

# ESG, CIRCULAR ECONOMY AND DIGITALISATION PRINCIPLES IN MINING

A study examining the  
convergence and impact of  
ESG/CE/DX in mining  
in South Africa  
March 2025

# INTRODUCTION

This study explored the intersection of ESG, CE, and DX for economic growth, social impact, sustainability and competitiveness in mining in South Africa.

The evolution of Environmental, Social, and Governance (ESG) principles into mining operations emphasises a strategic and data-driven approach to enhance sustainability and competitiveness. The integration of ESG principles with digitalisation (DX) and Circular Economy (CE) practices presents an opportunity for the mining industry to advance sustainability, enhance operational efficiency, and foster economic growth within the industry. CE principles aim to extend resource lifecycles, optimise material use, and minimise environmental impact, supported by digital technologies that improve transparency, traceability, and efficiency.

## Our exploratory approach used:

- Comprehensive literature reviews
- Expert interviews
- Focus group
- Use case analyses across the mine value chain
- SWOT and "So-what" analysis for deeper insights
- Maturity assessment model

## Problem statement:

Despite the potential synergies between ESG, digitalisation, and circular economies, these frameworks have not yet been amalgamated into a cohesive strategy for modernisation and responsible mining. Without integrated solutions, the mining sector risks lagging in global competitiveness, environmental sustainability, and social inclusion.

The study findings emphasise that the holistic application of DX, CE, and ESG significantly enhances the sustainability, efficiency, and competitiveness of South African mining.

# Setting the context

## ESG:

**Definition:** Environmental, Social, and Governance (ESG) factors are a set of non-financial indicators that are used to evaluate a company's environmental sustainability, regulatory compliance and social impact. ESG factors are of increasing importance to investors, stakeholders, and regulators as critical indicators of a company's long-term performance and risk.

### Significance:

- To Companies: Enhances risk management, attracts investors, and builds brand reputation.
- To Investors: Provides insights into a company's sustainability and long-term profitability.
- To Society: Promotes sustainable development and equitable growth while addressing global challenges like climate change and inequality.

### Components (including but not limited to):

- Environmental: Carbon emissions, resource use, waste management, biodiversity and ecosystem preservation.
- Social: Employee health & safety, and well-being, DEI, jobs & skills.
- Governance: Transparency and accountability, regulatory compliance.

## Digitalisation:

**Definition:** Digitalisation refers to the integration and application of digital technologies to transform processes, systems, and business models, enabling improved efficiency, innovation, and decision-making. It involves leveraging technologies to enhance productivity and deliver value.

### Significance:

- Enhances efficiency, productivity and longevity of operations.
- Supports improved decision-making.
- Allows industries to capitalise on innovation to seize new products and services.
- Facilitates smarter resource use and environmental monitoring to align with sustainability goals.
- Optimises processes, reducing operational expenses.

### Components (including but not limited to):

- IoT
- Big data and analytics
- Automation and robotics
- Artificial intelligence
- Virtual and augmented reality
- Blockchain

## Circular Economies:

**Definition:** A circular economy is an economic system aimed at eliminating waste and ensuring the continual use of resources. It replaces the traditional linear economy model of "take, make, dispose" with a regenerative approach focused on resource efficiency, reuse, recycling, and waste valorisation to create a closed-loop system.

### Significance:

- Reduces resource extraction, waste generation, and environmental degradation.
- Drives employment in recycling, remanufacturing, and waste management sectors.
- Ensures long-term availability of critical materials and minimises dependency on finite resources.
- Supports the United Nations Sustainable Development Goals

### Components:

- Design for circularity
- Resource efficiency
- Waste management and valorisation
- Closed-loop systems
- Business model innovation
- Collaboration across value chains

Convergence

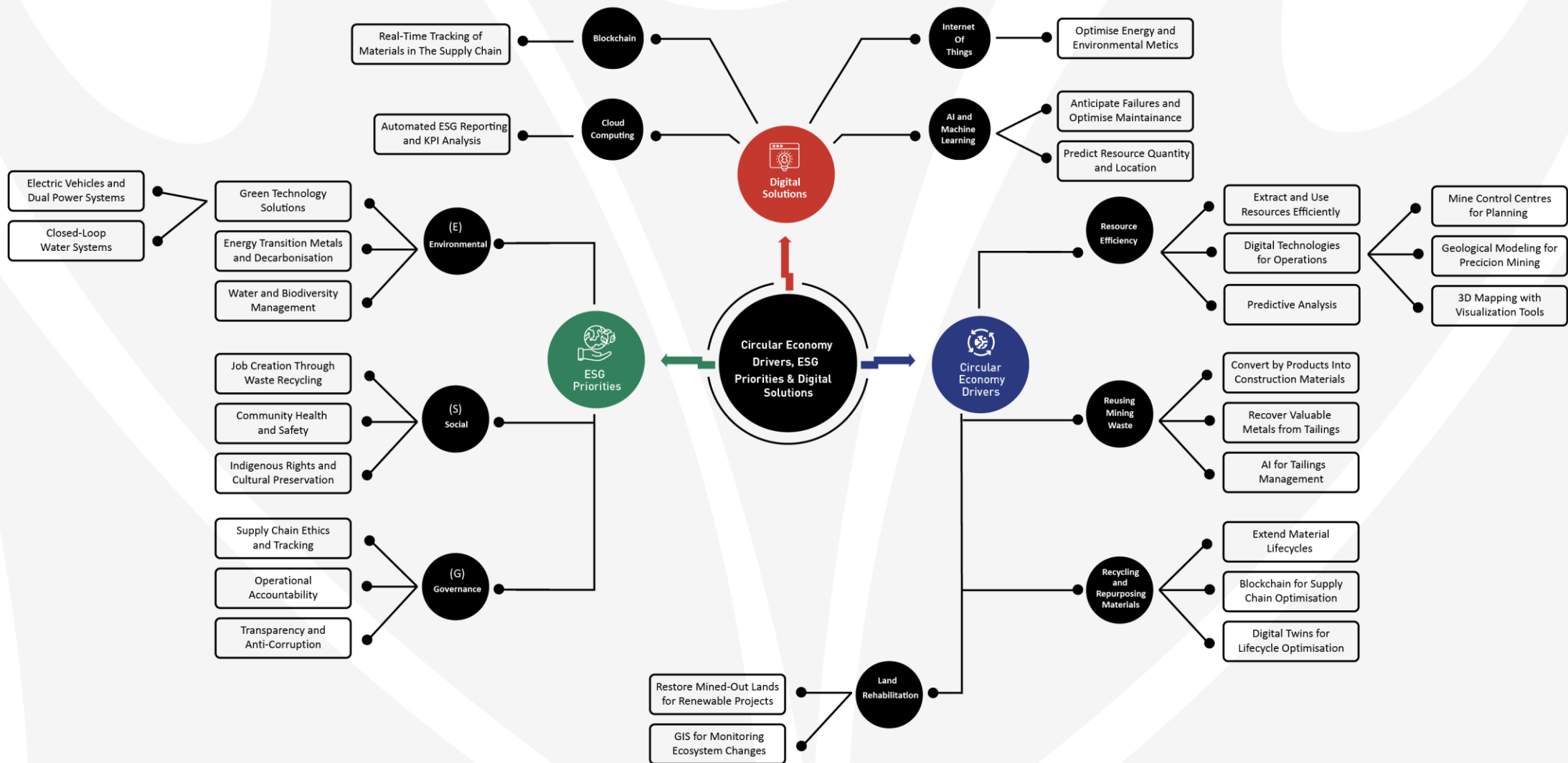
# DX DRIVES SUSTAINABLE MINING

- 1 **Enhancing ESG and CE goals:** AI, IoT, and blockchain enable real-time data analysis, operational efficiency, and environmental protection.
- 2 **Transforming the mine value chain:** AI, geospatial analysis, and drone surveying reduce environmental impact, waste, and improve resource efficiency.
- 3 **Improved ESG reporting:** IoT sensors, machine learning, and blockchain enhance transparency, traceability, and accuracy in reporting.
- 4 **Smart mining through digital platforms:** Predictive analytics and digital tools help mitigate risks, improve transparency, and engage stakeholders for sustainable practices.

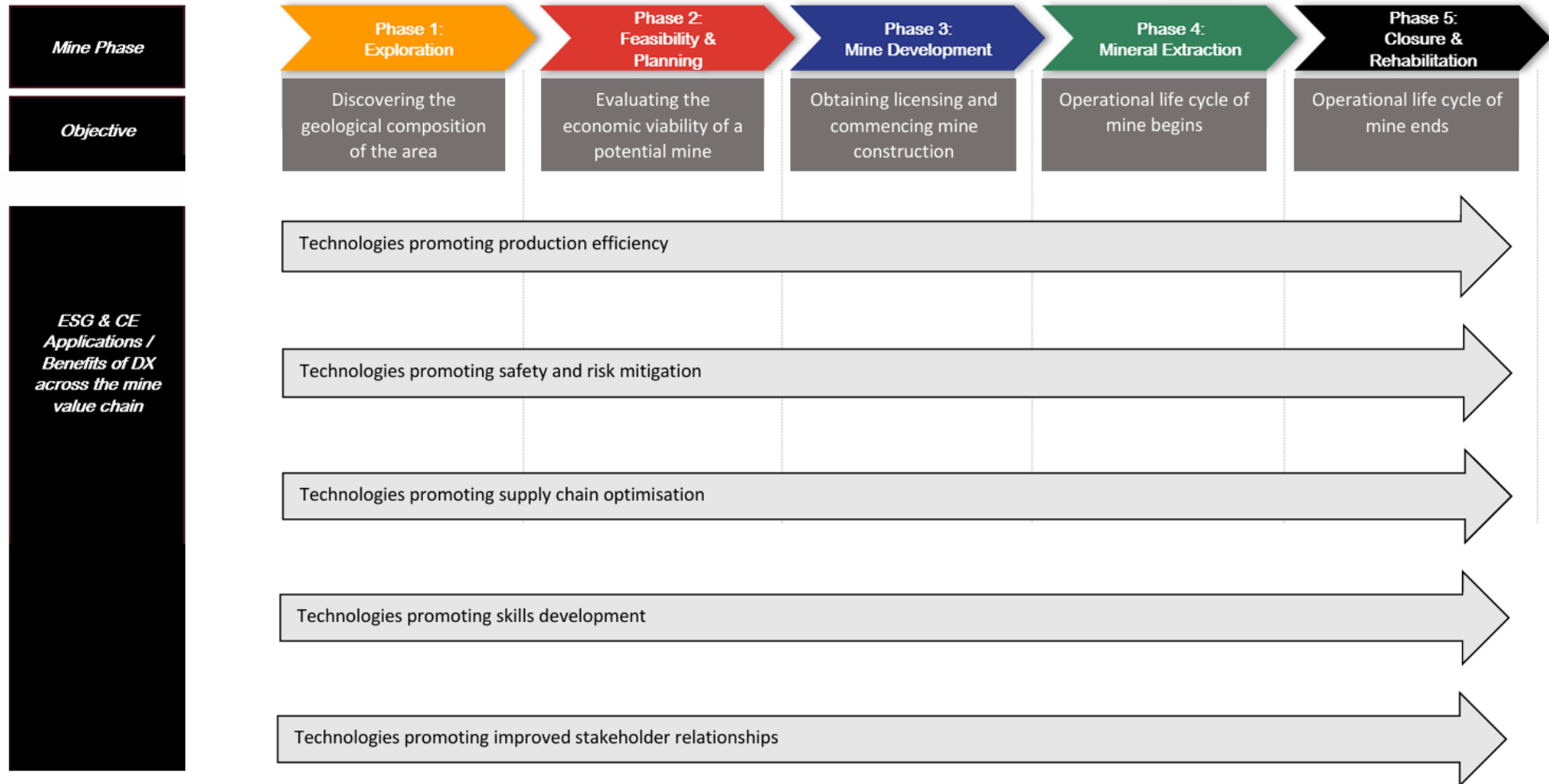


- 5 **Robotics and automation for green mining:** Autonomous vehicles and robotics improve efficiency, reduce emissions, and lower labour risks.
- 6 **Digital Product Passports (DPPs):** DPPs standardise data for ecological transparency (challenges with data harmonisation and standardised interfaces)

# CE drivers, ESG priorities and digital solutions mindmap



# SYNERGIES



# SYNERGIES

## Use case for digital applications across the mine value chain supporting CE and ESG priorities

| PHASE                             | EXPLORATION                                                                                                                                                                                                                                    | FEASIBILITY & PLANNING                                                                                                                                                                                                                                      | MINE DEVELOPMENT                                                                                                                                                                                                                                                              | MINERAL EXTRACTION                                                                                                                                                                                                                                                                                                                                     | CLOSURE & REHABILITATION                                                                                                                                                                                             |
|-----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Core Activities</b>            | <ul style="list-style-type: none"> <li>• Collection of data on target area.</li> <li>• Securing of necessary permits, property, and mineral rights.</li> <li>• Exploration planning.</li> <li>• Detailed exploration and samplings.</li> </ul> | <ul style="list-style-type: none"> <li>• Technical and economic evaluation.</li> <li>• Construction planning.</li> <li>• ESG baseline and impact assessment.</li> <li>• Initiation of permitting.</li> <li>• Exploring and securing Investments.</li> </ul> | <ul style="list-style-type: none"> <li>• Excavation.</li> <li>• Constructing all needed buildings facilities, and roads.</li> <li>• Installing the machin-ery and equipment to operate the mine.</li> <li>• Measures to reduce and minimise environmental impacts.</li> </ul> | <ul style="list-style-type: none"> <li>• Mineral extraction.</li> <li>• Mineral processing.</li> <li>• Product transportation.</li> <li>• Equipment maintenance.</li> <li>• Concurrent reclamation.</li> <li>• Community, Indigenous peoples, and government relations.</li> <li>• Supply chain Management.</li> <li>• Security management.</li> </ul> | <ul style="list-style-type: none"> <li>• Remediation.</li> <li>• Reclamation.</li> <li>• Decommissioning.</li> <li>• Monitoring.</li> <li>• Maintenance.</li> <li>• Social Transitioning.</li> </ul>                 |
| <b>Production efficiency</b>      | <ul style="list-style-type: none"> <li>• AI &amp; Machine Learning for Geological Modelling</li> <li>• Remote Sensing &amp; Drone For Mineral Mapping.</li> <li>• Geospatial &amp; GIS Technologies for Predictive Exploration.</li> </ul>     | <ul style="list-style-type: none"> <li>• Digital Twin &amp; AI-Driven Mine Planning.</li> <li>• Digital Life Cycle Assessments (LCA) for Sustainable Mine Design.</li> <li>• Geotechnical AI &amp; Predictive Analytics for Risk Reduction.</li> </ul>      | <ul style="list-style-type: none"> <li>• 3D Printing &amp; Modular Construction.</li> <li>• IoT – Enabled Smart Construction Sites.</li> <li>• Automated &amp; Robotics-Based Construction.</li> </ul>                                                                        | <ul style="list-style-type: none"> <li>• Autonomous &amp; Electric Mining Vehicles.</li> <li>• IoT-Enabled Real-Time Monitoring of Air, Water &amp; Tailings.</li> <li>• AI &amp; Machine Learning for Process Optimisation.</li> <li>• Hydrometallurgy &amp; Smart Sorting Technologies.</li> </ul>                                                   | <ul style="list-style-type: none"> <li>• GIS &amp; Remote Sensing For Land Restoration.</li> <li>• IoT-Enabled Water Treatment &amp; Recycling Systems.</li> <li>• Mine Repurposing Digital Platforms.</li> </ul>    |
| <b>Safety and Risk Mitigation</b> | <ul style="list-style-type: none"> <li>• Remote Sensing &amp; Drones for Geological Surveys.</li> <li>• Geospatial &amp; AI-Based Risk Risk Modelling.</li> <li>• IoT-Enabled Environmental Monitoring.</li> </ul>                             | <ul style="list-style-type: none"> <li>• Digital Twin &amp; AI-Driven Hazard Simulation.</li> <li>• Geotechnical AI &amp; Predictive Analytics.</li> <li>• Emergency Scenario Planning with VR Training.</li> </ul>                                         | <ul style="list-style-type: none"> <li>• Automated &amp; Robotics-Based Construction.</li> <li>• IoT-Enabled Smart Construction Sites.</li> <li>• 3D Printing &amp; Modular Construction.</li> </ul>                                                                          | <ul style="list-style-type: none"> <li>• Autonomous &amp; Electric Mining Vehicles.</li> <li>• IoT-Enabled IoT-Enabled Real-Time Equipment &amp; Structural Monitoring.</li> <li>• AI &amp; Machine Learning For Predictive Safety &amp; Process Optimisation.</li> <li>• Smart Wearables &amp; Proximity Detection for Worker Safety.</li> </ul>      | <ul style="list-style-type: none"> <li>• GIS &amp; Remote Sensing for Land Restoration.</li> <li>• IoT-Enabled Water Treatment &amp; Pollution Monitoring.</li> <li>• Mine Repurposing Digital Platforms.</li> </ul> |

| PHASE                                                   | EXPLORATION                                                                                                                                                                                                                                                      | FEASIBILITY & PLANNING                                                                                                                                                                                                               | MINE DEVELOPMENT                                                                                                                                                                                                                                        | MINERAL EXTRACTION                                                                                                                                                                                                                                                                                                         | CLOSURE & REHABILITATION                                                                                                                                                                                                                                                |
|---------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Digital Solutions:<br/>Supply Chain Optimisation</b> | <ul style="list-style-type: none"> <li>AI &amp; Machine Learning for Resource Estimation</li> <li>Blockchain for Transparent Supply Chain Tracking.</li> <li>Remote Sensing &amp; Drones For Low-Impact Surveys.</li> </ul>                                      | <ul style="list-style-type: none"> <li>Digital Twin &amp; AI-Driven Simulation for Optimised Resource use.</li> <li>Supply Chain Analytics for Optimised Procurement.</li> <li>CE Platforms for Waste Stream Managements.</li> </ul> | <ul style="list-style-type: none"> <li>3D Printing &amp; Modular Construction for Efficient Infrastructure.</li> <li>IoT-Enabled Smart Construction Managment.</li> <li>Automated &amp; Robotics-Based Construction for Percision.</li> </ul>           | <ul style="list-style-type: none"> <li>IoT &amp; AI for Real-Time. Supply Chain Monitoring.</li> <li>Predictive Maintenance &amp; Condition Monitoring for Equipment.</li> <li>AI &amp; Machine Learning for Process Optimisation.</li> <li>Autonomous &amp; Electric Vehicles For Efficient Material Transport</li> </ul> | <ul style="list-style-type: none"> <li>IoT-Enabled Land and Water Monitoring.</li> <li>GIS &amp; Remote Sensing for Land Restoration.</li> <li>CE Platforms for waste &amp; By-Product Management.</li> <li>Mine Repurposing Platforms for post Closure Use.</li> </ul> |
| <b>Digital Solutions:<br/>Skills Development</b>        | <ul style="list-style-type: none"> <li>Virtual Reality (VR) &amp; Augmented Reality (AR) for Immersive Training.</li> <li>AI-Powered Learning Platforms for Personalised Education.</li> <li>Remote Collaboration Tools for Global Knowledge Sharing.</li> </ul> | <ul style="list-style-type: none"> <li>Digital Twin Technology for Real Time Training Simulations.</li> <li>AI Driven Learning Management Systems (LMS)</li> <li>Blockchain for Credentialing &amp; Skills Verification.</li> </ul>  | <ul style="list-style-type: none"> <li>3D Printing for Hands On Skills Development.</li> <li>IoT-Enabled Smart Devices for On-the-Job Training.</li> <li>Mobile Learning Applications for Remote Training Access.</li> </ul>                            | <ul style="list-style-type: none"> <li>AI &amp; Machine Learning For Predictive Maintenance Training.</li> <li>Autonomous Equipment Simulation for Operator Training.</li> <li>Smart Safety Wearables for Continuous Skills Improvement.</li> </ul>                                                                        | <ul style="list-style-type: none"> <li>GIS &amp; Remote Sensing for Environmental Rehabilitation Training.</li> <li>Blockchain for CE Certifications.</li> <li>IoT &amp; Data Analytics for Rehabilitation Monitoring.</li> </ul>                                       |
| <b>Digital Solutions:<br/>Stakeholder Relationships</b> | <ul style="list-style-type: none"> <li>Blockchain for Transparent Resource Reporting.</li> <li>Geospatial &amp; Remote Sensing for Community Impact Mapping.</li> <li>AI-Driven Social Impact Assessment Tools.</li> </ul>                                       | <ul style="list-style-type: none"> <li>Digital Twin &amp; AI for Collaborative Planning</li> <li>Crowdsourcing Platforms for Community.</li> <li>ESG Reporting Platforms with Real-Time Data.</li> </ul>                             | <ul style="list-style-type: none"> <li>IoT Enabled Construction For Worker &amp; Community Safety.</li> <li>3D Printing &amp; Modular Construction for Localised Production.</li> <li>Collaborative Platforms for stakeholder Communication.</li> </ul> | <ul style="list-style-type: none"> <li>Real Time Monitoring &amp; Reporting Tools for Environmental Performance.</li> <li>AI for Workforce Safety &amp; Social Well-Being.</li> <li>Digital Stakeholder Engagement Platforms for Transparency &amp; Accountability.</li> </ul>                                             | <ul style="list-style-type: none"> <li>GIS &amp; Remote Sensing for Rehabilitation Monitoring.</li> <li>Blockchain for Transparent Closure &amp; Reclamation Reporting.</li> <li>IoT for Post-Closure Monitoring of Environmental Risks.</li> </ul>                     |

# ASSESSMENT

## Convergence in South African mining: The current state

Majority of mines are hybrid, combining intermediate DX, ESG, and CE principles while progressing toward modernisation. Larger companies lead with DX adoption while smaller ones face capital and skills gaps. ESG is growing, but governance currently leads over environmental and social integration.

### Key challenges include:



### Solutions include:



# MATURITY MODEL ASSESSMENT

Framework developed using Capability Maturity Model (CMM).

## Identify gaps and prioritise initiatives

They reveal shortcomings in areas like risk management; policy frameworks and governance; strategy development, implementation, and alignment; stakeholder engagement; and sustainability reporting. This then allows companies to focus resources where they can drive the most value.

## Continuous improvement

It is important to note that once KPIs and assessment frameworks are in place, a cycle of transformation involving change management and continuous improvement is needed.

## Enhance strategic planning

With a clear picture of their maturity in different focal areas and ensuring specific relevant KPIs are measured according to acceptable standards, mining companies can integrate implementation into their core business strategy, ensuring long-term value creation alongside risk mitigation.

## Build stakeholder trust

Transparent assessments demonstrate commitment to undertaking organisational transformation whether this focuses on ESG, CE, Just Transition and DX and adoption which is increasingly critical for attracting capital, satisfying regulators, and maintaining a social license to operate.

## Prepare for regulatory change

As reporting and governance frameworks develop for the mining industry (especially in newly emerging areas) and consolidation of standards become more prevalent, maturity assessments help companies stay ahead of regulatory demands. Hence companies are not reactive but proactive and can prepare for changes that impact operations and sustainability

Five levels of maturity in CMM :

- 1 Ad-hoc
- 2 Repeatable
- 3 Defined
- 4 Managed
- 5 Industry Leader

# Framework using the CMM to assess mine maturity in digital and sustainability transformation.

## Assessment framework with CMM maturity levels across strategic priorities in the mine value chain

| Stages of mine value chain |                            | Detail descriptors                                                                                                                                                                                                                                                                                                                     |                                |                        |                    |                            |
|----------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|------------------------|--------------------|----------------------------|
|                            |                            | Exploration Phase                                                                                                                                                                                                                                                                                                                      | Feasibility and Planning Phase | Mine Development Phase | Mineral Extraction | Closure and Rehabilitation |
|                            |                            | <p>Click on the hyperlink for the detailed list of descriptors per maturity level across each phase</p> <p>Select the maturity level for each strategic key priority, leave blank if not applicable.</p> <p>Note that it is possible to also include a retrospective view for strategic priorities in previous phases of the mine.</p> |                                |                        |                    |                            |
| Focus area                 | Strategic key priorities   |                                                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
|                            |                            |                                                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
|                            |                            |                                                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
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|                            |                            |                                                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
| ESG                        | Production efficiency      | <a href="#">ESG Production</a>                                                                                                                                                                                                                                                                                                         |                                |                        |                    |                            |
|                            | Safety and risk mitigation | <a href="#">ESG Safety</a>                                                                                                                                                                                                                                                                                                             |                                |                        |                    |                            |
|                            | Supply chain optimisation  | <a href="#">ESG Supplychain</a>                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
|                            | Skills development         | <a href="#">ESG Skills</a>                                                                                                                                                                                                                                                                                                             |                                |                        |                    |                            |
|                            | Stakeholder engagement     | <a href="#">ESG Stakeholder</a>                                                                                                                                                                                                                                                                                                        |                                |                        |                    |                            |
| Circular economy           | Production efficiency      | <a href="#">CE Production</a>                                                                                                                                                                                                                                                                                                          |                                |                        |                    |                            |
|                            | Safety and risk mitigation | <a href="#">CE Safety</a>                                                                                                                                                                                                                                                                                                              |                                |                        |                    |                            |
|                            | Supply chain optimisation  | <a href="#">CE Supplychain</a>                                                                                                                                                                                                                                                                                                         |                                |                        |                    |                            |
|                            | Skills development         | <a href="#">CE Skills</a>                                                                                                                                                                                                                                                                                                              |                                |                        |                    |                            |
|                            | Stakeholder engagement     | <a href="#">CE Stakeholder</a>                                                                                                                                                                                                                                                                                                         |                                |                        |                    |                            |
| Digitalisation             | Production efficiency      | <a href="#">DX Production</a>                                                                                                                                                                                                                                                                                                          |                                |                        |                    |                            |
|                            | Safety and risk mitigation | <a href="#">DX Safety</a>                                                                                                                                                                                                                                                                                                              |                                |                        |                    |                            |
|                            | Supply chain optimisation  | <a href="#">DX Supplychain</a>                                                                                                                                                                                                                                                                                                         |                                |                        |                    |                            |
|                            | Skills development         | <a href="#">DX Skills</a>                                                                                                                                                                                                                                                                                                              |                                |                        |                    |                            |
|                            | Stakeholder engagement     | <a href="#">DX Stakeholder</a>                                                                                                                                                                                                                                                                                                         |                                |                        |                    |                            |

## Outlook

- With leadership and innovation, South African mining is well-equipped for modernisation.
- Focus on addressing weaknesses (e.g., skills gaps) and leveraging strengths (e.g., mineral reserves) for global competitiveness.
- Develop practical, implementable solutions.
- Investments should prioritise long-term infrastructure needs and fit-for-purpose technology solutions that apply across the mine value chain.
- Integrating standards, frameworks, and governance across disciplines is critical.

## Future research

- Explore scalable DX, ESG, and CE strategies, especially for small mines.
- Establish shared infrastructure and co-investment models to fast-track CE and ESG initiatives.
- Strengthen alignment of reporting standards and better assess impact metrics.
- Conduct financial and technical feasibility studies and invest in strategic scenario planning for ESG, CE, and DX initiatives.
- Assessing industry progress requires understanding current mine stages and identifying measures needed for their digital and sustainability transition.

**THANK YOU**