all occurrences However, in two of the interviews, technical difficulties with Microsoft Teams prevented such recording, and handwritten notes were used instead.

3.7 RELIABILITY AND VALIDITY

To ensure reliability and a certain level of reproducibility, all documents and interviews were input into a database, the process of conducting the research was also carefully documented and input, which follows the case study protocol of Yin (2017).

At a high level, construct validity was sound. This was corroborated with literature and multiple sources of evidence, particularly for operationalisation of the terms, “innovation”, “capability”, “sustainable mining” and “fourth industrial revolution” (Yin, 2017).

Internal validity is a concern for explanatory case studies, and is minor or irrelevant for this exploratory study (Yin, 2017). However, exceptions may occur, such as new targets that may arise due to changes in the firm strategy or through policy and not due to the application of new technologies and innovation thereof. Instances such as these were carefully assessed and dealt with.

The case studies and their analysis were specifically designed for the precious metals mining sector, although policies and practices that arise may be applicable to mining in general in South Africa. However, the analysis may not be appropriate for other African countries, or other sectors in South Africa.

3.8 TIMELINES

- Proposal Refinement November 2020 – December 2020
  Improve literature review, understanding of theoretical framework and conceptual model with feedback from panel and supervisors
- Interviews
  Prepare and test questionnaire, collect secondary data, conduct case study interviews.
- Analysis and write-up: May-June 2021
  Verification, theming, analysis, proposed practices and policies.

3.9 SUMMARY

The study follows an explorative qualitative case approach with mines and PROs in the mining sector as the unit of analysis. In-depth interviews were conducted with a set of individuals in these organisations to determine the propensity for adoption of Fourth Industrial Revolution technologies for catch-up in the mining sector. The study seeks to understand the relevant PRO's approach to solving these challenges simultaneously, and the agency's role in facilitating such solutions. The case study protocol was strictly adhered to, ensuring the reliability and validity of the results.

CHAPTER 4. PRESENTATION OF FINDINGS

4.1 INTRODUCTION

This chapter presents the research data obtained from the in-depth interviews any secondary data. In-depth interviews were conducted with the main case studies, the Large Scale Mining (LSM) firms and Mintek, and additionally with the Mandela Mining Precinct, WITS Digimine, Gold Ore, and HySA, used for triangulation. Secondary data was obtained from these participants and the DMRE. The focus was on advanced technology projects, technological capability building, interactions with stakeholders and efforts to catch up with international peers. For each research question, the relevant findings are presented.

4.2 PROFILE OF PARTICIPANTS

This section provides a profile of each of the participants involved in the study.

4.2.1 LARGE SCALE MINES

Two Large Scale Mining (LSM) firms participated in the study. These participants wish to remain anonymous in the study.

The first participant is a local firm with some presence internationally, which owns and operates several gold and platinum mines within South Africa. The LSM firm has a track record of profitability in each of the assets, with a focus on cost-cutting initiatives as well as moderate exposure to advanced technology to improve operations. The LSM has centralised engineering and development teams responsible for optimizing operations as well as introducing new technology to the mines.

The second participant is a multinational firm (MNC) with local ownership, which also owns and operates several precious metal mines within South Africa. The LSM firm also has a track record of profitability, but mainly due to the adoption of cutting-edge technology. The LSM firm has a centralised engineering and development unit with a similar role as the first participant, with the added ability to leverage experience from international operations.

4.2.2 MINTEK

Mintek, the Council for Mineral Technology, has a proud history dating back to 1934. The continued existence of Mintek is captured in an Act of Parliament, Act No. 30 of 1989 (Mintek, 1989). The Act also outlines the mandate of Mintek, which is,

"*the objects of Mintek are through research, development and technology transfer, to promote mineral technology, and to foster the establishment and expansion of industries in the field of minerals and the products derived from them*."

Mintek is a Public Research Organisation (PRO) mandated to conduct research and to develop new technologies to assist the mining sector. This includes beneficiation and downstream value-addition. A state grant constitutes approximately 60% of Mintek's income while commercial income constitutes 35% (Mintek, 2020).

Mintek performs the following activities to achieve its objectives:

- Conduct research, development and technology transfer to improve utilisation of mineral resources, improve technical process and methods, and to establish, promote and expand industries in minerals and products derived therefrom.
- Provide technical expertise
- Grant bursaries and educational loans
- Create and publish knowledge
- Establish and run facilities for research purposes
- Research collaboratively with other countries

Mintek employs around 520 employees of which 43% are SET based, and as science and engineering are core to Mintek, in 2019 a new Human Capital Development programme was launched to improve the SET base, focussed on granting bursaries to employees for postgraduate studies in science and engineering (Mintek, 2020).

Mintek is comprised of nine technical divisions, focussing on research, development and commercialisation (products and services):

- Advanced Materials
  Research in end-use metals in manufacturing, fabrication and mining.

- Analytical Services
  Provides analytical chemistry laboratory services

- Biotechnology
  Develops biotechnology for mining, for example, bioleaching.
- Hydrometallurgy
  Develops hydrometallurgical processes and flow sheets for recovery and refining of metals
- Measurement and Control
  Develops measurement sensors and advanced process control solutions for metallurgical processes
- Mineral Economics and Strategy
  Provides strategic research insight for minerals
- Mineralogy
  Provides mineralogical services to quantify and describe minerals in ore
- Pyrometallurgy
  Conducts high-temperature research and process development
- Small Scale Mining and Beneficiation
  Support of the SMME sector

The core technical divisions in Mintek conduct varied research and development across the mining value chain.

4.2.3 MANDELA MININNG PRECINCT

The Mandela Mining Precinct (MMP), a public-private partnership between the Department of Science and Innovation, the Department of Mineral Resources and Energy and the Minerals Council of South Africa (formerly the Chamber of Mines South Africa), was launched in 2018 in an effort to revitalise mining through RDI to ensure the sustainability of mining in South Africa (Mandela Mining Precinct, 2021). The Mandela Mining Precinct implements the South African Mining Extraction, Research Development and Innovation (SAMERDI) strategy as set out in the National Development Plan (NDP).

The precinct focusses on six research-based programmes:

- Mechanised Drill & Blast

- Non-explosive Rock Breaking
- Longevity of Current Mines
- Advanced Orebody Knowledge
- Real-time Information Management Systems
- Successful Application of Technologies Centred Around People

The Mandela Mining Precinct facilitates collaborative research between various stakeholders in the mining sector including mines, government, research facilities and equipment manufacturers towards improving capability in mining RDI. The Mandela Mining Precinct provides access to test mining infrastructure and enables development of local technologies for mining. One mechanism that has proven successful is the presentation of mining challenges to industry, in an open innovation model. This is an effort to promote development of new equipment to solve specific problems such as that posed by the Isidingo Drill Design challenge, which resulted in the creation of two rock drill prototypes by local innovators (Mandela Mining Precinct, 2021).

4.2.4 DMRE

The Department of Mineral Resources and Energy (DMRE) is a department of government that aims to promote economic growth through development of the mining and energy sectors. The DMRE was formed in 2019 through the merger of the former Department of Mining and the Department of Energy (DMRE, 2021). The DMRE is responsible for the issuing of mining rights in South Africa, as well as mine health and safety, mineral regulations, the mining charter and other mine and energy related aspects (DMRE, 2021).

4.2.5 WITS DIGIMINE

Digimine is the digital mine laboratory at Wits university founded in 2014, and is a mock mine with a surface, vertical shaft and underground mine. The underground mine is fitted with a control room. Digimine aims to conduct research to bring digital technologies to the underground mine environment to be able to “automatically observe, evaluate and take action” (Wits Mining Institute, 2021). Ultimately, Digimine hopes to improve the safety of miners in underground environments. Digimine’s founding partners include Sibanye-Stillwater, the Mine Health and Safety Council (MHSC) and IBM. Digimine research is centred around a number of themes, including reliable mine-to-surface communications, laser scanners for rock health, advanced modelling techniques as well as integration of systems, underground UAV's, risk detection, training and skills development (Wits Mining Institute, 2021).

4.2.6 HYSA

Hydrogen South Africa (HySA) is an initiative by the Department of Science and Innovation (DSI), officially launched in 2008, to bring about high technology industries based on the Platinum Group Metals (PGMs) found in South Africa (HySA, 2021). HySA has three main objectives:

- The "Use and Displacement of Strategic Minerals", that is the beneficiation of PGMs
- Promotion of the hydrogen economy and renewable energy
- Seeking methods to cost-effectively and sustainably incorporate PGMs in hydrogen fuel cells.

The HySA structure is composed of three Centres of Competence:

- HySA Catalysis
  Collaboration between the University of Cape Town and Mintek to develop catalysts for fuel cells
- HySA Systems
  Hosted at the University of the Western Cape with the aim of developing fuel cell systems, prototypes and demonstrations and validation of those systems
- HySA Infrastructure
  Collaboration between North West University and the CSIR to develop systems for hydrogen production, storage and delivery

The history of HySA is described by one of the participants of the study as follows:

> "HySA was borne out of the need to add value through the beneficiation of minerals, particularly platinum, since South Africa has the richest reserves of platinum in the world. Platinum is used in automotive catalysts, but South Africa

had not participated in that cycle. The new vision that was coming was around the hydrogen economy and fuel cells, and the part that platinum would play as a catalyst. The idea was that South Africa, through HySA, would have a chance to develop technologies and enter into that market, because at that time around 2007, the markets were just being established, and in that way South Africa could beneficiate and manufacture fuel cells, fuel cell components, actually the entire value chain of fuel cells from catalysts to stacks to systems. Since then, technologies have been developed, and some of them have been commercialised, but it's not so easy to break into the markets. Maybe the focus has changed from the need to sell overseas, a bigger flavour of the programme now is that there is a definite desire for some form of local hydrogen usage, and not just for export overseas."

4.2.7 GOLD ORE

Gold Ore, a South African start-up company founded in 2012, has developed the MACH REACTOR™, which is a device that improves chemical reactions and metal extraction in the gold mining industry (Gold Ore, 2021). The company is currently headed and run by the CEO, and has taken the approach of outsourcing development, production and installation of the device to other local small companies in South Africa to help stimulate economic growth.

4.3 RQ1: LEVEL OF CAPABILITY

4.3.1 CAPABILITY IN ADVANCED TECHNOLOGY

4.3.1.1 OVERVIEW

Participants unanimously agreed that South African mining was lagging in terms of competitiveness and the use of advanced technology, when compared to global leaders in the sector such as Canada and Australia. This may be due to differences in the mining environment and include factors such as the deep mines in South Africa, lower ore grades, high labour dependence, as well as issues such as high electricity costs and unstable power supply. Open pit mines and on surface operations in general are more amenable to automation and implementation of advanced technology. The age and size of mines in South Africa also plays a role in technology adoption. Some key technology used underground dates back to the 1940's, some are pneumatically driven, and would incur significant capital cost to replace.

However, the participants also agreed that South Africa was a leader in deep level mining.

> "When it comes to deep mining, South Africa can still claim to be the experts, but this may be more due to persistence rather than new technology."

This apparent contradiction was clarified by another participant,

> "on the mining front itself, deep level mining, the book was written in South Africa. South Africa is the leader in deep level mining, and in solving problems such as ventilation and the cooling problems that go with it, and roof support and so forth, and if you take the resource estimation technology methodology, that was born in South Africa and is still used internationally. When compared internationally, South Africa can be said to be a slow adopter of technology, because we have always operated on a much bigger scale than anywhere else, and it's difficult and slow to replace technology at such a scale. I remember a presentation where someone said that all the scrap heaps on mines are filled with old equipment but were attempts to mechanise the mine, costing millions but going nowhere, but actually it's not going nowhere, it is learning lots of lessons as to what to avoid the next time. It's not a reason to actually say, no but mining mechanisation cannot work in SA, it's just that we've figured out a couple of ways that are not going to work."

The participants did note that some newer, smaller mines employed more advanced technology. There are also hybrid mines which are partially modernised, using both the older and newer technologies.

Participants from the mine indicated that Platinum Group Metals (PGM) mines, which are often closer to the surface, do seem to have some vision to ensure their sustainability, and are investigating hydrogen fuel cell technology, both to power their operations as well as creating demand for PGM. Surface mines have seen the adoption of advanced technology such as the implementation of driver augmentation systems on mine haul trucks for fatigue monitoring, and improved safety and maintenance. However, technology such as automated mine haul trucks are still not prevalent.

4.3.1.2 RESEARCH AND CAPABILITY BUILDING

Both the mines participating in this study promote research through bursaries for post graduate degrees granted to their employees. However, the majority of the improvement initiatives are through partners and suppliers.

Mintek, as a Science Council, is mandated to conduct research for the development of new technology, but the consensus is that Mintek is

> "stuck between routine services and trying to be innovative."

Mintek's R&D is described as "disjointed" as some activities involve established technology and results in application of established techniques to ore samples, whereas only a few involve novel research. Sometimes there has been investigation into areas just to gather knowledge on the topic, in the hopes that someday when someone comes looking for that expertise, that Mintek will be able to assist. However, as one participant stated,

> "Mintek's expertise lies with the person. Of course you can try to capture the knowledge in the reports and technical documents, but once that person leaves, the knowledge is really lost."

On the TRL scale, Mintek's projects are typically from TRL 3 onwards, but generally towards the mid-TRL levels, and operate at quite a small scale. These projects progress up to a stage, but then there is no opportunity to implement the technology, or no sponsor willing to finance further development. As stated by one respondent from Mintek,

> "there have been challenges commercialising products and services recently."

Mintek has in the past developed technology that has revolutionised the industry, for example the Carbon in Pulp technology has been successfully deployed at a number of gold plants. However, recently, much of the R&D has not been effective, especially if considering effectiveness as acceptance of the technology in industry. Mintek's CynoProbe, which measures cyanide concentration in a slurry, for example, has been installed in over 40 countries and would be classified as effective, but others such as the SAVMin have not had the same results thus far.

Often, even the idea comes from outside of Mintek,

> "in a few instances we found that breakthrough innovations don't come from inside Mintek, an idea is born in the mining industry or even by other entrepreneurs, and when you see it you kick yourself for not thinking about that, but we didn't because we're not really there, we're not having to solve that problem on the ground where they see it, so they come up with a breakthrough idea but are not well versed in the underlying fundamentals and are unable to take the concept forward… and that's where Mintek comes in to assist in the development and to actually understand the fundamentals and to optimise it."

Mintek's apparent lack of focus is due to pursuing multiple opportunities in the various disciplines, for processes and technologies that they are already familiar with, and it is easier and more convenient to continue on that path, to optimise, instead of looking for new opportunities. To correct the path requires access to information which is not readily available, and broad exposure to people in the industry to understand and then solve the actual challenges.

The Mandela Mining Precinct collaborates with the three mining universities in the region, WITS, UJ, and UP, as well as the CSIR for research. A participant noted that honours and post graduate students are typically sponsored to work on relevant projects. The technologies are developed up to TRL 6, when industry collaboration, such as with the Mining Equipment Manufacturers of South Africa (MEMSA), is sought for further development. The Mandela Mining Precinct does not own IP or sell any products, and in this way ensures establishment and support of local companies. The Mandela Mining Precinct conducts R&D on a number of themes, and one of the participants was engaged in research in the "Glass Rock" initiative, which aims to identify the mineralogical makeup of the ore using advanced technology. Another example, the Isidingo Drilling Rig, shows the support given to local companies in trying to improve the design and manufacture of drill rigs with exacting specifications, as well as in improving the overall quality of the equipment. As one respondent from the Mandela Mining Precinct stated:

> "one of the reasons people prefer international suppliers is the quality issue."

Commenting on the effectiveness of the R&D at the Mandela Mining Precinct, a participant based at the precinct, noted that the programme had only been in existence for four years, and that would be too soon to determine if they have been effective. According to this respondent there have been many instances where the mines would pose a problem and the research would propose a solution that was satisfactory, however there have also been occasion when there has been misalignment,

> "When we do diamond drilling, we've got these holes and we want to install either cameras or probes inside these holes to be able to get more information. But the challenge has always been, how do you get this probe or this camera into these holes, when some of the holes are really long? So, we're looking at deploying a little gadget that will keep the hole open. We developed this fancy little gadget, and it works, we can just put it in, but in the end that's not what the mine actually wants. They would rather want the camera to crawl into the hole, and so we had to stop the project."

On other occasions just procuring technology to begin customisation, with a possible risk of failure, has proven too costly, and work could not even begin.

Mining equipment originates from countries such as Sweden, Germany and Finland, which have a tradition of equipment supply, and have built this over centuries. Mintek also has a role in testing foreign technology for local mines at the request of these mines, for example novel flotation acceleration units such as reflux classifiers were tested on local commodities to determine effectiveness, configuration parameters, and so on. However, the major focus for Mintek is in developing in-house technologies. The Mandela Mining Precinct on the other hand, has programmes specifically designed for localisation of technology. They work in collaboration with the Mining Equipment Manufacturers of South Africa (MEMSA) to promote local equipment companies. Support is offered to help improve manufacturing and then to encourage the mines to procure locally.

Participants at the WITS Digimine have worked on technologies related to 4IR, for example the remote piloting of an aerial drone in constrained underground environments without GPS. This particular problem remains a challenge globally, with the Defense Advanced Research Projects Agency (DARPA) offering a million-dollar prize in the sub-T challenge. The sub-T challenge invites world leaders in robotics and automation to enable drones and other robotic vehicles to function autonomously in underground environments. The Digimine mock mine, which is a sixty-meter stretch of tunnel, two meters tall and three meters wide, located below the Minerals Council (formerly Chamber of Mines) building, serves as a test facility for advanced mining technologies. Since the trend is towards remote control, much research is around underground communications, algorithms for collision avoidance, underground mine mapping, use of a variety of sensors, including those for safety, and so on. Underground network communication is still a challenge, and because of the lack of a fixed fibre backbone network underground, communication is slow, intermittent or non-existent.

A number of participants pointed out that implementation of new technology generally comes down to one individual on the mine or the processing plant. For instance, one of them stated that:

> "Most employees are very busy on the plants making things happen and making sure things work, and very few are able to think longer term."

Those few individuals have some sort of understanding of the advanced technology and are willing to risk an implementation, whereas others do not fully understand the technology and may feel threatened about giving away their control. However, once a new technology has been implemented and has shown value, others immediately follow. A participant from Mintek stated that:

> "People are so scared to try new things unless everyone else is doing it."

There is also a sense that employees on mines and processing plants do not have an understanding of the fundamental chemical and physical processes, and would not seek help lest it expose their inability. There is also evidence of improvement in skills to be able to work with new technology, and one participant indicated that mines have trained employees to install some of the new technology, to maintain it, and then to interpret the data that it generates.

When HySA was established, around 2007, South Africa was about two decades behind in capability, but since then, HySA has caught up to the point where fuel cell components such as the catalyst and the membrane electrode assembly (MEA) can be manufactured locally. HySA lacks only the ability to build full systems. This is quite an accomplishment considering that the investment has been a fraction of that of overseas automotive and fuel cell companies and other government programmes. The technology is well known and published in the literature and in patents which have now expired. However, the methods needed to be derived through experimentation and trial and error, with constant output benchmarking to ensure equivalent performance.

A participant from HySA expressed concern over the lack of capability in simultaneously scaling up manufacturing and being able to create the markets that would demand the higher volumes of output. Current global manufacturers already produce components and fuel cell systems at large scales, but some of those manufacturers have been posting massive loses for a number of years. One major producer, Ballard, has only recently posted a profit. HySA currently produces around 1kg batches of catalyst, but easily has the capacity for 5-10kg batches, while HyPlats is able to produce 125 000 MEAs per year, which are relatively small volumes. However, there is nothing that warrants increasing output at this stage, since there is no demand. There seems to be an expectation in the National Innovation System (NIS) that government, and other investors create these national programmes and that once the technology is understood and components can be produced, then, as a participant from HySA stated:

> "magically factories start popping up."

The support for industrialisation is non-existent in South Africa for large scale deployment, both from the policy and from the financial aspects. To be able to compete, say with Tesla in battery manufacture, at least to reach the scales where the costs are reasonable, requires exorbitant capital investment that is difficult to attract. The alternative then is to aim for component manufacture and become tier one or two suppliers to those global companies. Then gradually build a reputation and improve the quality that can be the basis for the next step up the value chain.

The report produced by the Presidential Commission on 4IR adds valuable insight into the capabilities required to fully exploit opportunities of 4IR. There is intent, for example to update basic and higher education to include components of digital technologies, creation of a dedicated Artificial Intelligence (AI) Institute and competence in Additive Manufacturing (SAGOV, 2020). The report also highlights the intent to modernise local infrastructure in the form of expressed rollout of 5G technologies and data centres for high performance computing. However, as with the previous white paper on Science and Technology, the references to mining are few (SAGOV, 2019). The report has one reference to deep level mining with the intent to automate deep level mines with the use of robots, as well as rock-face mapping initiatives using novel technology. However, the details of how robots will assist with underground mining, has not been discussed.

4.3.1.3 KNOWLEDGE SHARING AND CO-DEVELOPMENT

In most cases, knowledge sharing was seen as a collaboration with universities and PROs to conduct basic or applied research as once-off projects. Mintek prefers to engage with post graduate students with the possibility of later employment with mechanisms such as bursaries or through encouraging employees to study further. Research is focused on well-known problems in the industry, but with a view to commercialising any intellectual property derived therefrom. The participants from the mine indicated that their respective firms invest in university laboratories, also supporting employees, but also seek opportunities with established firms to improve their operations. One of the participants indicated that their partner programme is dedicated to ensuring suppliers continuously improve, often using their mines as a test bed for new products and services. Sibanye-Stillwater is instrumental in the formation of the WITS Digimine centre, and supports other institutions such as the Mandela Mining Precinct. Research is focused on specific problems that the mine experiences, and prototypes are trialed at the mine.

The various HySA centres collaborate with one another to coordinate the programme, with the universities, Mintek and the CSIR participating in knowledge production. The development at the centres could also be classified as co-development since there is a common goal. The Mandela Mining Precinct invests in R&D at universities and PROs and facilitates research programmes with mines and suppliers. Since the research project might be shared across the institutions, this requires collaboration and cross knowledge flows to share expertise. A participant also indicated that they publish articles in mining related journals, create media briefings, and speak at various forums to disseminate information.

However, in the majority, co-development is limited to testing and validating new technology at mines in a contractor relationship, with minimal participation from the mines, except in providing a test environment, and then acceptance or rejection of the system. The mines that participated in this study indicated that the provision of a test environment to prove the effectiveness of the new technology often has benefit for the mine, usually in the form of discounted license fees when the technology is eventually commercialised. The risk for the mine is low. Often, tests are conducted on a trial basis at the cost of the technology development company, for example HySA demonstrates their catalyst and MEA technology in a complete system provided by a fuel cell assembly company. HySA benefits from exposure to international standards and performance criteria, and the assembly company evaluates supply chain alternatives. The SAVMin is an example of another technology that Mintek has developed to treat mine waste water that has been piloted at a facility in Randfontein. A participant from Mintek stated:

> "The ultimate vision would be to have a full-on partner, not just for test sites (eventual buyers), but someone envisaging and developing from the beginning. ConRoast was an example, but that was a long time ago."

The participant elaborated that the Mintek ConRoast technology is used to remove sulphides when producing high grade PGM concentrate.

Another participant echoed this sentiment, and gave an example of Heap leaching technology that was co-developed with a client many years ago, with the aim of determining a mechanism to raise the temperature in heaps for leaching. In that example, both parties shared rights to the technology.

A participant from Mintek indicated that the paucity of co-development is surprising,

> "You read about in Mining Weekly, a CEO of a mining company is looking for someone or has a problem or you read about how they had to solve it themselves, and you question why or how does Mintek get involved in those sorts of conversations at that level."

Another participant in Mintek described recent challenges in starting a co-development project, where it was difficult to finalise the legal aspects. The participant was hopeful that the new Technology Transfer Office (TTO) that was proposed in the updated

Mintek organisational structure would alleviate this burden and provide the necessary support.

In the past, mining companies have had the capacity to conduct in-house R&D, but this is no longer the case, and is further compounded by ageing expertise. PROs should be leveraged for their expertise, but this does not occur, and could be due to awareness, reputational issues, or costs.

The Mandela Mining Precinct creates innovation challenges to stimulate the development of novel technology for the unique problems experienced at the mines. In the Isidingo Drill Design challenge local equipment manufacturers were tasked with creating drill equipment with specific acceptance criteria. A number of suppliers took up the challenge, and two promising prototypes were selected, and are currently undergoing testing and validation before they can be accepted and manufactured.

WITS Digimine relies on problems, and funding from the local mining houses. This ensures that the research is then highly relevant, based on real-world problems. The mine has access to high calibre research, often leagues ahead of industry in terms of technological capability.

HySA promotes knowledge sharing and co-development between its centres. External partnerships are also established to assist with testing and commercialisation of the technology, for example, HySA has partnered with PowerCell, as Swedish fuel cell assembly company. The HySA catalysts and MEAs are tested in PowerCell's systems and deployed locally for demonstration. HySA benefits from the exposure to real world system performance criteria and specifications, and PowerCell has a potential alternative supplier. PowerCell is not otherwise actively involved in catalyst or MEA development. HySA also has collaborations with local platinum mines, for example, Impala Platinum, which provides access to the large quantities of platinum required for the fuel cells. The platinum can be recycled, recovered and returned to Impala. However, there is always potential for some minor losses. Impala would benefit from the future increase in demand for platinum. Impala is also involved in a project with the OR Tambo (ORT) IDZ provincial entity in developing a Special Economic Zone (SEZ), in Springs, just east of Johannesburg (GIDZ, 2021). The SEZ, amongst other initiatives, would include high-tech business focussing on PGM technologies, such as fuel cells.

4.3.2 FIRM ENVIRONMENT

Some of the participants indicated that capabilities in 4IR would require more than mere attendance of a training course. The basic education system would have to play a role in introducing these technologies to learners at an early stage. There is evidence of deficiencies in the basic and higher education systems in preparing learners in digital technologies, but the intent is to bolster the education system with updated curricular for such technologies (SAGOV, 2020). Then exposure in the work environment can lead employees to become visionaries in these technologies. Fortunately, we have seen tertiary education systems evolve to offer courses and degrees in these systems, and some, such as WITS Digimine trying to merge 4IR technologies with mining. The report also highlights other infrastructure inadequacies that will receive attention.

Load shedding and intermittent as well as costly electricity supply stood out as an urgent issue that has already had widespread negative impact on mines and processing facilities. It is no longer economically viable to operate furnaces for certain commodities, or to operate certain types of mines in South Africa. The industry has subsequently seen the closure of such facilities and mines. The electricity supply issues also affect investor confidence and access to further investment finance to implement 4IR technologies.

Due to commodity cycles, when there is a downswing, that is a global decline in demand, mines are less willing to take on any risk, such as implementing new technology, and would rather concentrate on cost reduction and on optimisation projects. However, in times of upswing, there's willingness to try new technology, sometimes frantically. The general trend then is one of short termism, as stated by a participant from Mintek:

> "there's never any kind of long-term thinking about what they want to do or where they want to be with their operation. There are one or two rare people who are thinking ahead and seeing the bigger picture, but they are few and far between."

4.4 RQ2: EVIDENCE OF CONDITIONS FOR TRANSVERSALITY IN THE MINING SECTOR

4.4.1.1 REGIONAL STAKEHOLDERS

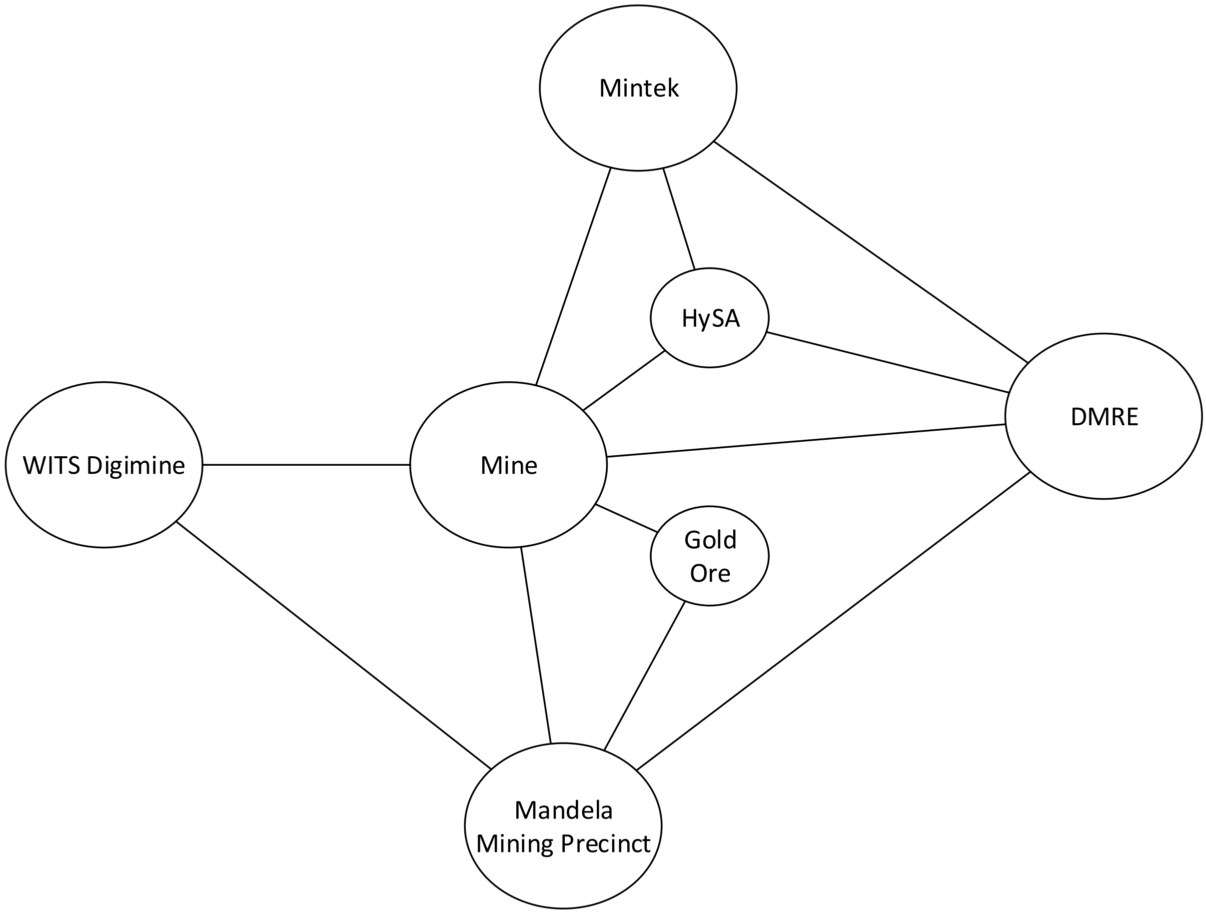

Figure 2. Participants in the Regional Innovation System

Each of the organisations interact with each other either directly or indirectly in a narrow innovation system as depicted in Figure 2. The organisations are also located close to each other in Gauteng and the North West province, and the participants often interact with each other for research as well as for commercial work, for example participants from Mintek and the Mandela Mining Precinct often travel to one of mines participating in this study, for onsite work.

The regional innovation system also extends to organisation not involved in this study, such as the University of Pretoria, the University of Johannesburg, local mining equipment manufacturers and suppliers, the CSIR and the DSI, although the CSIR and the DSI are represented in the study by the Mandela Mining Precinct.

The HySA model was also an exception, preferring to operate in a hub-and-spoke model where, for example, the centres are located across the country, in Johannesburg and Cape Town.

4.4.1.2 KNOWLEDGE SPILLOVER

Formal conferences seem to be the primary means of interacting with peers and with others in the industry, however, the participants often attend the same type of conferences annually, with some taking place every two to four years. Conferences occasionally offer the opportunity for social interaction when there are social outings planned, although this is not the norm. Other interactions are also through formal meetings or actual work on a mine or processing plant. This is the case with HySA, where meetings are usually at a high level, related to programme management.

Mintek participants indicated that they had formed a “Gold group” that invites experts from the gold industry for roundtable discussions on a quarterly basis. This gives the mines an opportunity to discuss current challenges, and ways to collaboratively solve issues. Participants at the mines and at the Mandela Mining Precinct indicated that they participate in similar strategic sessions with industry.

Only the participants from the Mandela Mining Precinct indicated that they actively schedule activities such as coffee or lunch or just a catch-up when they are in the vicinity of someone they are working with. The participant emphasised the importance on building strong relationships and bonds with others on a project. Two things are of value, that is, strong linkages with the various stakeholders such as the DMRE, universities, MEMSA and so on, and then personal relationships with the employees there.

The participant from Gold Ore indicated that engagements with senior executives at mines and mineral processing plants were crucial in gaining acceptance for the MACH REACTOR™. Gold Ore places great value in the networks with mines, and often participates in seminars and presentations. Networks with other small local companies, such as with electronic and mechanical production workshops, are also nurtured, and helps ensure production of the device according to high quality standards.

One interesting exception was the response of a participant at Mintek who had spent about six months on a co-development in Mexico, and a few months on rotation on a project in Iran, a number of years ago. In both cases, strong bonds, which last to this day were formed with the employees at the hosting organisation. According to the participant, this helped improve collaboration.

Mintek is an organisation of the DMRE, and it was then surprising to hear that interactions with employees of the DMRE were limited. Representatives from the DMRE met exclusively with the Mintek executive. A participant indicated that this was a lost opportunity for sharing a common vision for inspiration, and to seek new opportunities closer to the interests of the DMRE, and without such interaction, the DMRE is seen as an obscure administration function. This is the reason cited for Mintek's lack of influence on policy, especially with regard to advanced technology such as 4IR.

Interactions over the last year have been impacted by COVID-19, and Microsoft Teams and Zoom have become the new meeting rooms. Physical onsite work resumed once the interprovincial travel ban was lifted, but online meetings are preferred.

4.4.1.3 INNOVATIVENESS

Some of the technology introduced by the participants organisations are novel and locally invented, while others are foreign. However, those foreign technologies are introduced into new contexts, often undergoing some sort of localisation, and can be considered as innovation. In this regard, as stated by one of the participants at Digimine:

> "Digimine's ability to track global trends, rather than local trends, by definition is innovative."

Digimine's showcase consists of a large format video wall composed of a three-by-three array of LCD screens to simulate a remote operations centre. The concept exists elsewhere in the world already, but was relatively unheard of in South African mining operations, and is a simple example of innovation that appeals visually to potential sponsors.

The Mandela Mining Precinct spurs local manufacturers to develop new or updated technologies. They also actively seek new technology for use underground, for example, a technology known as "tunnel seismic tomography" used in Europe for sensing when boring tunnels, has been tested in an underground environment and shows promise. There are a number of technologies that have been evaluated to determine if they are “underground worthy”.

At HySA, the Human Capital Development (HCD) programme supports post graduate students who conduct research at the technological frontier, such as investigating material properties and uncovering improved catalyst technology. HySA also investigates improved production methods, for example HyPlats, the spin-out company charged with manufacturing MEAs, improved the process by introducing “dual direct coating” of the membrane which simplified the process and reduced production costs. Even with the catalysts, the real know-how is not contained in the patent, and takes effort to discover. There is innovation in the method, as the costs have been reduced by about sixty percent compared to the original laboratory version, and these methods have been kept trade secrets.

4.4.1.4 4IR

All of the study participants had a working understanding of 4IR and the potential impacts on the mining industry. However, most recognised that the dialogue with executives and non-technical employees required the use of simplified language for better understanding. The use of technical jargon is not suitable especially for buy-in, and participants rather described the problem and the benefits of the solution in simple terms. Impact of potential solutions on the employees must also be carefully explained.

Some of the participants were aware of the Presidential Commission and the report recently published and were confident that at least at country level, preparations and plans were taking shape to ensure South Africa progresses. However, it was apparent that references to mining were scarce.

It was found that the hype around 4IR has had some positive effect; people are more willing to think about new technology, even if the technology does not match the criteria of 4IR specifically. People now want more dashboards, are willing to look at their data proactively, instead of reactively for troubleshooting, and are more open to connected measurements and automated systems. COVID-19 has also created traction with technologies such as remote operation centres.

There was a mixed reaction to whether the participants’ organisations had any strategies or plans in place to introduce 4IR technologies. Mintek seems to be in the process of developing a new strategy which aims to integrate technologies such as digital twins, the Internet of Things (IOT) and Artificial Intelligence (AI) into new products and services aimed at improving safety, productivity and quality on processing plants. AI and IOT, for example will be used to bring new measurements online, particularly manual, unreliable and missing measurements, while digital twins of processes will be created to allow improved design of equipment and processes.

Reflecting on the evidence of 4IR technologies in the mining sector, participants indicated that there is certainly evidence in other countries, and this includes technologies such as automated mine-haul trucks, and remote operations centres, which are now quite common in Australia. Anglo American Platinum has similar remote operations systems, but this was more from organic growth than the predetermined implementation of 4IR technologies. The technology allows a group of experts to monitor and correct issues at mines and processing plants from a central command centre, rather than having to drive out to site for diagnosis. A number of mobile applications have been developed for the mining environment and an example is that of a maintenance logging application that allows an employee to use a phone or tablet to perform routine inspections of the equipment and surrounding environment. New maintenance tasks can be logged immediately with a corresponding picture, and approval for new parts can be obtained instantly. Should the employee require assistance with maintenance, a request can be made, and a someone dispatched immediately to assist. The previous process flow required the employee to write down maintenance tasks on paper, then go back to surface and place a request for a supervisor's approval, and then when the part arrived, physically try to find someone to assist with the installation should it be required. Asset tracking such as with location and operational status of underground vehicles or conveyor belts has also been automated such that technology managers have an immediate overview of the constraints in the system which they can immediately solve.

In South Africa, unique challenges such as underground communications have been a major hurdle for the adoption of 4IR technologies. A number of research initiatives have thus focussed on such technology. One participant commented on a simple example of an airflow sensor that previously required a person to take a reading, which had subsequently been connected to a network and to a computer to store a history, and then modelled so as to predict future measurements, as being indicative of 4IR.

These digital airflow sensors are now common in underground mines, but similar incremental changes are becoming more prevalent.

One project that Mintek is involved in for the European Union (EU), starts with the tracking of ore from an aerial survey of a mine, testing of different blasting technologies, then tracking the performance of crushing and screening circuit, and ensuring that the data is easily accessible in dashboards and for machine learning. The participant commented that unfortunately, funding for such a project in South Africa would be hard to come by, especially in the aggregate industry as is the case with the EU project.

Participants from the mine indicated that determining value from the implementation of digital technologies can be difficult. The process is not as simple as applying a net present value (NPV) financial calculation to determine pay back. One participant indicated that their CFO had to be urged to sign-off on a multimillion-rand project to improve the network backbone on the mine, just so that the infrastructure for further 4IR projects was available. The new projects implemented thus far have resulted in efficiency improvements, reduced safety incidents, as well as reduced fatality. Fatalities have major cost and time implications, as the DMRE conducts thorough investigations, often resulting in a two- or three-week suspension of activities. However, other benefits of 4IR implementations are difficult to justify in monetary terms, but have impacts such as reduced error rates and improved quality, improved communication, and improved and predictive fault monitoring and diagnosis.

The participant from Gold Ore indicated that implementation of 4IR technologies was on the roadmap for future development, and that aspects such as preventative maintenance, live access to dashboards and to some extent the allure of 4IR would impact the attractiveness of the MACH REACTOR™ device. The plan would be to contract an ICT firm to configure the data collection from the device and then develop a mobile application to allow anyone to view data and recommendations at any time. However, the technology would need to be as secure as possible to prevent possible leakage of data, some of which may expose the inner workings of the patent.

A participant from the Mandela Mining Precinct commented that the geological surveying and mineralogical analysis that occurs during exploration is a bit closer to 4IR. The process involves interpretation of large quantities of data, to create models and maps, requiring advanced data analysis. However, in the underground environment, particularly deep underground, the technology has been compared to 2IR, one participant even went as far as saying that it ought to be “0IR”.

Another concern echoed around 4IR technologies was the threat of breaches into digital systems at the mines and the extent of protection of data and of the digital systems. Participants expressed concern over malicious actors gaining remote control of systems, such as remote operated machinery, which could then lead to physical harm or destruction of property, and in an underground environment, could prove disastrous. Participants expressed concern of potential access to data which could result in theft of intellectual property, for example the MACH reactor’s internal calculations could be exposed. The technology that protects networks and systems must be carefully selected to ensure that such breaches do not occur.

The work done at HySA is still largely manual in nature, but there are no plans to automate, given the current lack of demand of fuel cell components. The participants indicated that markets would need to be created to stimulate demand, but given the alternatives such as electric battery technology, this would prove difficult.

Some participants were of the opinion that the universities and particularly PROs and agencies like the Mandela Mining Precinct have a role in making 4IR technology more accessible, that is, to package the technologies to ease implementation and usage. A participant from the Mandela Mining Precinct indicated that this is part of their vision, to have equipment that anyone can use, where one does not need to be a specialist, instead data should be relayed to the surface so that the specialist can, on exception, advise the miner. On the mine, employees who are excited by new things and willing take on risk will seek out these technologies, but employees who are aware of the technology often lack capability and may require assistance from the PROs and agencies. For the latter case, results, that is, improvements in operations, or safer conditions will be necessary to convince the employee. Another trend is that the large mines create entire departments whose primary objective is continuous improvement and deployment of new technology. This is often the case when more than one mine is owned, and resources are pooled to support a central technology implementation department.

All the participants in the study were not concerned about job losses due to implementation of 4IR technology. Those involved in technology development, even at university level, indicated that the technology currently being developed complements and augments employees' normal activities, and makes their work easier or safer in some way. This may be due to the maturity of technology in place currently. Much of the technology is old, and simple enhancements such as bringing measurements online is the next logical step.

There was also a comment about the quality of the work which will improve with less human intervention. The consensus is that even though South Africa is still a number of years away from full automation, the employees must be informed about future decisions and their concerns addressed. This is the approach taking by the Mandela Mining Precinct, which actively involves mine unions, and employees in generating the strategy to modernise the mine. Automation efforts currently focus on remote control rather than autonomy, thus ensuring that the employees continue to do the work, for example drilling can be done remotely, above ground in a safe environment. This will also bring opportunities for the configuration and maintenance of these new systems, creating new jobs which requires new skills. The current dialog indicates that the mines will play a direct role in upskilling employees.

All the women in the study commented on the opportunities that 4IR offered women in mining. There are currently very few women in underground mines, and this is due to labour intensity, and harsh underground conditions, as stated by a respondent from the Mandel Mining Precinct:

> "there's not even proper toilets for us."

The introduction of technology has the ability to bridge this gender gap.

The report produced by the Presidential Commission on 4IR introduces the intent to modernise deep level mining operations with two specific initiatives, robotic mining as well as rock face mapping (SAGOV, 2020). The specific implementation of this plan is yet to be determined.

4.5 RQ3: WINDOWS OF OPPORTUNITIES FOR CATCH-UP

One participant indicated that there is room for more intra-country collaboration in South Africa, and cited the example of Pelchem, based in the North West province, which at some point required high quality fluoride feedstock and was unable to link with a new mining company that was also looking for someone who would purchase their product. Most of South Africa's resources are exported overseas, but there might be some need in the country, which is easy to overlook,

> "That fluoride story was shocking to me, someone who is desperate to buy and someone who has something to sell but they can't meet each other, and maybe this is something Mintek could try to do with rare-earths, where it takes long term strategic vision to build the process and to shape the markets."

The reference to rare-earths includes an opportunity for South Africa to create a central processing facility which services the disparate rare-earth mines in the country, instead of shipping the raw unprocessed ore out of the country. There is then further opportunity to stimulate manufacturing of magnets and the supporting markets.

Another opportunity is in electric vehicle battery manufacture which leverages the raw materials available in South Africa. There are plans to process the material up to battery pre-cursors, which can be sold to battery manufacturers as a starting point.

Sibanye-Stillwater in partnership with a local technology company and three local universities demonstrated an additive manufacturing (3D printing) prototype for PGMs (Sibanye-Stillwater, 2021). The partnership was able to successfully produce PGM metal powders as input to the machine which could "print" the object required. Similar opportunities exist for gold, and particularly the jewellery industry, however, this is currently hampered by the high costs associated with 3D printing.

Another participant from Digimine commented on the development of apps for the mining industry. Digital innovation in the form of an app presents an opportunity to capture and monetise South Africa's expertise in deep level mining.

A participant from the Mandela Mining Precinct had a unique perspective on the challenges that South Africa experiences in mining, especially with deep mines, low grade ore and complex ores; that we are ahead of the world in resource maturity. South Africa has depleted the easily accessible, high grade resources, particularly in commodities such as gold, and has been forced into deeper mines and the processing of increased tonnage due to lower grades. A number of challenges such as underground rock stability, ventilation and cooling have already been solved, and others such as underground communications, and underground modernisation are yet to be solved, and are the focus of research and development by multiple institutions. Once those issues have been solved, the technology and expertise could be exported, as the other countries also exhaust their easily accessible resources. Long term strategies and planning are necessary to prepare for that future.

A participant from HySA commented that the cost of fuel cells is prohibitive at the moment, and even at scale, alternative technologies such as electric battery vehicles would be cheaper. There is also the lack of infrastructure, with respect to hydrogen production, storage and transport, as well as fuel stations and the supporting structures. Internationally, markets have pulled battery technology and the supporting infrastructure, but there is no similar market for fuel cells vehicles. There might be opportunity in niche applications where battery powered vehicles have some weakness, and that is still to be uncovered. In the South African context, there are plans to build the hydrogen-linked platinum valley corridor which will run from King Shaka airport in KZN, through to OR Tambo airport in Gauteng and then all the way up to Limpopo. The corridor will support hydrogen fuel stations and develop technology for heavy duty trucks to run on fuel cells. The participant cautioned, however, that this will need to be subsidised to begin with, and there is a risk that if the costs remain high the technology will not disperse, and when the subsidies run out, the corridor may gradually collapse.

The HySA programme has shown that beneficiation of our raw materials is possible, catalysis more than doubles the level of value-addition, and then the MEA adds layers of factors. A few participants have observed that in order to succeed at value-addition, South Africa requires some sort of policy and associated incentive scheme (or taxation) at the level of government. However, they caution that taxation, for example to incentivise local production and deter import, might have other unintended negative consequences.

4.6 SUMMARY OF DATA PRESENTATION

The data shows that South Africa experiences a number of unique challenges that require new capabilities to overcome. Some of these challenges, such as unreliable and costly electricity supply and requisite skills necessary to implement 4IR technology, are environmental, and must be addressed in parallel with the specific challenges the mines experience.

There is a drive to improve capability in new technologies and for focussed application to solve new and existing challenges. Actors have supported initiatives through sponsored research, for individuals and research departments, or have supported suppliers in trialling potentially breakthrough technologies. Digital technologies have been embraced where there is potential benefit for safety, environment and productivity. The Mandela Mining Precinct and the mines have made concerted effort to collaborate with the workforce and labour unions to ensure smooth adoption of these technologies.

The data also shows that opportunities for catch-up and leapfrogging exist but will require considerable effort by all stakeholders to exploit.

CHAPTER 5. ANALYSIS OF RESEARCH FINDINGS

5.1 INTRODUCTION

This chapter presents the analysis of the research data in context of the literature. For each of the research questions the findings are compared and contrasted with the existing literature. The analysis focuses on the level of capability relative to Fourth Industrial Revolution (4IR) and mining technologies. It also engages with the theoretical concept of transversality in the role of catch-up, and highlights any windows of opportunity for leapfrogging in the mining sector.

5.2 BACKGROUND

Research data was obtained through in-depth interviews with the main case studies, the mines and Mintek. The mines elected to remain anonymous. The Mandela Mining Precinct, WITS Digimine, HySA, the DMRE and Gold Ore were included for data triangulation. Interviews were conducted with employees at these organisations, except for the DMRE where prospective participants were unavailable. Secondary data such as policy documents, annual reports, and internal project lists from the participants were analysed.

Interviews were held with senior employees who worked with advanced technology directly or indirectly applied to mining. At WITS Digimine the participants comprised students completing their post graduate studies. Secondary data was obtained through publicly available policies and reports, as well as internal private documents which were then analysed.

The interviews were conducted as in-depth guided conversations to obtain a better understanding of the participants experiences, particularly to understand capabilities in advanced technology and possible avenues for applying 4IR technologies to mining for catch-up. The final research question referring to windows of opportunity for leapfrogging was addressed based on the participants' opinions.

5.3 RQ1: LEVEL OF CAPABILITY

The South African mining sector's ability to adopt advanced technology, including existing technology, is impeded by challenges that prevent direct adoption of such technologies. The continuous miner, for example, is used in coal mining and other areas where the rock is soft, but this technology cannot be used in deep level mines where the rock is hard. Similarly, automated roof shaft equipment is not designed for local conditions, and would be especially difficult to deploy in underground platinum mines where the seam is narrow (Cramer, 2001). Digital technologies face similar constraints such as with network connections in the underground environment.

The participants from the mines indicated that they do not have formal strategies to implement 4IR technologies, while the participants from Mintek indicating that plans are in the process of being formulated. Others have implemented such technology through improvement initiatives without a specific 4IR strategy. Mintek has sufficient capacity to conduct R&D, but current efforts seem to be out of sync with industry. It is surprising that the plans to build capability and leverage 4IR technologies have not yet been formulated. The mines tend to lack inherent capability, but rather depend on research conducted at universities for niche problems, or on partners and suppliers for operational improvement.

There is, however, evidence of the intention to apply ICT technologies to mining, ranging from basic networking to advanced 4IR technologies such as AI-assisted analysis and modelling as well as drones and advanced sensors. In most cases these are applications or customisations of existing technology. The challenges experienced with the technology, such as underground communications, are the subject of ongoing research.

The taxonomy of technological capability by Wu et al. (2009) can perhaps be applied as an aid to understand successes and failures of technology customisation and development of new technologies for the local environment. In the case of deep level mining, South Africa has a rich history of building capability in solving the various challenges that the local conditions afford, and this includes such aspects as underground ventilation and cooling, roof support, and here technological capability would include knowledge utilisation, understanding and localisation, being able to exploit the technology and optimise it, and finally aspects of advancing the technology via explorative innovation. There is evidence of exploitative and explorative innovation in the underground context, which sets South Africa as a leader in such technologies. On the other hand, with respect to downstream innovation such as with hydrogen fuel cells, South Africa is not yet successful at explorative innovation, although the intent and resources were made available to allow for the intense learning required to master the existing technology. In the case of network communications, South Africa has been an implementer of existing technology, importing foreign components for installation and use locally. There has not been a perceived need to develop such components locally, and no real opportunity for imitation, exploitative or explorative innovation. Thus, the expertise necessary to customise the technology for the extreme underground conditions requires considerable effort. Similarly, exposure to 4IR technology is at an early stage, where the technology is being understood and used in limited contexts. This is consistent with the perspective that knowledge is a key factor in catch-up (Lee, 2013b, pp. 25-34). There is an opportunity to absorb and master 4IR technologies to build the knowledge required to exploit and then begin the process of search and of explorative innovation.

Rogers (2004) as well as Fagerberg and Srholec (2017) argue that firm capability is a focal driver of catch-up and in the South African context this requires mines, equipment suppliers and support agencies to work together to improve their capability. There is evidence of this, with the work of the Mandela Mining Precinct, which is intimately aware of the problems the mines experience and have initiatives to improve the capabilities of equipment suppliers to be able to solve these problems. Research at WITS Digimine is also aligned to this agenda.

From the investigation it was also clear that managerial willingness plays an important role in ensuring the adoption of new technologies. The hype around 4IR has at least piqued the interest of managers into advanced technologies, particularly digital technologies to help improve productivity in their daily work. However, there remains a reluctance to introduce new technologies, particularly in the case where operations with older technologies are already running smoothly. A manager's ability to champion adoption seems to be correlated to the manager's propensity for risk taking and an understanding of the benefits the new technology offers.

Senior line managers have a role to play in ensuring adoption of technology, to assess the new technology to ensure that it would solve the problem, but also to create the shared vision for the acceptance of the technology (Macfarlane, 2001). Participants from the mines followed this approach when implementing improvement initiatives at their respective mines. Communication with all stakeholders included the description of impact and benefits for each employee, and employees and supervisors worked together to ensure that new technology was integrated into their daily routines. This gave a sense of ownership of the technology and is an indicator of success.

The Sibanye-Stillwater 3D metal printing demonstration for creating platinum components from metal powder, as well as the initiative of HySA to produce hydrogen fuel cell components, are clear examples of attempting to move up the value chain to escape the resource curse. The Sibanye-Stillwater case is a firm's individual initiative to prove that a new technology can be successfully demonstrated in local conditions. The markets for such technology are yet to be cultivated. HySA in contrast is a government initiative, supporting a long-term programme, through concerted capability building in hydrogen fuel cell technologies as well as the patient capital suitable for long-term, high risk projects such as this. However, HySA also experiences non-technical issues such as the lack of a market for such technologies, and capability in large scale manufacturing. The market is thus the next barrier for both firms, and will require entrepreneurial capability to build, given the strong competition of electric battery and other technologies as well as the current high cost of 3D metal printing.

This is a similar approach that Botswana has taken, in the systematic upgrading capability to export high quality diamonds (Iimi, 2006). Norway's approach is consistent with the advice of Grossman and Helpman (1994) who advocate for diversification of industry, stimulating production, initially through the application of existing technology. For countries wishing to escape the resource curse, they advise pursuing production that exploits existing technology in order to improve capabilities and catch-up, before pursing R&D in new technologies. Botswana and South Africa pursue opportunities to move up the value chain in the very commodities these countries export. South Africa has long been successful in the diamond industry, the market for which already exists, with Botswana following recently. However, South Africa also pursues technologies, for example in hydrogen fuel cell technologies, not yet in global demand, or to be more specific, not yet cost comparative with existing alternative fuel sources.

The Sibanye-Stillwater demonstration of 3D printing raises an important question, as to who is responsible for driving catch-up in the country. Similar examples for platinum can be seen with Impala Platinum and Anglo American Platinum also pursuing hydrogen fuel cell technologies. In the case of South Korea, the state had a hand in influencing policy, protecting industries and creating short and long term strategies to begin a systematic upgrading of the country's capabilities (Lee, 2013a). The state was responsible for improving the education system, and in creating training institutes to ensure there was sufficient capability in specific technologies to improve firms' capabilities. In South Africa, there is an intent to improve capability in specific 4IR technologies as documented in the 4IR report, but the implementation needs to follow (SAGOV, 2020). The government has also taken the lead in backing specific technologies such as nanotechnology and hydrogen fuel cell technology, which represents attempts to move up the PGM value chain. However, although intent exists for the government to support large firms such as Sibanye-Stillwater, or the mines participating in this study, in catch-up efforts for downstream value-addition, this has yet to materialise.

Government, through the lead of the Department of Planning, Monitoring and Evaluation (DPME) spearheads this systematic upgrade of the mining industry. It is therefore surprising that the recommendations from the presidential commission for the Fourth Industrial Revolution largely excludes mining (SAGOV, 2020). This may have been an ideal opportunity for government to reaffirm support for the sector and to drive rejuvenation efforts. Lee (2013a) highlighted the approach that the government took in South Korea's catch-up process. Government's role was crucial in setting the strategic intent for catch-up, and then mobilising the various departments and state organisations in operationalising the plan. In South Korea, this was implemented through a series of five-year strategies that created and implemented policies to stimulate economic growth (Lee, 2017). The Mining Phakisa, however, is a once-off strategy with a specific goal in one sector of the economy. The plan has already been mobilised through the various iterations of the Mining Charter, the formation of the Mandela Mining Precinct, and financial investment from government. Some of the objectives in the Mining Charter are not in alignment with the objectives in the Phakisa, so there is some work to be done to reach consensus. It is yet to be determined whether the initiative receives continued attention.

Participants showed concern for the firm environment in South Africa, some citing the electricity challenges as a major hurdle for any form of catch-up. The skills shortages, corruption, inefficient state organs, lack of favourable policies, including rent seeking behaviour are just some examples that have significant negative impact on business. However, the DMRE now offers mines the opportunity to generate their own power to ensure consistent supply, five years after the matter was raised in the Mining Phakisa (Mantashe, 2020). Mines now have the opportunity to chart their own course.

For South Africa, a current challenge is the electricity crisis, which could benefit from mission-oriented innovation. Following the advice of Mazzucato, mission-oriented innovation has a role to play in catch-up, which drives innovation in a way that encourages experimentation and learning in a number of R&D and innovation projects, across multiple sectors with multiple actors, with policies across all type of public institutions, with strategic division of labour, allowing interactions and feedback and some chance of serendipity, to achieve a specific objective, in this case improving the supply of electricity (Oqubay & Ohno, 2019, pp. 63-81). This could bring together various sectors and departments of government to, for example, intensify R&D and the manufacture of hydrogen fuel cells for fixed location electricity, local development and manufacture of solar panels and batteries, as well as the supporting infrastructure for these technologies. Each of these examples leverages strengths of the country, including an abundance of minerals and metals, and long periods of sunshine.

5.4 RQ2: EVIDENCE OF CONDITIONS FOR TRANSVERSALITY IN THE MINING SECTOR

Transversality centres around the possibility of new path creation, taking cues from current economic activity, whether activity is stagnant, in economic decline, whether change is path dependant, only exhibiting in incremental change, or whether there is opportunity for path interdependence, with other firms, clusters, industries or sectors in a Regional Innovation System (RIS) (Philip Cooke, 2012b). In the ICT sector, 4IR has stimulated investigations into a number of digital technologies. The awareness that productivity in mining is in general decline, and lagging behind international peers who employing advanced technology to improve their operations, has revived interest in improving local conditions, since mining plays an important role in South Africa’s GDP, particularly for export. The study reveals that the mining sector is not stagnant, and that change is spurred by 4IR technologies and modernisation.

The possibility of knowledge recombination to form new clusters, industries and sectors is difficult to determine ex ante. However, there is some evidence of preadaptation where digital technologies are applied to mining technologies in the form of new connected sensors, remote control, and modelling and prediction. There is also evidence of the "adjacent possible" in the increased intensity in R&D in the face of current mining challenges. Indeed, the WITS Digimine laboratory was created to conduct such research. The Mandela Mining Precinct has also actively sought improvements and customisation to mining equipment as well as to conduct R&D in themes such as "Glass Rock". Mintek, on the other hand, seems to conduct disparate R&D with a high level of early-stage research that does not progress any further. However, a 4IR strategy formulation for the integration of modern digital technologies in above ground processing, is underway.

The challenges Mintek faces in conducting relevant R&D could be related to the strength of linkages with mines, suppliers, and other stakeholders. The participants from Mintek are of the view that interactions with mines occur through enquiries for products and services and quarterly discussions on the challenges that the mines experience, for example through the "Gold Group". This is in the hope that Mintek could offer a solution to their problems. Of the participants involved in the study, only the Mandela Mining Precinct valued strong linkages and acted to cultivate and nurture these linkages. The mines themselves valued strong linkages with suppliers as well as research institutions. Mintek, further, does not share details of current or proposed R&D with any of the mines or suppliers, except at a high level in journals and conferences, unless there is no possibility of new intellectual property rights (IPR). The participants at WITS Digimine indicated that the details of most projects were shared in research publications, however, a few were conducted under secrecy. The Mandela Mining Precinct, on the other hand, openly shares R&D and progress with their network. Conference attendance was commonly viewed as the de facto mechanism for knowledge sharing amongst the participants. The participants mostly attended technical conferences in their respective disciplines to present and hear about the latest developments.

This impacts the possibility for knowledge spillover effects among the organisations. Philip Cooke (2012b) mentions that opportunity for knowledge interaction lies either in the organisation's own initiative, or through an intermediary organisation that might host such events as innovation "theatre". The work of the Mandela Mining Precinct sets a precedence against which the other organisations involved in this study can be measured, and the finding is that there is much room for improvement for these organisations. Conference attendance could be viewed as a means of innovation “theatre”, however with the number of presentations, as well as singularity of discipline, there is low likelihood of spillovers from other industries and sectors.

The difference in knowledge diffusion between Mintek and the Mandela Mining Precinct requires some analysis. Mintek prefers to protect intellectual property, through trade secrets and patents with an intent to commercialise the technology if successful. In stark contrast, the Mandela Mining Precinct openly shares the results of research, and purposely ends investigations at around TRL 6 in order to help establish new local ventures, and support existing ones. Mintek also strives to create new ventures, but requires new sources of revenue in order to remain economically sustainable. Mintek conducts R&D funded through its state grant and other research streams, but also generates commercial revenue through the exploitation of new technology, either directly, or through the sale of licenses. This then requires the protection of IP at research stages and reduces the number of opportunities for knowledge sharing and for spillover effects.

In the catch-up theory, Lee (2013a) advocates for strong linkages with state organisations such as PROs and agencies for capability building, through knowledge sharing. The state organisations investigate new technology and build capability to leverage them in industry, this knowledge and capability is then shared with firms, and each actor in the system learns from each other, with the ultimate goal of improving private firm capability (Lee, 2013a). In the mining sector, organisations such as Mintek and the Mandela Mining Precinct should share knowledge and capability with private firms such as the mines and the equipment manufacturers.

Universities also have a role to play in building capability through training and with industry interaction to solve problems (Mazzoleni & Nelson, 2007). WITS Digimine engages in this manner and this is consistent with the notion that universities located near technology hubs, have specialities in those technologies. WITS Digimine is part of the larger WITS Mining Institute and shares the purpose to improve capability in mining. According to Velho and Saenz (2002), universities usually interact with industry through isolated projects, and this is found to be the case with WITS Digimine, however, they point out that PROs have the opportunity to build long lasting relationships with industry. There is no current evidence of this type of relationship at Mintek or at the Mandela Mining Precinct. As one of the participants in the study commented, it comes down to relationships with people, and when people leave the organisation, the relationship ends, or is transferred to the new organisation. At Mintek, only one participant had spent more than twenty years within the organisation and had participated in a joint project in Mexico and in Iran. The close relationships that had been established on those projects still exist today.

There is ample evidence that each of the participants' organisations are actively searching for opportunities for 4IR related technologies. Some basic challenges that prevent adoption of such technologies, such as underground communications and skills, are being addressed. Mintek's initiatives around IOT retrofitting, the use of AI for process control and improving modelling and simulation to create Digital Twins will assist in improving the overall quality of their products, as well as improving the fundamental understanding of mineralogical processes. The high level of enthusiasm around 4IR signals a new technological paradigm which is often associated with immense innovation opportunity in related fields (Perez, 2009). These opportunities could be leveraged to improve productivity in developing countries, towards catch-up (Póvoa, 2008).

Participants at the mine commented that it was difficult to justify the benefits of 4IR technology adoption in monetary terms. This is often the case with technology that does not directly impact production output, or business processes, rather impacting areas such as safety, communication, risk management and in reducing administrative, menial and physically demanding work. However, the work of Bai et al. (2020) brings new models and methods of assessing such technologies.

Job loss due to the adoption of 4IR technologies has not been a concern to any of the participants, provided that the technology is introduced responsibly. In South Africa's context, some technology is quite outdated, and must gradually be updated to include aspects of 4IR. The change will not occur suddenly, and there is sufficient time to prepare the workforce through shared vision, deliberation and training, particularly to improve workplace safety. The current direction, also accelerated through COVID-19, is to implement remote control solutions and to apply technology to augment workers. New technologies require installation and maintenance of new equipment, thereby bringing about new types of jobs. This is in line with Naudé (2017) who argues that new jobs in different sectors would be created.

Participants expressed concern over the security of the 4IR implementations, wary of new types of attack that could take control of physical equipment to cause damage or harm. This is a valid concern given the greater exposure that these systems create, and organisations should heed the advice of Culot et al. (2019) to ensure that adequate measures are in place and that security is on the minds of every employee.

5.5 RQ3: WINDOWS OF OPPORTUNITIES FOR CATCH-UP

One of the paths to achieve catch-up is to follow directly in the path of a predecessor. However, it is unclear which country would serve as a suitable role model for South Africa, given that some have asserted that South Africa could actually be the role model for other African countries (Akinboade & Makina, 2005). As the study unfolds, the unique challenges experienced in the South African deep level mines demonstrates that mining cannot continue in the path of international leaders, notably Australia and Canada. The challenges faced in adopting basic technology underground, will require novel solutions and a new path. However, there may be opportunities to emulate international leaders in mines closer to the surface, for example with the direct adoption of existing 4IR technologies.

Scholars recommend building capability with the adoption of older or obsolete technology as these technologies are well established, simplifying knowledge acquisition; targeting short-cycle technologies and then long-cycle technologies, as short-cycle technologies require new knowledge even for the incumbent firms; and then participate in the global value chain (GVC) for learning (Lee, 2019, pp. 56-100). South African mining employs technologies that range from obsolete to advanced, but not much attention has been given to imitative innovation to produce technologies locally, such as mining equipment typically imported from Sweden, Germany and Finland. Perhaps, given the current challenges in mining, new efforts could aim at developing and customising the technologies. In the context of South Korea, large firms were key to increasing participation in the global value chain, and according to Lee (2019, pp. 35-55), technological capability remains the underlying facilitator for each of these approaches. There are a few local LSM firms in South Africa. However, mining is a low value export market, but there are hopes to move up the global value chain. Participation in the global value chain is of particular importance in catch-up, and opportunities to do so must be taken, even if these are for learning purposes, to determine the necessary skills and quality that is required (Malerba & Lee, 2020). The HySA initiative has the potential to play such a role, as it is supported by the government, and has the potential to grow as the hydrogen economy is developed. The local development of hydrogen fuel cells as well as the supporting infrastructure for hydrogen production, storage and transport, and the formation of the hydrogen-linked platinum valley could be an opportunity for South Africa to leapfrog other countries into renewable fuels.

ICT technologies, and in particular Fourth Industrial Revolution (4IR) technologies are short-cycle technologies relevant to this study. The 4IR represents a new technological paradigm which offers a window of opportunity for catch-up and to escape from existing technological systems (Lee, 2019, pp. 229-233). There are a number of opportunities the new paradigm might offer, including niche production, and access to knowledge and funding in the sharing economy (Lee, 2019, pp. 229-233). Niche production could utilise technologies such as 3D printing that Sibanye-Stillwater has demonstrated for metal printing. Perhaps, the technology would be more suited to gold, particularly gold jewellery as it offers an opportunity to create intricate designs, where the South African jewellery industry struggles.

There are a number of opportunities for leapfrogging that became evident during this study. Apart from the opportunity to enter the hydrogen economy ahead of our peers, opportunities exist to adopt 5G technologies ahead of many countries, with the goal of high quality, high speed networks available to all South Africans and as a foundation for technologies such as IOT. Similar opportunities exist for embracing solar energy and alternative energy sources, especially when driven through mission-oriented policies to resolve the energy crisis in the country.

4IR technologies also offer the opportunity to solve some of the challenges with deep level mining and has been the focus of research at WITS Digimine. Local mining equipment suppliers could also employ 4IR technologies as part of their equipment, and with the help of the Mandela Mining Precinct, create new equipment towards productivity improvement in underground mines. South Africa could then become a global contender in deep-level mining equipment supply.

The 4IR also affords the opportunity to correct past social injustices, particularly the lack of inclusion of women in the mining sector. Lugonzo and Chege (2021) describe a number of factors that hamper prospects for women in mining, including labour convention, gender restrictions, and safety and security amongst others. While the Mining Charter has improved the situation since its first inception in 2002, women constitute only around twenty percent of employees in the mining sector (Lugonzo & Chege, 2021). The authors point out that the 4IR technologies offer the opportunity to improve that statistic through the automation of processes, provided that women are sufficiently skilled, and that incentives exist to increase the demand for women in the labour market. Failure to do so may result in increased gender disparity, as women are "left behind" (Lugonzo & Chege, 2021).

5.6 SUMMARY OF THE DISCUSSION

Capability building is currently disparate with pockets of activity spread across the mining value chain and amongst subsets of actors, with intellectual property protection also hampering growth. The literature advocates for collaborative effort between mines, suppliers, research institutions and government to share in knowledge production to improve the sector. The government has put forward policy to breathe life into mining, and to stimulate downstream beneficiation, but plans are slow to be implemented, and are further disabled by lack of short-term goals, and the monitoring and evaluation thereof.

The study revealed that there is renewed interest in revitalising the mining sector through 4IR technologies and modernisation. This reveals the possibility for knowledge recombination to form new clusters, industries or sectors. Low-hanging fruit such as building stronger linkages with actors in the system would improve the opportunity for transversality. Contrary to expectation, job losses due to 4IR have not been a concern, with the anticipation that jobs will be augmented, or new jobs created. The 4IR presents opportunities to solve gender disparities, provided women are skilled and that there is a demand for such skilled persons in the mining labour force.

The benefits of 4IR initiatives are difficult to quantify, especially for environment, safety and health impacts. However, new models, such as that of Bai et al. (2020), are being created to help substantiate the benefit. Cybersecurity also remains a concern for those implementing the technologies, and will require the attention of multiple departments in the corporate environment.

It is evident that the path to catch-up for South African mining is not directly in the path of the leaders in the industry, especially in deep-level mining. South Africa experiences a unique set of challenges that will require a new path. For mines closer to the surface, an opportunity exists to emulate these leaders. Technologies such as 4IR, a focus on solving unique challenges, and beneficiation of local resources offer an opportunity for technological leapfrogging against the leaders such as Australia and Canada.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This chapter summarises the findings of the study, draws conclusions related to the research question and outlines recommendations for the various stakeholders from the literature review and the interviews. The study was undertaken to determine the possibilities for transversality in the ICT and mining sectors, seeking to understand the level of capability required for catch-up and to highlight promising windows of opportunity for leapfrogging in the mining sector.

6.2 MAJOR FINDINGS

South Africa is a global leader in deep level mining, having solved many of the unique challenges experienced with deep level mining. However, challenges such as low-grade ores, ore complexities and increasing operational costs have had a negative impact on the profitability of mining. These challenges also affect surface mining and shallow mines. The mining sector turns to newer technology in the hopes of improving productivity, although the scales of operation, as well as unique challenges experienced at such great depths currently prohibit modernisation. Above ground operations and shallow mines tend to adopt more advanced technology, and there is also evidence of hybrid adoption of technology.

Fourth Industrial Revolution (4IR) technologies represent a new technological paradigm that could improve mining productivity. Some of the applications of 4IR technologies developed for the manufacturing industry are directly transferable to mining, while others need some investigation and search before opportunities emerge. Thus far, the cross-fertilisation of mining with 4IR shows evidence of customisation of the technology for particular problems, but the majority of effort is in direct adoption. This implies a DUI model where capability is improved through application of advanced technologies and is the recommended path for technology adoption.

An Science, Technology and Innovation (STI) approach would be required to solve the many challenges that pose barriers for the adoption of 4IR technologies in underground environments. For example, the lack of basic ICT network infrastructure, absent location awareness, with no access to Global Positioning Systems (GPS), and the exposure to harsh underground environmental conditions. Fortunately, the current research focus is on solving these issues.

Mines closer to the surface do not experience these challenges and are able to forge ahead with 4IR technology adoption, however, the larger the scale of the operation, and the older the mine, the more costly to “upgrade” existing technology. Hybrid adoption is then becoming popular, where parts of the mine are retrofitted with new technology while the rest of the mine uses older technology. Another barrier to adoption is the difficulty in quantifying value, especially in monetary terms, that the new technology would deliver. While some applications of 4IR technology have a direct impact on productivity, efficiency, quality and reduced downtime, other applications impact a number of non-financial measures and requires the adoption of suitable evaluation methods such as multiple attribute decision making models (MAKM) developed for 4IR. Lastly, the lack of understanding of the technology and the possibly adverse impact on jobs, and to the daily routine of employees could impact successful adoption. However, we have seen that mines are following in the advice of Juma (2016) and in including all stakeholders in the innovation process. Mines ensure that employees understand the role of the new technology, in either augmenting or improving processes, have opportunity to use or benefit from the new technology, and have opportunity to improve their skills to maintain and support the new technology.

The government has put forward support for mine modernisation in South Africa to stimulate investment, for social inclusion, job creation as well as a renewed focus on downstream beneficiation, and stimulating local manufacturing in mining equipment and hydrogen fuel cell technologies. The government’s lead is crucial in setting the policy intent and then supporting the sector in overcoming the hurdles that would ensure that mining becomes sustainable once more. This is in line with the catch-up theory as proposed by Lee (2013a), albeit in a specific sector. Success will depend on continued support and agility over the medium and long terms.

In the context of the theory of transversality, there is certainly evidence of cross-fertilisation of 4IR with mining. Much of this is in direct adoption, for example in asset tracking, preventative maintenance, data analytics, improved communications, and remote operations. Technology is also customised for the unique conditions in mining, for example the research into underground drone piloting, development of new mapping as well as network technologies for underground environments and the development of advanced sensors, for example to detect rock stability, as well as in minerals processing. Hydrogen fuels cells are an example of new industry creation, where the green energy revolution influences and benefits mining in the creation of the new hydrogen economy. Similarly, 4IR technologies could be used in new mining equipment to stimulate the local mining equipment manufacturing industry. There is hope that South Africa is able to solve the adoption challenges of 4IR, and create an export market for the equipment, as mining in other countries matures. 4IR technologies also offer the opportunity to correct gender disparities in the mining sector. The new skills required to adopt and exploit these technologies, as well as the new jobs created must be equally afforded to men and women, failing which there is a risk that the gap is widened.

The support of Public Research Organisations (PRO) has been below par, and may be due to challenges in maintaining financial sustainability in these organisations. Some of the research seems to be conducted in ivory towers, with no anchor in the real world. Research also seems to be disparate without specific focus, and loss of tacit knowledge hampers progress. PROs involved in this study do not have strong linkages with industry and are not able to perceive the real challenges the industry experiences. PROs prefer to build technological capability internally, and then exploit any intellectual property derived. This is in contrast to South Korea's approach, where state organisations shared knowledge freely with firms in the private sector since there was a common goal to improve capability (Lee, 2013a).

However, other research organisations involved in this study took a different approach and have created strong linkages with industry. The WITS Digimine, a laboratory of WITS University, conducts research aimed at using digital technologies to solve problems mines experience. Research projects are sponsored by the mines and offer students opportunities to solve real world challenges, while the mines gain access to cutting edge technology. The Mandela Mining Precinct also values linkages through relationships with individuals in each of the organisations they interact with. The research undertaken by the precinct is aligned with mining challenges and has further goals of local manufacturing. This is in line with the expectations of Mazzoleni and Nelson (2007) as the Mandela Mining Precinct is an initiative of government to support universities and mines in absorbing and tailoring foreign technology, as well as developing new local technology suitable for the local environment.

In this Regional Innovation System (RIS), the universities host mining engineering faculties to support the mines. Government is represented by the DMRE and DSI through their organs, CSIR, CGS, and Mintek, and the Mandela Mining Precinct, which is managed through the CSIR. These actors each have a role to play in improving technological capability in mining and minerals processing. HySA is also a government initiative and has linkages with universities across the country. HySA has a role to place in beneficiation of platinum in the form of hydrogen fuel cell component development. There is much emphasis on technological capability, however, the study found that entrepreneurial capability may be lacking. Mintek as well as HySA find it difficult to develop the markets required for their technology, and HySA, in particular, fails to attract the requisite investment to begin mass manufacturing. At Mintek, technologies are developed to the mid-TRLs, but then fail to find match with a commercial partner willing to take the technology further.

The HySA initiative is an example of an opportunity for leapfrogging advanced countries into the hydrogen economy.

6.3 KEY CONCLUSIONS OF THE STUDY

The consensus is that South African mining is lagging behind international leaders, however, there is concerted effort, albeit disparate, to close that gap. The unique challenges that South African mining experiences, has in the past been overlooked, mainly due to the scale of operations, however, a turning point has been reached where scale can no longer be sustained, requiring renewed focus on those challenges. There is a hope that modern technology, most notably 4IR technologies, offers a new approach to solving these problems. To that end, research has been revived in the form of university-industry collaboration, and to a lesser extent the involvement of PROs. Mining companies are building internal capability or onboarding external partners to embrace the new technologies.

Largely, the adoption of 4IR technologies has been in copying the example of peers, in both international mining and from the manufacturing industries. Concepts such as central operation centres, logistics tracking, preventative maintenance, and optimisation of processes, as well as improvements in safety and health have yielded significant impact. However, focus has also been turned to solving the unique challenges that South Africa experiences such as deep underground network communications, and the high cost of ventilation.

Thus, there are clear examples of cross fertilisation between industries, facilitated by 4IR technologies. The variety and volume of innovation spurred by 4IR has spilled over into the mining sector. The challenges so far have been in convincing senior executives of the potential benefit of 4IR initiatives, since there is no simple financial calculation to demonstrate this.

The South African mining sector has a window of opportunity to catch-up with international peers by embracing 4IR technologies to improve operations as well as solving unique challenges. There are also opportunities to leap frog other countries in avenues such as the hydrogen economy, solar energy production as well as expertise and possible export of deep level mining solutions. On a mining maturity scale, South Africa can be said to be ahead of the curve, and other countries could experience similar challenges as their easily accessible resources become depleted.

6.4 RECOMMENDATIONS FOR THE STAKEHOLDERS

The linkages among actors in the regional innovation system, with particular attention to mining, have been shown to be weak, except for the Mandela Mining Precinct. Stronger linkages improve opportunities for cross-fertilisation, for collaborative problem solving and exposure to new ideas and approaches to solve problems. This may also present in the form of attendance of diverse conferences, or technology theatre, which also helps create new firms, clusters and industries. Industry-university linkages give mines access to cutting edge technology and contribute to the mining knowledge base.

Mission-oriented innovation is also recommended as a means to focus acutely on specific “grand challenges” where actors across industries, government and universities collaborate to solve challenges, such as sustainability transitions. Currently, government institutions are tasked with solving specific challenges, but flounder when the challenge is too daunting. For example, for South Africa to embrace the hydrogen economy, significant collaboration between a number of role players is required. Mission-oriented innovation provides a framework to embark on that journey.

The greater firm environment must be nurtured with programmes to improve the quality and access to education, stable energy supply, as well as quality internet access, with favourable regulation, access to international markets and strategies to improve industrialisation, and beneficiation of natural resources. Firms require the support of government, but in the face of lack of support, firms should manage their own fate. Managerial willingness, with attributes such as being proactive to embrace technology and to take risk, must be cultivated. Policies and strategies may be promising; however, it is often the effort of a few individuals in a firm that drive transformative change.

6.5 SUGGESTIONS FOR FUTURE RESEARCH

This study raised additional questions that would benefit from future research.

There is an apparent weakness in entrepreneurial capability in South Africa, evident in the failure to transform research and concepts into new industries. How important is entrepreneurial capability in the catch-up process, and what are the possible paths to improve entrepreneurial capability?

Can the Global South continue to emulate advanced countries in knowledge production with continued pressure to protect intellectual property and to commercialise? How does one ensure knowledge sharing when financially sustainability is at the forefront of preoccupation of many actors?

This research study focussed on the precious metals industry in a regional innovation system, and it is advised that research be extended to other commodities across South Africa. The study also focussed on large scale mining (LSM) firms, and more attention should be focussed on junior mining firms, and artisanal and small-scale mining (ASM) firms.

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APPENDICES

APPENDIX A INTERVIEW QUESTIONS FOR MINE

Question 1.

Please explain your role in the organisation, with reference to your qualifications, current line of work and involvement with the mining sector.

Question 2.

How would you classify your organisation and the mining sector in general, in terms of level of technological capability?

- Who is your competition and would you say you are lagging or ahead of the competition?

Question 3.

What innovative solutions have you implemented recently? Do they employ innovative use of existing technology, cutting-edge technology, or have your developed your own technologies?

- What would be the goal of these innovative initiatives?

Question 4.

What are the challenges that affect profitability and sustainability for your company?

Question 5.

In your experience, how has your organisation leveraged 4IR technologies?

- What new technology do you plan to implement in the near future?
- [Follow up: If not, does your organisation have a strategy to introduce these technologies? Are you involved with any such projects or will be in the near future? Do you know of any in your organisation?]

Question 6.

How do you intend to improve your capability in 4IR technologies?

- Have you implemented or plan to implement upskilling programmes? What are your employee's expectations in this regard?

Question 7.

What role do strategic partners play in implementing 4IR solutions?

- In your experience, has there been opportunity for co-development?
- Describe your interactions outside of the mine/office?

Question 8.

How do you (or intend to) improve capability of the workforce with regard to 4IR technologies?

- How has government, public research organisations or other development agencies assisted you in both capability enhancement as well as technology upgrading?
- [Follow up: Are there any other stakeholders that have a role to play in improving capability?]

Question 9.

Based on your experience, what other challenges have there been regarding 4IR technologies and how has this impacted your plans?

Question 10.

Based on your experience, what evidence do you have that 4IR technologies have been successful in your organisation?

Question 11.

How does your organisation play a role in downstream value-add such as manufacturing or beneficiation?

- [Probing: How can South Africa improve downstream value-add?]

Question 12.

Are there any other insights that you would like to share with me? If so, please feel free to express them. Otherwise, is there anyone else in your network or in the industry that you think that would have a different perspective that I might interview?

APPENDIX B INTERVIEW QUESTIONS FOR P.R.O

Question 1.

Please explain your role in the organisation, with reference to your qualifications, current line of work and involvement with the mining sector.

[Probing: What is your organisation's role in the mining sector?]

Question 2.

How would you classify your organisation and the mining sector in general, in terms of technological capability?

- Who is the competition, and is South Africa lagging or ahead of the competition?
- [Follow up: If lagging, what plans are there to change that?]

Question 3.

How would you describe the R&D activities of your organisation [research to uncover phenomenon, or novel use of existing technology]?

- Please comment on the effectiveness of your organisation in terms of assisting the mining industry, with some examples

Question 4.

How does existing foreign technology benefit the mining sector?.

- What is your role in the process?
- Please can you provide some examples?

Question 5.

How has 4IR technologies helped improve operations in the mining sector?

- Does your organisation have a strategy to introduce these technologies?

Question 6.

Does your organisation engage in any knowledge sharing or co-development with mining companies in South Africa? Please can you elaborate?

- Describe your interactions outside of the mine/office?
- How has your organisation influenced policy with regards to 4IR technologies?

Question 7.

What is your organisations role in improving capability in 4IR technologies?

- [Follow up: Who are the other stakeholders that have a role to play in improving capability?]

Question 8.

How will your organisation alleviate concerns that the industry has expressed around 4IR?

Question 9.

What evidence do you have, of the effectiveness of 4IR technologies in the mining sector?

Question 10.

What role does your organisation play in downstream value-add such as manufacturing or beneficiation?

- [Probing: How can South Africa improve downstream value-add?]

Question 11.

Are there any other insights that you would like to share with me? If so, please feel free to express them. Otherwise, is there anyone else in your network or in the industry that you think that would have a different perspective that I might interview?

APPENDIX C INTERVIEW QUESTIONS FOR OTHER STAKEHOLDERS

Question 1.

Please explain your role in the organisation, with reference to your qualifications, current line of work and involvement with the mining sector.

[Probing: What is your organisation's role in the mining sector?]

Question 2.

What is the role of mining in South Africa's future?

[Follow up: How would you describe the mining sector, in terms of technological capability, especially when compared to other countries?]

[Follow up: What can be done to change that?]

Question 3.

Does your organisation engage in any knowledge sharing or co-development with mining companies in South Africa? Please can you elaborate?

Question 4.

Would you consider your organisation as innovative?

- Please can you provide examples of recent innovations.

Question 5.

What is your observation of 4IR technologies in the mining sector?

- Does your organisation have a strategy to introduce these technologies?

Question 6.

How do you help improve capability in 4IR technologies?

- [Follow up: Who are the other stakeholders, and what is their role?]

Question 7.

How have the concerns and challenges around 4IR impacted your plans?

- [Probing: How will you go about overcoming these challenges?]

Question 8.

How has implementation of 4IR technologies affected your organisation?

Question 9.

How does your organisation play a role in downstream value-add such as manufacturing or beneficiation?

[Probing: How can South Africa improve downstream value-add?]

Question 10.

Are there any other insights that you would like to share with me? If so, please feel free to express them. Otherwise, is there anyone else in your network or in the industry that you think that would have a different perspective that I might interview?

APPENDIX D PERMISSION LETTER FOR THE MINE

Permission Letter

University of the Witwatersrand,
WITS Business School
2 St David's Place,
Parktown,
Johannesburg,
2193

Contact: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Manager
Sibanye-Stillwater
Constantia Office Park
Cnr 14th Avenue & Hendrik Potgieter Road
Bridgeview House, Ground Floor (Lakeview Avenue)
Weltevreden Park
1709

25 January 2021

Dear Sir/Madam,

Re: Permission to conduct research at Sibanye-Stillwater

My name is Mahendren Thorulsley. I am studying towards a Master of Management in Innovation Studies at WITS Business School. The purpose of this study is to determine the opportunities and capabilities required for transversality in the ICT and mining sectors of South Africa, towards catch-up and sustainable mining.

I am seeking permission to do research at Sibanye-Stillwater.

I am conducting research on applying Fourth Industrial Revolution technologies in mining for catch-up and towards sustainable mining in South Africa. Developed countries have made advances in mining through automation, robotics and other Fourth Industrial Revolution technologies, but South Africa lags behind. I seek to understand the capabilities required to catch-up or perhaps opportunities for leap frogging in this sector. Sibanye-Stillwater is a shining example of a progressive organization willing to take risks and try new initiatives, and would add valuable insight for my research.

I request permission to access project information for classification purposes.

I also request permission to invite individuals from your organisation to participate in this study. These employees would be involved in or manage projects, especially relating to Fourth Industrial Revolution technologies. If they agree, they will be interviewed. I would like to interview at least three employees, and each interview would require an hour to be set aside, through an online meeting system such as Zoom or Microsoft Teams. The meeting would be recorded initially, but then destroyed once the dialog has been transferred to text.

Participants will be asked to give their written or verbal consent before the research begins. Their responses will be treated confidentially, and identities (their names) will be anonymous unless otherwise expressly indicated. Individual privacy will be maintained in all published and written data resulting from the study.

The results will be communicated in a dissertation.

The research participants will not be advantaged or disadvantaged in any way. They will be reassured that they can withdraw their permission at any time during this project without any penalty. There are no foreseeable risks in participating in this study. The participants will not be paid for this study.

All research data will be destroyed once the research has been published.

I therefore request permission in writing to conduct my research at your organisation. The permission letter should be on your organisation's letter head, signed and dated, and specifically referring to myself by name and the title of my study.

Please let me know if you require any further information. I look forward to your response as soon as is convenient.

Yours sincerely,

Researcher: Mahendren Thorulsley
Tel: 0828040917
Email: Mahendren.Thorulsley@students.wits.ac.za

Supervisor: Dr. Diran Soumonni
Tel: 011-7173646,
Email: Diran.Soumonni@wits.ac.za

APPENDIX E PERMISSION LETTER FOR PRO

Permission Letter

University of the Witwatersrand,
WITS Business School
2 St David's Place,
Parktown,
Johannesburg,
2193

Contact: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Manager
Mintek
200 Malibongwe Drive
Randburg
2125

25 January 2021

Dear Sir/Madam,

Re: Permission to conduct research at Mintek

My name is Mahendren Thorulsley. I am studying towards a Master of Management in Innovation Studies at WITS Business School. The purpose of this study is to determine the opportunities and capabilities required for transversality in the ICT and mining sectors of South Africa, towards catch-up and sustainable mining.

I am seeking permission to do research at Mintek.

I am conducting research on applying Fourth Industrial Revolution technologies in mining for catch-up and towards sustainable mining in South Africa. Developed countries have made advances in mining through automation, robotics and other Fourth Industrial Revolution technologies, but South Africa lags behind. I seek to understand the capabilities required to catch-up or perhaps opportunities for leap frogging in this sector. Mintek is a Public Research Organisation mandated to assist the mining sector through research and development, and it would be invaluable for my research to determine the how Mintek plans to leverage Fourth Industrial Revolution technologies to assist the mining sector.

I request permission to access project information for classification purposes.

I also request permission to invite individuals from your organisation to participate in this study. These employees would be involved in or manage projects, especially relating to Fourth Industrial Revolution technologies. If they agree, they will be interviewed. I would like to interview at least three employees, and each interview would require an hour to be set aside, through an online meeting system such as Zoom or Microsoft Teams. The meeting would be recorded initially, but then destroyed once the dialog has been transferred to text.

Participants will be asked to give their written or verbal consent before the research begins. Their responses will be treated confidentially, and identities (their names) will be anonymous unless otherwise expressly indicated. Individual privacy will be maintained in all published and written data resulting from the study.

The results will be communicated in a dissertation.

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All research data will be destroyed once the research has been published.

I therefore request permission in writing to conduct my research at your organisation. The permission letter should be on your organisation's letter head, signed and dated, and specifically referring to myself by name and the title of my study.

Please let me know if you require any further information. I look forward to your response as soon as is convenient.

Yours sincerely,

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Supervisor: Dr. Diran Soumonni
Tel: 011-7173646,
Email: Diran.Soumonni@wits.ac.za

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APPENDIX F PARTICIPANT INFORMATION SHEET FOR MINE

Participant Information Sheet

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

You are cordially invited to participate in a research study conducted by Mahendren Thorulsley as part of the Master of Management in Innovation Studies at WITS Business School. The purpose of this study is to determine the opportunities and capabilities required for transversality in the ICT and mining sectors of South Africa, towards catch-up and sustainable mining.

Please take note of the following:

- Studies are conducted in a private capacity as a requirement for the degree.
- The interview is anonymous, your particulars will not be disclosed, and any response you provide will be treated as strictly confidential.
- Your organisation will be referred to by name.
- Your participation is voluntary, and you may elect to stop participating at any time during the interview.
- The interview is expected to be completed within an hour and you will be given advanced notice of the scheduled date and time.
- The results of the study may be provided to you on request.
- The supervisor or program director may be contacted should you have any queries or concerns.
  Supervisor: Dr. Diran Soumonni, 011-717-3646, Diran.Soumonni@wits.ac.za
  Program Director: Prof Mjumo Mzyece, 011-717-3649, mjumo.mzyece@wits.ac.za

APPENDIX G PARTICIPANT INFORMATION SHEET FOR PRO

Sculpting global leaders

Participant Information Sheet

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

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  Program Director: Prof Mjumo Mzyece, 011-717-3649, mjumo.mzyece@wits.ac.za

APPENDIX H PARTICIPANT INFORMATION SHEET FOR GOVERNMENT

Sculpting global leaders

Participant Information Sheet

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

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  Program Director: Prof Mjumo Mzyece, 011-717-3649, mjumo.mzyece@wits.ac.za

APPENDIX I PARTICIPANT INFORMATION SHEET FOR COMMERCIAL COMPANY

Participant Information Sheet

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

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  Supervisor: Dr. Diran Soumonni, 011-717-3646, Diran.Soumonni@wits.ac.za
  Program Director: Prof Mjumo Mzyece, 011-717-3649, mjumo.mzyece@wits.ac.za

APPENDIX J PARTICIPANT INFORMATION SHEET FOR RESEARCHER

Participant Information Sheet

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

You are cordially invited to participate in a research study conducted by Mahendren Thorulsley as part of the Master of Management in Innovation Studies at WITS Business School. The purpose of this study is to determine the opportunities and capabilities required for transversality in the ICT and mining sectors of South Africa, towards catch-up and sustainable mining.

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  Program Director: Prof Mjumo Mzyece, 011-717-3649, mjumo.mzyece@wits.ac.za

APPENDIX K CONSENT FOR MINE

Consent Form

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam

Please mark with an X, the relevant options below:

I agree that the researcher may use anonymous quotes in his / her research report	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that I have read and understood the information provided	YES	NO
I give consent to participate in the study in a voluntary basis	YES	NO

Participant Name: ____________________ Signature: ___________________ Date of Consent: __________

Researcher Name: ____________________ Signature: ___________________ Date: ___________________

APPENDIX L CONSENT FOR PRO

Consent Form

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam

Please mark with an X, the relevant options below:

I agree that the researcher may use anonymous quotes in his / her research report	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that I have read and understood the information provided	YES	NO
I give consent to participate in the study in a voluntary basis	YES	NO

Participant Name: ____________________ Signature: ___________________ Date of Consent: __________

Researcher Name: ____________________ Signature: ___________________ Date: ___________________

APPENDIX M CONSENT FOR GOVERNMENT

Consent

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

Please mark with an X, the relevant options below:

I agree that the researcher may use anonymous quotes in his / her research report	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that I have read and understood the information provided	YES	NO
I give consent to participate in the study in a voluntary basis	YES	NO

Participant Name: ____________________ Signature: ___________________ Date of Consent: __________

Researcher Name: ____________________ Signature: ___________________ Date: ___________________

APPENDIX N CONSENT FOR COMMERCIAL COMPANY

Consent

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

Please mark with an X, the relevant options below:

I agree that the researcher may use anonymous quotes in his / her research report	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that I have read and understood the information provided	YES	NO
I give consent to participate in the study in a voluntary basis	YES	NO

Participant Name: ____________________ Signature: ___________________ Date of Consent: __________

Researcher Name: ____________________ Signature: ___________________ Date: ___________________

APPENDIX O CONSENT FOR RESEARCHER

Consent

Transversality and innovation capability-based catch-up for sustainable mining in South Africa

Researcher: Mahendren Thorulsley, 0828040917, Mahendren.Thorulsley@students.wits.ac.za

Dear Sir/Madam,

Please mark with an X, the relevant options below:

I agree that the researcher may use anonymous quotes in his / her research report	YES	NO
I agree that the interview may be audio recorded	YES	NO
I agree that I have read and understood the information provided	YES	NO
I give consent to participate in the study in a voluntary basis	YES	NO

Participant Name: ____________________ Signature: ___________________ Date of Consent: __________

Researcher Name: ____________________ Signature: ___________________ Date: ___________________