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Scalable & Adaptable Mining

Reimagine mining through modular
architecture and flexibility

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The future is full of uncertainty and change. To deal properly with this reality, we need the adaptability to seize new opportunities, to avoid lock-in to bad outcomes, and thus to increase economic efficiency. In short, we need flexibility in both strategic planning and operational design. This white paper provides an excellent contribution to introducing this innovative approach to the mining industry. I'm looking forward to collaborating on future developments.



- Richard de Neufville, Professor of Engineering Systems, MIT Institute for Data, Systems, and Society

PURPOSE AND ACKNOWLEDGEMENTS

This paper explores the potential for a scalable and adaptable approach to mining to create value through flexibility.

Purpose

If the modern mine can be imagined, it can be created. The Think & Act Differently (TAD) Incubator, powered by OZ Minerals, is building an ecosystem of the curious who are exploring and accelerating themes that prioritise social and environmental responsibility for the development of the modern mine. The 'Scalable & Adaptable Mining Challenge' focused on finding flexible and modular solutions that could be deployed as part of an integrated mine design. This document details how the challenge cohort collaborated and what they learned.

Acknowledgements

Acknowledgement of Country

From the past, to today, and for forever into the future: these are the Lands of the Traditional Owners. Always have been, always will be.

Andy Reynolds, Scalable & Adaptable Challenge Partner

The TAD team would like to acknowledge the invaluable role that Andy Reynolds of Inspire Resources played in selecting and mentoring the innovators throughout the challenge. The role of the partner in this challenge was to help innovators connect the dots by providing industry context, access to networks and subject matter expertise.

“ New minerals projects are facing a headwind of uncertainty from volatile metal prices, greater focus from communities, decarbonisation goals and increasing resource variability. In the future, only the most adaptable minerals businesses will thrive and be able to develop and operate projects that create value for everyone. ”

- Brett Triffett

The Think & Act Differently team



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The TAD team would like to acknowledge the input received from the companies and teams in imagining, delivering and running the Scalable & Adaptable Crowd Challenge, including the composition of this document.



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EXECUTIVE SUMMARY

The Scalable & Adaptable Challenge, delivered by Think & Act Differently, sought to demonstrate the value of flexibility in mine operation.

OZ Minerals has an aspiration that our assets are scalable and adaptable.

The 'Scalable and Adaptable Mining Challenge' focused on finding flexible and modular solutions that could be deployed via an integrated mine design. Using new mining and processing methods may unlock access to new deposits, accelerate the development of projects, decrease environmental impact, open alternate ownership models, and improve the ability to respond rapidly to volatility and uncertainty during the life of a project.



1 Scalable & adaptable mining

There are several themes that will accelerate the attraction of scalable and adaptable processing and mining over the next decade. These are the commitment to low emissions mining, including renewable-only operations, and the exhaustion of larger higher-grade deposits, with satellite deposits becoming the next targets for new mines. Smaller satellite deposits do not lend themselves to the economy of scale considerations that drive current large mining plans. Instead, targeting higher grade small deposits economically may be better served by relocatable equipment and flexible fleets. In addition, flexible equipment able to manage energy supply variation may also become more attractive.

2 Systems thinking for big challenges

Today's mining value chain is complex and efficiency-driven. Implementing change demands a systems approach that enables trade-offs and risks to be fully understood and depends on a high degree of collaboration. Think & Act Differently is as much about developing these ways of working as it is about taking advantage of new technologies. A systems-led approach allows flexibility to be accommodated between each element of the mining value chain. No single organisation can solve this problem alone. Instead, it will require collective insights, domain expertise and collaboration from each element of the value chain to potentially reveal the value of flexibility and modularity in mine design and operation.

3 Challenge framing

The goal of the Scalable & Adaptable Challenge was to (1) build an ecosystem of companies that each hold a 'piece' of the flexibility puzzle that unlocks the potential for scalable and adaptable mines, and (2) to harness modelling and simulation technology to enable rapid and low-cost testing of new technologies. The challenge team scoured the globe for companies, teams and individuals with solutions, technologies or approaches that could be implemented or ideated as part of a scalable and adaptable mining project.

4 A global team for a global challenge

The Scalable & Adaptable team was selected from applicants around the world, with 190 participants from 33 countries vying to take part in the challenge. Ultimately, seven innovators were chosen to form the collaborative cohort. The finalists were selected based on their domain expertise, willingness to contribute and share learnings transparently and iteratively with the collective, and their coverage of the end to end value chain.

5 Learnings & outcomes

The Scalable & Adaptable cohort developed a whole-value-chain concept for a flexible operation based on a known satellite deposit. The architecture developed enabled a more agile extraction plan and just-in-time exploration. Two major conclusions were drawn from the challenge, (1) short-term flexibility of discontinuous operation is an economically preferable alternative compared to adding energy storage to allow for continuous operations on solar power, and (2) the flexibility to augment equipment fleets in response to varying metal prices can create value which can be calculated by Monte Carlo simulation. These insights may pave the way to future all-electric, zero-entry, low-footprint mines in large numbers.

6 Continuing the innovation journey

The challenge has drawn to a close, and the cohort has made bounds in simulating and setting up the frameworks in which to determine the potential value of flexibility within a mine's operational systems. To continue on the journey, TAD and the challenge innovators will explore potential subsequent work packages for scalable and adaptable; investigating how the learnings from this round could be applied on a mine site for an identified ore body. This is an exciting test case for the way future mines could be designed and has led to the TAD team developing a Concept of Operations business stream to experiment with sets of capabilities that may be employed to achieve a modern mine.

THINK & ACT DIFFERENTLY

Think & Act Differently is a discovery-driven incubator, whose purpose is to accelerate the achievement of the OZ Minerals strategic aspirations, whilst benefitting all stakeholder groups.

OZ Minerals' purpose is going beyond what's possible to make lives better. The work of the Think & Act Differently Incubator and the Scalable & Adaptable Challenge aims to accelerate progress towards this.

Think & Act Differently provides a unique approach to innovation, attracting the best minds from both inside and outside the mining industry, connecting the dots in new and exciting ways.

Central to its success is the active participation of a network of thousands of people from across multiple industries, organisations, community groups, governments, research organisations and others who want to play a role in solving complex mining challenges.

The incubator provides these stakeholders with access to tools, skills and processes to help identify new, low impact ways to mine and process minerals and create valuable opportunities for society.

At the core of Think & Act Differently is a unique human driven process where the ecosystem works together to **Frame** opportunities, **Diverge** in our thinking to generate ideas, **Converge** experiments that we can use to test the best ideas and then **Accelerate** these ideas by providing funding, technical expertise, access to sites and support.

Value Created by Scalable & Adaptable

Employees

- Over 90 employees attended the "Meet the Innovators" event
- 90 members of our workforce and ecosystem participated in the Insights Panel, which shared progress of the simulation
- Potential to harness flexible principles and low cost testing of new technologies on existing and future mine sites

Suppliers

- 190 innovators from 33 countries registered as a part of the Crowd Challenge
- 37 submissions to the challenge received
- Cohort upskilled their understanding of the mining value chain through TAD capability program
- International network of partners established

Government

- Potential to reduce environmental impact from mining operation by avoiding large and upfront infrastructure and approvals necessary in conventional mining methods
- Aspiring to create sustainable approaches to mining through relying on renewable energy whilst generating optimal throughput

Community

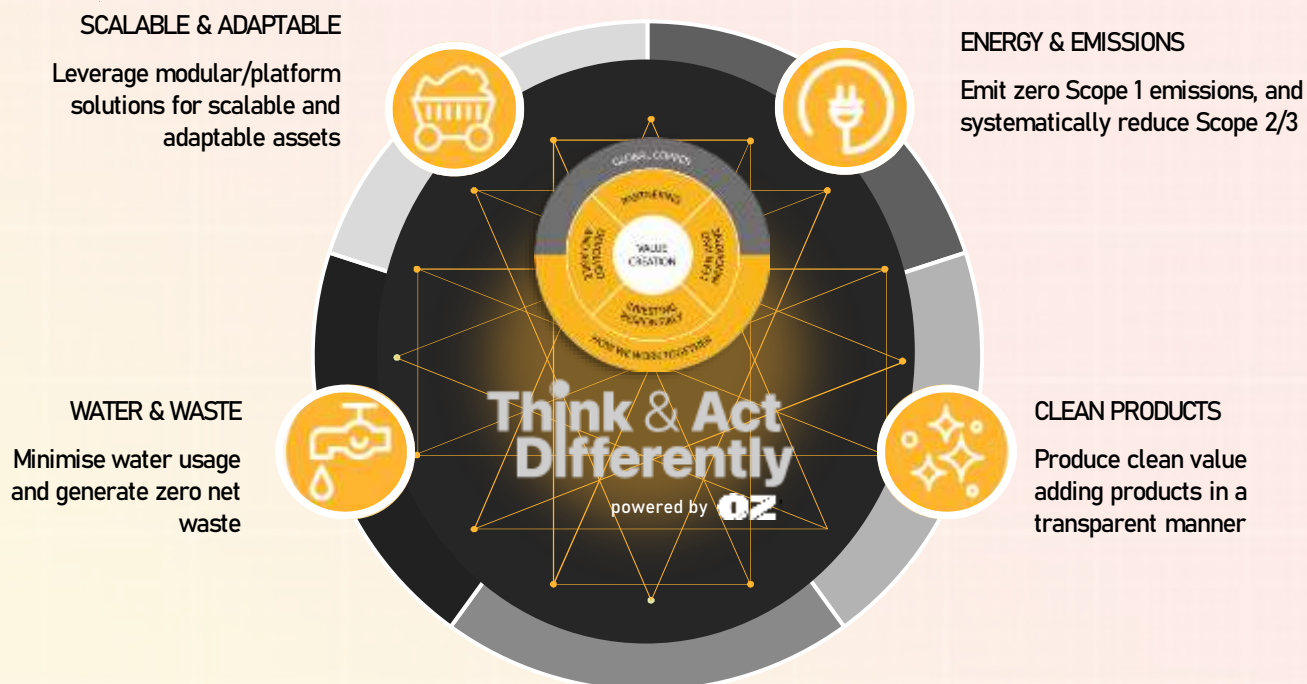
- Identification of potential solutions with lower environmental impact across the value chain
- Potential change in how communities are engaged and involved in operations

Shareholders

- Identification of opportunities to test and benefit from sustainable and novel mining methods
- Potential to access smaller, higher grade deposits through utilising scalable and adaptable approaches, including mines that are uneconomic using traditional mining methods, contributing to profitability

THINK & ACT DIFFERENTLY

Think & Act Differently is a discovery-driven incubator, whose purpose is to accelerate the achievement of the OZ Minerals' strategic aspirations, whilst benefitting all stakeholder groups.



Humanistic systems driven innovation, Sustainable Development Goals and TAD

OZ Minerals' Strategic Aspirations are aligned with the United Nations Sustainable Development Goals (SDGs). TAD's human to human, systems-driven approach to work acknowledges the complexity of our challenges and prioritises the interests, needs and welfare of people in synergy with the OZ Minerals purpose of 'Going beyond what is possible to make lives better.'

SDGs are addressed through TAD themes of clean products, energy & emissions, water & waste, and scalable & adaptable. TAD is committed to demonstrating the impact of technologies developed through the incubator process towards the SDGs and their associated targets.

If the modern mine can be imagined, it can be created

01

SCALABLE AND ADAPTABLE MINING

In partnership with:



Andy Reynolds
Challenge Partner



Economy of scale has served the mining industry well in the pursuit of steady-state efficiency. But we may now be entering times that call for more flexibility and resilience. How would that affect system design and operation? In this Challenge, we combined a whole-system approach with some new technology and a great deal of collaboration among industry partners to go beyond the incremental and reimagine the entire value chain.

- Andy Reynolds



1.1 Key drivers and enablers

Scalable and adaptable mining provides the opportunity to redefine how mines are designed, how they create value, and offers flexibility to suit the economy and the environment.

What is scalable and adaptable mining?

For many years, the mining industry has favoured large, fixed infrastructure builds that require stable and consistent energy supply. As metal grades have decreased, operational footprints have increased to achieve economies of scale. These large, capital-intensive projects are constrained by fixed designs developed against long-term assumptions that can often change, making some projects uneconomic in the long term. Despite often higher grades, smaller and satellite deposits do not lend themselves to the economy of scale considerations that drive current large mining plans. Instead, small deposits may be better served by relocatable or shared equipment fleets.

“ **Scalable and adaptable mining offers an opportunity to unlock different ore bodies.** ”

The traditional method of extraction described above leverages the economy of scale and decreases risk as a result. New opportunities are presented in the form of smaller, high grade, satellite deposits. Previously, establishing an economical process for extraction has precluded these deposits from being targeted.



Scalable is the ability to start an operation small, enabling cash flow, and having the ability to ramp up or down in size as required.



Adaptable refers to the degree to which a system can sustain the required performance when influenced by external factors, such as unexpected ore properties or environmental constraints.

Together, these two attributes appear in the real world in the form of flexible and modular solutions which could allow for mining operations to dynamically move between sites or rapidly incorporate innovative technologies or techniques.

Why now?




The traditional method of extraction has been successful across many minerals, mines and models, so why change now? Large, well-defined, open-pit, long-life mines would benefit less from the value which could be offered by a flexible, adaptable, and modular solution. The real value from this change in thinking comes as we begin to consider clusters of small underground mines, where the resource volume and ore grade have made these deposits previously uneconomical. The value potentially spreads beyond the mine site, as this approach offers an opportunity to consider alternative ownership models and decarbonisation opportunities.


MODULARITY & FLEXIBILITY IN INFORMATION TECHNOLOGY (IT)


The concepts of modularity and flexibility have been applied across other industries with great success. The Information Technology sector showcases the value and power of applied modularity and flexibility. This sector creates a platform for scalable and adaptable products by leveraging modular software and firmware programs. These modules can be built small to start, and can scale up rapidly as demand changes. This allows the industry to adapt to its changing customer base, and allows new technology, or new software modules, to be quickly incorporated into the existing systems via software updates.


What challenges are being faced?

The traditional methods of mining that have been developed over years have been fit for purpose and fit for their time. When looking to the future, the current method of mining poses several threats when considering a mine's operating environment:

-  **Risk** – As the level of uncertainty in the market, ore deposit or industry increases, the associated costs for the project approval increase, which then flows on to an increase in project size.
-  **Technology** – The mines operating today utilise heavily customised equipment and solutions designed around traditional energy supply. This existing custom infrastructure makes it difficult to incorporate future technologies. A solution needs to be found to enable the timely incorporation of innovation.
-  **Investment** – The value systems of investors are rapidly changing towards creating a sustainable planet on which to live. This is driving a change in where and how money is spent, and what business behaviours are supported.

 **Demand** – There is an increased demand for commodities associated with decarbonisation (copper, lithium, aluminium etc). Existing mines and systems need to be able to respond accordingly.

 **Scarcity** – 'Investment grade' mining projects are becoming more scarce, which will naturally have an impact on the supply of commodities in the future.

 **Opportunity** – The traditionally economic ore deposits have been targeted and mined out. The industry now faces the future of declining grades of mineral deposits, fewer discoveries, and more technically difficult ore bodies in more challenging locations. If known ore deposits are plotted (Figure 1), it is possible to draw envelopes to identify those sites considered to be economical. Finding a way to expand the economical envelope towards lower grades and resource volumes will change how we perceive value.

As a result of these factors, the industry is primed for disruption to change the way we mine in the future. The solution will not be simple, but its opportunity to create value is vast.

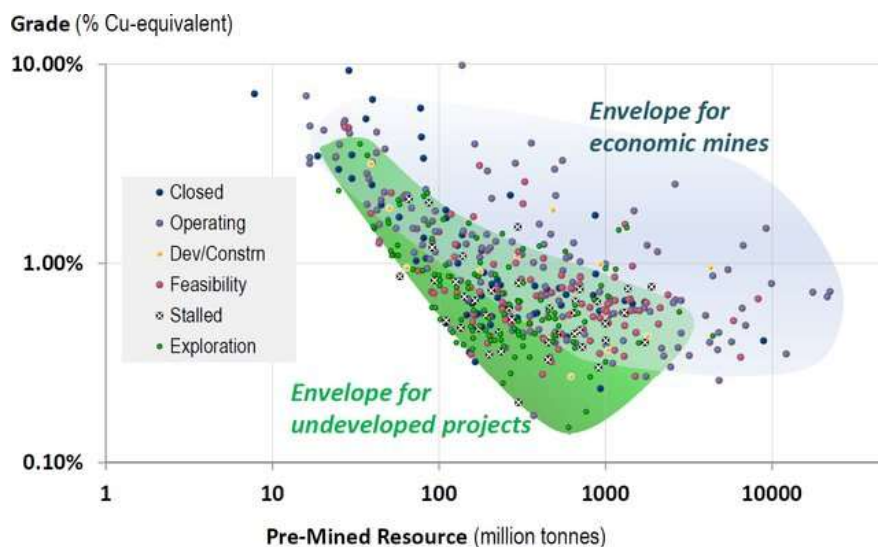


Figure 1 - The envelopes of mine economics under traditional mining methodologies ^[1]

1.2 Taking a systems approach

Flexibility is a whole-system trait because it depends on the interactions between the parts of the system. In a complex system, point-solutions alone will not deliver whole-system flexibility.

Why is a systems approach required?

Mine designs today, and the valuations that depend on them, typically take a static view of the world in which they will be operated. The result is mining and processing value chains that are not built for change, but rather for economy-of-scale, to provide risk-absorbing margins. But the world does change, and things often don't turn out as expected. At these times, static designs make it harder than it could be to introduce innovations that address emerging problems.

Taking a systems approach allows the mining value chain to be re-architected for a world of increased change and uncertainty. Change scenarios can be defined and calculated to determine how well a given architecture would respond – and even to put a dollar value to the benefits of flexibility. For example, a modular architecture may be chosen – even if it is more expensive up front – because of the ease of switching or reallocating modules later.

“ Taking a systems approach allows the mining value chain to be re-architected for a world of increased change and uncertainty. ”

The systems approach is brought to life by two critical factors: collaboration between domain experts, and system models that allow complex interactions between elements to be revealed. It demands that the whole system is examined for its entire life, and dictates the avoidance of being drawn into fine details that don't impact whole-system behaviour.

What are the systems/elements needed to be considered across the value chain?

A simplified representation of the major value chain stages was the starting point for the concept of operation, and is shown in Figure 2 below.

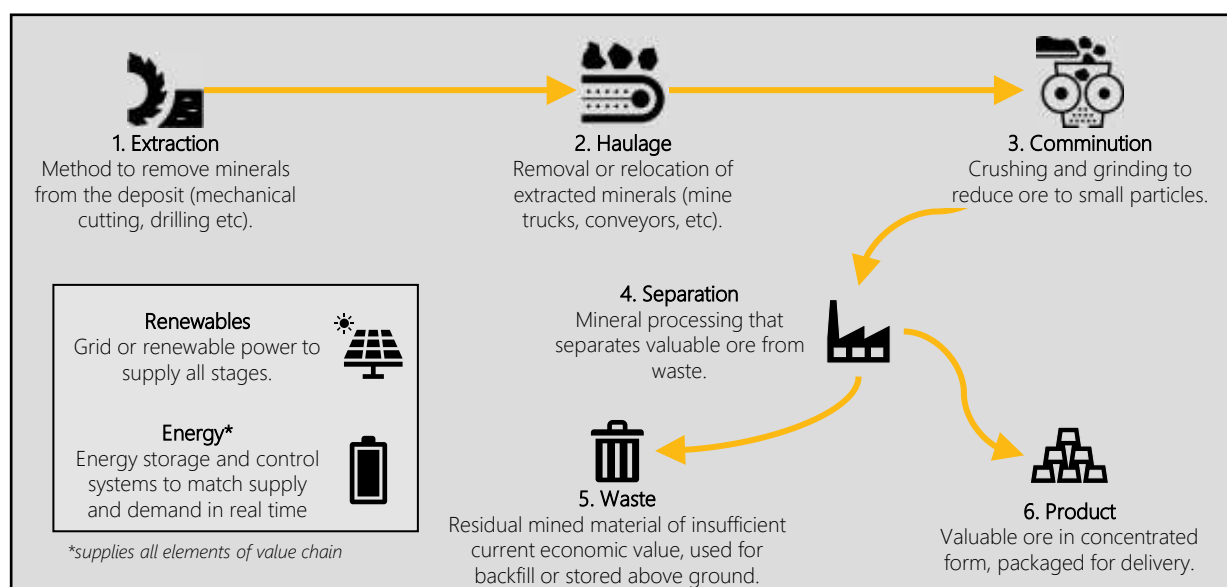


Figure 2 – The elements of a value chain considered in the systems approach

What are the design attributes of a scalable and adaptable system?

A scalable and adaptable lens allows us to see expected benefits from certain system design attributes (as shown in Figure 3) in the face of industry-wide uncertainty. From workshoping with stakeholders in the industry, the critical uncertainties identified were: (1) Ore Body Uncertainty, (2) Community Expectations & Host Nation Relationships, (3) Permitting Uncertainty, and (4) Metal Price Uncertainty.

These uncertainties could then be potentially addressed by translating them into system requirements which drive a scalable and adaptable design. When this approach was explored, a large positive association was found between the design attributes of flexibility and the system's ability to address the industry's concerns for uncertainty. For example, requiring standardized interfaces in a modular architecture can accelerate innovation by easing technology substitution and avoiding whole-system re-test.

While there are many potential avenues of benefit, and many scenarios that can be simulated, one worth noting is to 'Align Production Capacity to Market Prices,' which has been treated as a key test scenario in our iterative simulation process in the context of both power availability and metal price.

Although these relationships between uncertainty and system flexibility are intuitively easy to grasp, the challenge for system designers is to choose the right kinds of flexibility for the expected uncertainty during the system's life – a quantitative task.

The previous work of de Neufville and Scholtes^[2] showed that Monte Carlo simulation of management decisions (such as the response to varying commodity prices) is an appropriate tool for determining the expected value of flexibility (EVoF) of a design under uncertainty. Drawing inspiration from these insights, this method forms the basis of the approach used in the Challenge.

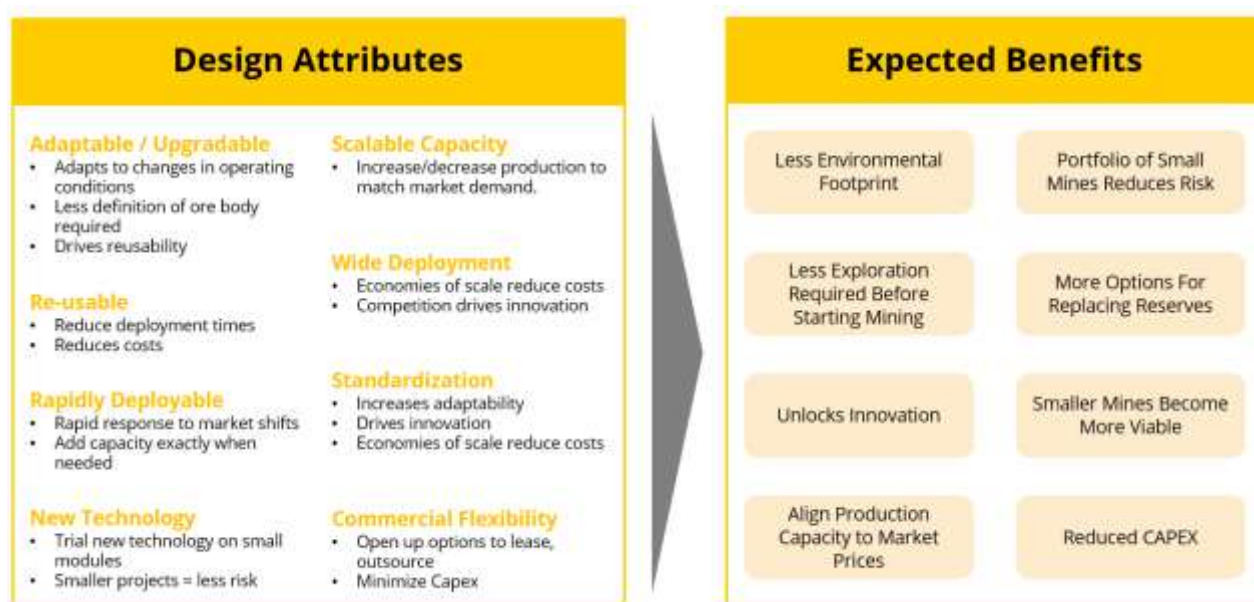


Figure 3 - Mapping Design Attributes to Expected Benefits

1.3 Impact to the mining industry and beyond

Scalable and adaptable approaches will only unleash the full impact of flexibility when the concept is applied to the entire mining value chain.

Opportunities in mining

Although scalable and adaptable concepts can be retrofitted to operating mining value chains, the full benefits of flexibility are unleashed only when the whole system is designed for them. This requires intervention early in the project lifecycle, where big bets are rarely made. It will be important to pursue project-specific feasibility studies, and model-based design will quickly bring down their cost.

Below are three opportunities within mining in relation to the successful exploration, rollout and adoption of scalability and adaptability across the industry:

1 The ability to target resource deposits which were previously too complex, small, remote or uneconomical.

2 The ability to insert new innovations at low cost thanks to standard interfaces and test protocols. This could accelerate the industry's response to new regulatory requirements for example, or to shocks such as fuel shortages or extreme climate shifts.

3 The facilitation of greater collaboration and faster design processes through module reuse and potentially through innovative business models with industrial partners.

Going forward, it could be possible to see flexibility-oriented equipment deployed in narrow point-solution use cases, which will build an operating track record in the hands of early adopters.

Looking 5+ years out, there may be the first whole-system concepts being commissioned, and by 10+ years there may "clustered" or multi-site value chains creating portfolio risk reduction through shared flexible equipment.

Of course, there will be resistance to change, and it will be necessary to validate models with operational experience at every opportunity. However, we should also recognise that the incumbent economy-of-scale approach will be increasingly challenged wherever volatility, uncertainty and complexity increase. As megaproject expert Professor Bent Flyvbjerg outlined in a recent Harvard Business Review article⁽³⁾, large integrated projects are notorious for cost and schedule overruns, and modular replicability is increasingly seen as a better alternative in sectors as diverse as construction, transportation and energy.

1.4 Diverse specialist perspectives



Deen Sanders

*Partner,
Deloitte: Integrity,
Deloitte Indigenous
Space Practice*



How does the concept of Scalable & Adaptable fit within our current regulatory frameworks? Does the current bespoke nature of mine design make this easier, or harder?

Whether a new design, a new development, a new extension, or a rehabilitation of a mine site that has reached the end of its life, all mining activity in Australia is taking place on Indigenous lands. Scale in Indigenous systems thinking is a fractal concept, rather than a leveraging one. In the regulatory systems of nature, regulatory architecture does not punish small scale with burdensome requirements of large-scale regulation. Integrity is maintained at every level by a focus on the shared health of the whole system. Real systems thinking (for mining or regulation) prioritises the whole system over self-interest because it is self-interest that doesn't scale equally.

If Scalable & Adaptable mining methods would allow for more community engagement, what would that mean to First Nations people or what benefits could you see transpiring?

The invitation to scale is an invitation to Indigenous people to participate in their own landscape in a scale that suits the capacity of the land from a cultural and lore perspective, not solely a market perspective. Mining that is scalable, adaptable, profitable and responsible to both the land and Australia's First Nations peoples is not a remarkable idea – it is a very real one, but one that will take courage and will require a very different way of thinking to what has been done through history.



Emily Humphreys

CEO & Co-founder



How complex is the mining industry for applying systems-led thinking?

Embracing complexity and shifting a whole industry to taking a system thinking approach is no small undertaking. It's a fundamental shift in valuing collaboration and partnerships over competition, embracing uncertainty and emergence over outputs and outcomes.

But the power of applying systems thinking is immense, and the mining industry has the potential to have a powerful impact on accelerating technologies to tackle some of the biggest global challenges through cultivating partnerships and collaboration.

What are some challenges teams face when implementing solutions arising from systems-led thinking?

The biggest challenge I see for teams using systems-led thinking in mining is communicating the benefits of taking this approach and demonstrating impact.

This is hard as organisations are attached to linear, cause-and-effect thinking, where they believe they are in control of outcome. Measurement and monitoring flow on from this, and it can be incredibly hard for teams working a systems-led way to visualise and measure the change they have helped create.



Andy Reynolds

President



What are the biggest challenges in tackling Scalable & Adaptable in the mining industry?

The major obstacle to unlocking value from flexibility is the economic modelling that is used to communicate with investment markets. Because investors do not demand dynamic cash flow models in feasibility studies, those studies are based on static scenarios (albeit with sensitivity analysis to establish margins for risk absorption). As a result, economy of scale always wins in design choices, leading to monolithic, inflexible mining and processing systems.

What is your motivation for partnering to launch this challenge?

Flexibility is a whole-system attribute, and demands a whole-system approach to design. This challenge was an irresistible opportunity to bring some attention to how companies could work together to solve complex problems, or even create transformational concepts. This is the kind of collaboration that has been sorely missing from the mining industry for several decades, and bringing it back is the best thing we can do to unlock innovation at this global time of need.



Graeme Stanway

Director



If Scalable & Adaptable achieves its potential, what could that mean for the mining sector?

Many aspects here point to the ability to start small and modify on a scenario-by-scenario basis, but draws on modularity to enable this. The ability to produce lower cost and standardised modules that cover elements of the mining process would allow for ease of upgradability (physical and digital), relocation and re-use of modules and increased safety (modules are built in a controlled environment offsite)

How might we realise the large scale transformation required?

To start, we would need a forcing function to push for this transformation, that could be a challenging orebody, tight delivery schedule, or an inhospitable environment.

To realise it, we would likely need to reach fully virtualised designs to allow for pre-fabrication to increase, and to generate interest in OEM's. If they see the potential for a volume increase, they would likely pursue it.

How could we ensure effective collaboration to realise this change?

Like all collaboration, a common goal needs to be outlined, one which transcends the inevitable competitive tensions. This goal must be tangible and have real value to all parties involved. To help mitigate the competitor tensions, bringing independent thinking from outside the industry will likely help the teams to not lose sight of the bigger picture.

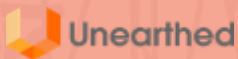
02

THE CHALLENGE

In collaboration with:



Zane Prickett
Director,
Uearthed



As an industry, our mining practices have to become more sustainable, which includes rapidly improving how we reuse and scale. With innovative submissions from across the globe and a variety of industries, this challenge is a great example of how to connect with innovators and SMEs to raise the bar and drive sustainability. We, at Uearthed, are excited to see how the top innovators work with OZ Minerals to implement their solutions and ultimately change the industry.

- Zane Prickett



2.1 Challenge scope

The Scalable & Adaptable Challenge takes a truly collaborative approach toward innovation by applying a humanistic, systems-driven problem-solving lens to mining operations.

What were the goals of this challenge?

The aim of the Scalable & Adaptable Challenge was to identify companies, teams and individuals from around the world with solutions, technologies or approaches that could be implemented as part of a modular mining project in the areas of Mining and Processing.

Unlike previous challenges (see Table 1) where the TAD incubator identified companies and solutions and funded individual experiments within a collaborative cohort, TAD's third challenge looked to establish one cohesive team to work in unison to visualise mining projects that can be designed and built with a different philosophy than what drives value by traditional methods.

As part of this, the team were looking to identify innovators who represent each part of the value chain. This would allow for a complete solution to be developed, utilising each team's contributions as building blocks and create value for all parties involved.

THE TEAM'S GOALS FOR THE SCALABLE & ADAPTABLE CHALLENGE

Specifically, the two goals that the team were looking to establish was to:

- (1) Harness modelling and simulation technology to enable rapid and low-cost testing of new technologies and approaches; and
- (2) To build an ecosystem of companies that each hold a 'piece' of the flexibility puzzle.

While the aim is focused on the benefits when applied in an OZ Minerals context, the ultimate intention is to contribute to the mining industry by challenging traditional, high capital intensity mining practices.

Table 1 - Previous challenges hosted by the TAD incubator

Challenge	Launched	Status
Ingenious Extraction	16 Feb 2021	Completed
Hydrogen Hypothesis	30 Mar 2021	Completed
Scalable & Adaptable	26 May 2021	Completed
Electric Mine Simulation	15 Sept 2021	Ongoing
Waste to Value	27 Oct 2021	Ongoing

Overview of how the challenge was delivered (phased approach)

Framing – Curating the crowd

Global research was conducted by Uearthed for the challenge, with the cohort primarily based in Australia and North America. The challenge outreach focused on identifying research teams, professionals and organisations that have the interest, expertise and capabilities to investigate novel and innovative approaches to reimagining the mining value chain.

Divergence – Building the innovator community

Over an eight-week period, the challenge attracted over 190 participants from 33 countries, with 37 teams putting forward a submission.

Teams that expressed interest were primarily established organisations within the mining or adjacent industries that were eager to test new technologies and approaches, coupled with some early stage, start-up companies and researchers. By nature of the requirements of the challenge, submissions were distributed across the entire mining value chain.

During this phase, the TAD team hosted a mid-challenge webinar on the topic of ‘Scalable & Adaptable Mining’, hosted by experts in the field. It was promoted widely on social media and attended by people from across the globe.

Convergence – Narrowing down on ideas

In selecting a cohort to support through the experimental Acceleration stage, TAD focused on ensuring a spread of technologies across the mining value chain, with minimal, if any, overlaps. In addition, innovators were selected that were highly collaborative, willing to share their learnings and had expressed interest in working by utilising modelling and simulation technology. Ultimately, seven innovator teams were offered participation from a group of fourteen finalists (see Figure 4).

Accelerate – Validation through testing

The seven teams of the Acceleration cohort (profiled on the following pages) spent a total of seven months together developing the simulation. All the members recruited by TAD and Inspire Resources generously volunteered their time in this phase of the challenge, building upon their shared interest and uniting in the pursuit of the vision for what could be realised through the Scalable & Adaptable Challenge.

Within three months a minimum viable product model was developed. The phase was then extended to allow for further refinements. They met every two weeks to share learnings and experiment progress in Learnings Roundtables. Additionally, they have shared insights with OZ Minerals via virtual Insights Panels; virtual events for the OZ Minerals workforce and innovators from other challenge cohorts to learn and develop their own understanding of new topic areas.

The challenge period, now complete, sparked ongoing interest in the cohort, and options are being explored to discover what a subsequent work package may look like, leveraging shared findings from the simulation, and how it could tie in to identified and unmined ore bodies. All innovators will be invited to propose how they can contribute to future works in this space as well as stay connected to TAD through our Alumni program.

The TAD team would like to acknowledge the time and effort all participants and innovators that have contributed and will continue to contribute to the realisation of ongoing value from the Scalable & Adaptable Challenge.

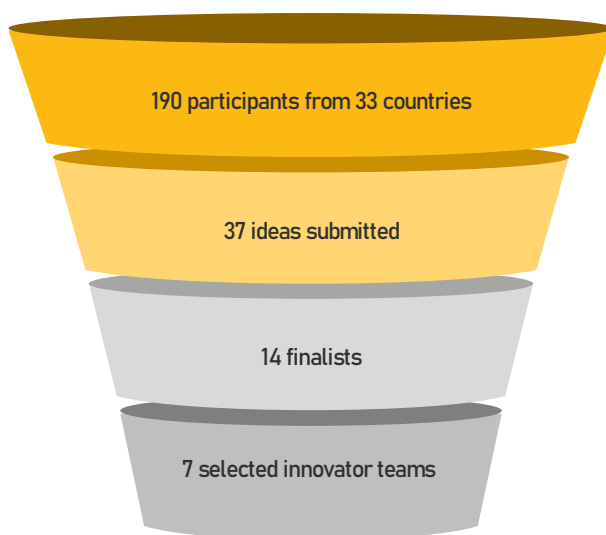




























Figure 4 - Challenge phases

2.2 Innovators across the value chain

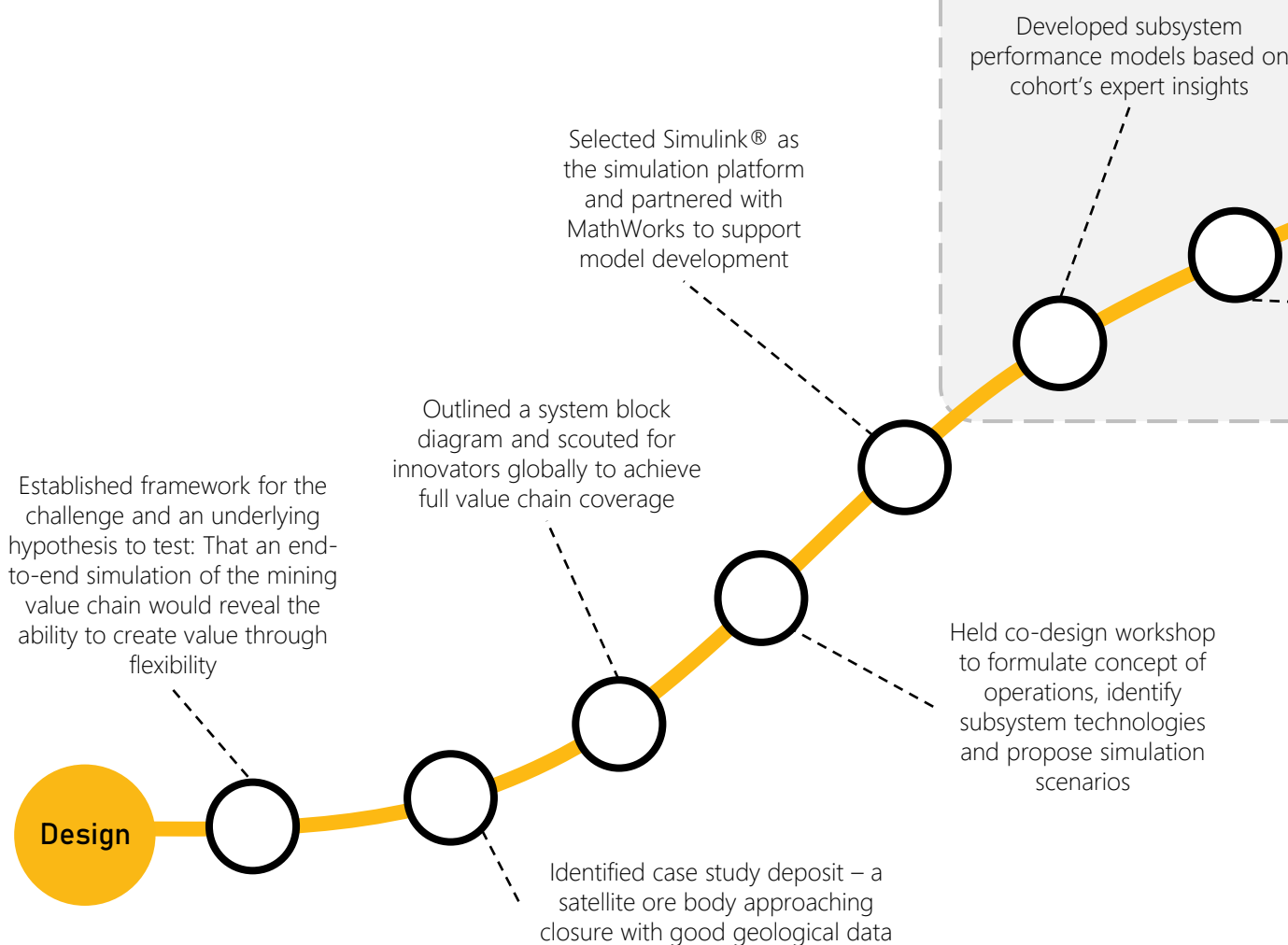
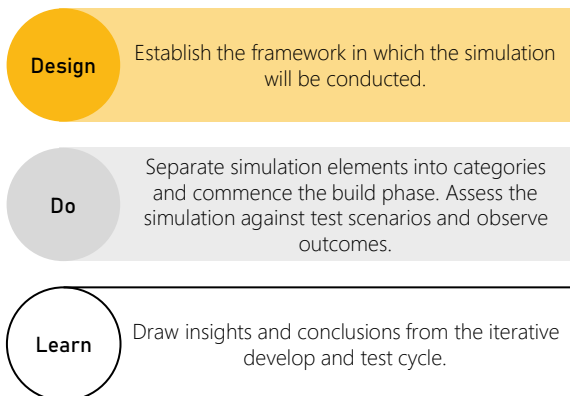
The Scalable & Adaptable Challenge teamed up experts across the value chain and across the globe to tackle a transformational change in design and thinking.

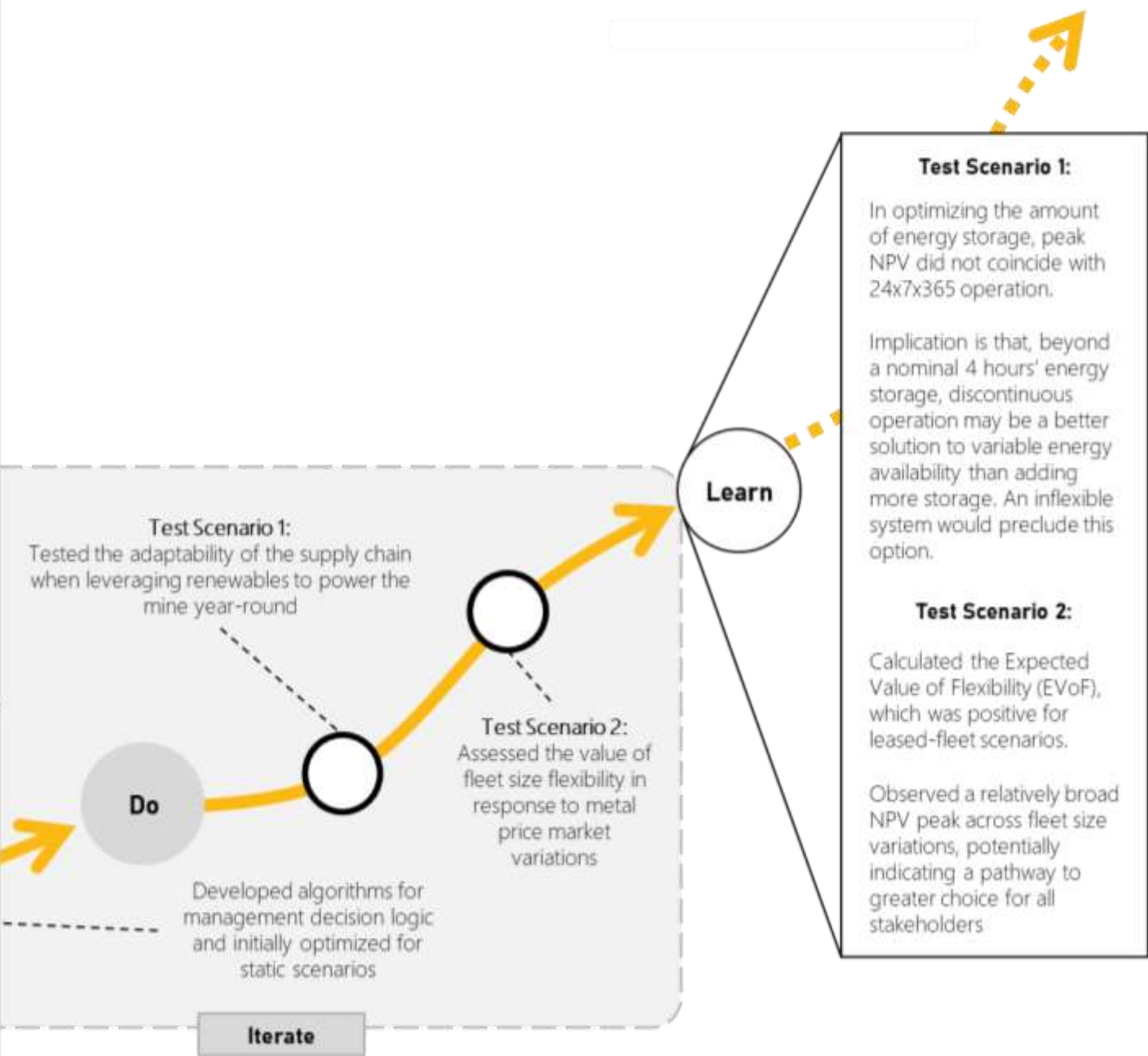
Table 2: Overview of the innovators of the Scalable & Adaptable Challenge

		Innovators	Technology	Value chain
	Novamera	 Dustin Angelo  Shannon McCrae	A novel drilling-based extraction method with a downhole guidance system to enable precision mining	Extraction
	Drilling & Extraction Start-up			
	Komatsu	 Steve Styles  Tony De Sousa  Phil Rosenstern	Electric, hard rock mechanical cutting machines	Extraction
	Manufacturing OEM			
	Comminution Reimagined	 Prof. Malcolm Powell	Low-energy comminution, assembled from modular units	Comminution
	Researcher			
	Sedgman	 Lyndon Ryan  Ryan Bracey  David Way  Jenny Agnew	Modular plant design for precious and base metals	Infrastructure, Waste & Separation
	Processing & Infrastructure Specialist			
	Sepro Mineral Systems	 Andrew Gillis	Mobile and modular mineral processing modules for scalable and adaptable mineral recovery	Separation
	Mineral Processing Specialist			
	Juwi	 David Manning  Tom Littlechild	Modular, deployable solar photovoltaic and microgrid solutions	Renewable Energy and Energy Storage
	Renewable Energy Specialist			
	EnergyFlex	 Garry Harding  Craig Phasey  Taylor Woods	An energy mining system, to identify and extract the full value of energy use in complex assets	Energy Management
	Energy Management Specialist			

2.3 Developing the simulation

The Innovators' Journey





Leveraged iterative process of developing and testing simulations to continuously 'Play-to-learn' and thereby identify the key levers for each sub-system that would allow us to visualise how changes in one domain would cascade into others

“ Building a simulation allows us to 'Play-to-learn' and identify synergies and levers which are obscured when we view the system from only one point in the value chain. ”

03

LEARNINGS AND NEXT STEPS



Michelle Ash
*Technology Executive,
OZ Minerals*



'It has been fantastic to see the progress that has been made by the Scalable and Adaptable Challenge participants, now I look forward to seeing that thinking being put into practice as we transform the way we think and act in mining.

- Michelle Ash



3.1 Learnings and next steps

The Challenge has demonstrated the value of a collaborative, whole-system approach, and has successfully used simulation to analyse the value proposition of flexibility throughout the value chain.

Insights & outcomes

The Scalable and Adaptable Mining challenge was a collaborative team exercise, focused on learning together and from each other. The Acceleration phase was initially allocated an ambitious schedule of 3 months. The team raced to a minimum viable product (MVP) simulation by that point, but it was no surprise that more time was needed to ensure the test scenarios and management decision logic algorithms were robust. The Acceleration phase ultimately lasted 7 months, bringing to life a design of breadth and novelty made possible by the cohesion and commitment of the individuals representing the companies in the cohort. The demonstrated motivation to stay engaged and contribute, even on a pro bono basis, bodes very well for a future digitally-enabled Concept of Operations with a suitable commercial framework underpinning it.

In terms of the test scenarios for the specific ore body studied, there were two major conclusions:

1 Short-term flexibility of discontinuous operation is an economically preferable alternative to the additional energy storage needed to enable fully continuous operation on solar power. This poses challenges for workforce scheduling, but also opens opportunities for improved equipment maintenance and potentially improved night-time safety and environmental impacts via reduced emissions.

2 The flexibility to augment equipment fleets in response to, for example, metal prices, creates value that can be calculated by Monte Carlo simulation. For the specific case modelled, a positive EVofF could not be generated with an owned equipment fleet, because the short mine life limits returns on the capital cost of the fleet additions. However, modelling a leased fleet yielded a positive EVofF.

This result demonstrates the importance of modelling not just technology and systems, but also business models. Additionally, we noted that increased flexibility may broaden the economic value peak; making the profitability of the operation more resilient in the face of change.

How could the simulation be improved?

The simulation developed for this challenge was as versatile a model as could reasonably be expected for an MVP. However, there are aspects that are specific to the ore body used. Over time, with application to more case studies, the model architecture will evolve to become more generally applicable, including to other sources of variability such as in ore properties. As the skills of cohort companies increase, the architecture of the model could also become more open, allowing value chain participants to experiment with subsystem models of their own, and providing insights into the value of their innovations.

Interestingly, today's cloud compute capabilities are not a significant limitation. This challenge regularly ran 1000 mine-life simulations per hour on a 128-core Amazon Web Services cluster at a cost measured in tens of dollars.

Scalable & Adaptable Challenge reflection

With the Scalable & Adaptable Challenge completed, the TAD team reflects upon the challenge process, its goals, accomplishments and learnings, and how they may relate to aspirations at the outset. The purpose of this challenge was to find flexible and modular solutions that could be deployed as part of an integrated mine design. The TAD team were able to identify and assemble a cohort of organisations who saw the potential value in a scalable and adaptable approach to mining and that could collaborate and pursue this purpose.

The team proved their hypothesis that an end-to-end simulation of the mining value chain would identify the ability to create value through flexibility and identified test scenarios indicating the impact of flexibility when operating a mine site via renewable energy sources.

Additionally, this challenge expanded the TAD and OZ Minerals global network. The process saw input primarily from Canada and Australia, but importantly, established strong relationships with innovators across all elements of the mining value chain. This is an exciting test case for the way future mines could be designed and it has led to the TAD team developing a Concept of Operations business stream to experiment with sets of capabilities that may be employed to achieve a modern mine.



Where to from here?

The overall success of the Scalable & Adaptable Challenge provides an encouraging foundation for further work in this area. All members of the cohort have been engaged for their interest in proceeding with a potential subsequent package of work upon which to apply the simulation learnings. The intent is to test the translation from simulation to a physical asset and continue to build the knowledge base. Each team has been requested to put forward a proposal for their involvement in these potential works, identifying what role they would like to play and where they may add the greatest value. Where necessary, additional expertise may be sought to build out the skill-set to deliver on the proposed scope.



An early learning was the impact of visual simulation to a systems based problem. This gave all team members the ability to ‘play to learn’ in the simulation and enabled iterative learning quicker than anticipated.

04

INNOVATOR CONTRIBUTIONS

In collaboration with:



Wilco Volwerk
*ANZ Energy & Mining
Industry Manager,
Mathworks*



MathWorks was pleased to support Inspire Resources as they combined the ideas of the challenge team members into a fast and comprehensive whole-system model. MATLAB and Simulink are ideal for modelling and simulation projects that need the maximum freedom to innovate, down to the fundamental mathematics level. The Inspire Resources team made great use of the platforms' capabilities, and our application engineers were able to both guide and learn as the model scaled up and migrated to the cloud.

- *Wilco Volwerk*



4.1 Innovator contributions

A global cohort of innovators who bring their technical excellence and passion for problem-solving to the table.

Inspire Resources

Challenge Partner

Company and Innovator Overview

Inspire Resources is developing and deploying a novel mining business model. By improving risk and reward allocation in the partner ecosystem, they look to escape from the adversarial processes of the incumbent mining industry, and deliver substantial sustainable development impact for communities of interest through mining-centred development projects.

Andy Reynolds, President of Inspire Resources, previously spent nearly 10 years managing resource sector research and development in Canadian government labs. He has a strong background in people leadership from a career of over 20 years with the UK's Royal Navy, where he held roles such as management of technology, procurement, programs and portfolios, and international collaboration.

Ken Murray, VP Engineering for Inspire Resources. He has led diverse teams to conceptualize and build mines across the world. He has a passion to improve our lives by continually learning and trying to develop new ways of solving industry challenges primarily by adopting a systems-based approach.



Andy Reynolds



Ken Murray

Contribution

Inspire Resources has facilitated the collaboration by building the simulation and running the scenarios, with each member of the team contributing expert insights along the value chain and Inspire Resources designing the decision-making engine that responds to variability. For example, the model includes an hourly load controller that dispatches equipment on and off, and manages battery charge, according to process flow management priorities and available solar energy.

Watch their interview



To be able to work together with a group like this and re-imagine the entire mine design process has been a very uplifting and tremendously rewarding experience.



– Andy Reynolds, President

Novamera Inc.

Company and Innovator Overview

Novamera Inc. has developed a surgical mining method using guidance technologies that unlock value in certain mineral deposits found worldwide that are uneconomic today because of their small scale and/or geometry.

Dustin Angelo, CEO and co-founder, has extensive experience in the mining industry and executive leadership as well as in start-ups and the capital markets. Dustin is passionate about leading the mining industry toward more environmentally friendly and efficient mining solutions, which is at the heart of Novamera's mission.

Shannon McCrae, Vice President of Business Development, has over 20 years of mining and exploration industry experience and numerous leadership roles. Shannon is a professional geologist and has worked throughout the mining and exploration value chain.



 **Dustin Angelo**



 **Shannon McCrae**

Contribution

Novamera brings a new mining method to unlock mineral resources that are currently difficult or uneconomic to mine using conventional techniques. Our proprietary navigation tools, software and methodology work in conjunction with conventional diamond core drills and modified large diameter drilling equipment to extract ore economically and in a low impact, environmentally friendly manner.

Watch their interview



“The S&A Mining Challenge has been a great experience and it's helped us connect with other mining technology companies in the ecosystem. TAD have gone beyond the challenge itself to support their partner companies.”

– Dustin Angelo, CEO

Komatsu

Company and Innovator Overview

Komatsu provides essential equipment, technologies and services for the construction, mining, forest, energy and manufacturing industries. Our global service and distributor network support customer operations using the power of data and technology to help enhance safety, productivity and performance.

Steve Styles, Product Manager (Hard Rock Mining), with over 12 years of experience managing innovative projects for underground continuous mining systems

Tony De Sousa, Hard Rock Cutting System Manager, with over 25 years of experience in design of underground mining equipment and cutting systems specific to our products.

Phil Rosenstern, Automation Manager (Hard Rock Mining), with over a decade of experience with the control and automation of underground mining equipment and processes across various applications and mining methods



 **Steve Styles**



 **Tony De Sousa**



 **Phil Rosenstern**

Contribution

Komatsu provides a transformational technology that enables the introduction of mechanical cutting to mining applications that were previously focused around traditional drill and blast methods. With this transformational technology, Komatsu provides the enabler to move towards a truly continuous operation that supports the scalable and adaptable principles at its core. This extends beyond mine planning – it makes it possible to move people further away from the hazardous areas and helps attract the workforce of the future.

Watch their interview



“The future of mining needs to be done differently if it is going to be achieved successfully.”

– Tony De Sousa, Global Manager – Hard Rock Cutting CTE

Comminution Reimagined



Professor Malcolm Powell

Company and Innovator Overview

Comminution Reimagined was established to develop step change, energy efficient comminution equipment. Specifically, providing low-energy comminution, assembled from modular units. The benefits include the flexibility from using modular units and a dramatic reduction in the required energy (<20% of conventional power requirements), allowing the use of renewable energy sources.

Malcolm Powell, founder, has over 35 years' experience in the field of comminution, with a blend of academic and applied site research, consulting, design, software and model development. He has published over 200 papers and collaborates extensively with compatriots across 5 continents within the Global Comminution Collaborative.

Contribution

Malcolm brought in the novel Comminution Reimagined equipment that is under development as a pivot in enabling a step away from conventional milling circuits. The dramatic reduction in power requirement provided an ideal hook into utilising solar power. The unique ability to rapidly ramp up and down in throughput, while maintaining product quality enabled a rethink of the circuit production and energy usage. Malcolm linked into the full mining, storage, processing production chain through process modelling and practical experience to open up new opportunities for a mine dependent on renewable energy alone.



Contributing within a stimulating and open group of multi-discipline experts was invigorating and educating, opening up future opportunities.



– Malcolm Powell, Founder

Sedgman

Company and Innovator Overview

Sedgman has been designing, constructing, and operating minerals processing plants and across various commodities and regions for over 40 years. They bring fresh thinking and leadership in technology integration, to realise plant designs ready for their clients to operate into the future.

Lyndon Ryan, Manager of Business and Project Development, has over 14 years of experience across the mining industry, flowsheet development, process design, construction and plant optimisation.

Ryan Bracey, Principal Process Consultant, has a history of process optimisation, simulation and integration of novel technologies over the previous 14 years across a range of commodities.

David Way, Manager Process Solutions, over 26 years experience in operations, R&D, M&A, project development and design across the mining value chain.

Jenny Agnew, Business Sustainability Manager, brings her diverse skillset gained across 20 years in the mining industry to lead Sedgman's sustainability team.



Lyndon Ryan



Ryan Bracey



David Way



Jenny Agnew

Contribution

Sedgman's experience in modular plant design and technology integration was integral to combining the respective cohort's contributions into a functional minerals processing value chain. Sedgman collaborated with each partner to identify the benefits they bring to a flexible system architecture, challenging conventional design assumptions. Sedgman provided input into key systems modelling assumptions and lead the overall plant design and costing.

Watch their interview



There have been a few 'a-ha!' moments where cohort members have supported each other to realise the value that their technology can add that they had not considered before.



– Jenny Agnew, Business Sustainability Manager

Sepro Mineral Systems

Company and Innovator Overview

Sepro Mineral Systems designs and builds modular systems, mobile and containerized mineral processing plants for a wide range of minerals. Complete mineral and metal recovery plants can be assembled utilizing Sepro's manufactured equipment, and are optionally designed to accommodate innovative solutions and equipment from a wide variety of vendors and subcontractors.

Andrew Gillis, Vice President at Sepro, oversees research and development activities, Sepro's intellectual property portfolio, technology commercialization, and marketing. Andrew holds a PhD in Mining and Mineral Processing from the University of British Columbia, an MBA from Simon Fraser University and is a registered Professional Engineer.



Andrew Gillis

Contribution

Andrew brought 2 key elements to the Scalable & Adaptable cohort. First, Sepro's experience developing mobile and modular mineral processing plants. Sepro has been working in this area for over 15 years, deploying equipment and processes in a modular way that can be used for small scale and early stage projects or for pilot plant demonstrations. Secondly, Andrew contributed four years of independent research via a recent PhD thesis identifying what goes wrong in mining projects (e.g., metal price and ore variability, ground conditions) and how to manage these negative surprises.

Watch their interview



“ Its a great opportunity to work with lots of different people all over the world. I've made connections with collaborators who I have been in contact with outside of TAD regarding other innovative projects & ideas. ”

– Andrew Gillis, Vice President

JUWI

Company and Innovator Overview

JUM provides turnkey project development and further services around engineering, procurement, construction (EPC), technical and commercial operations and maintenance for renewable energy plants. For this challenge, their focus was in testing their modular, deployable solar photovoltaic and microgrid solutions.

David Manning, Managing Director at JUWI, is focused on pursuing mining projects that combine solar, wind and batteries with thermal power stations or the grid. This includes overseeing the installation and operation of hybrid installations worldwide, with Africa and Australia being the prime focus regions.

Tom Littlechild, Hybrid Engineer at JUWI, is focused on hybrid power solutions. This includes providing technical advice to suppliers and project stakeholders to ensure the best design can be achieved.



David Manning



Tom Littlechild

Contribution

Juwi provided real time data and results from several projects completed several years ago. The juwi engineering team provided input into the design parameters, and assisted with cost analysis. The team also provided guidance into the type of technology available, and what could be possible in the coming years.

Watch their interview



“ This was like a dream come true for our design engineers. The team found almost all of the answers we had been searching for. It was a change in the mindset and a different approach to production. ”

– David Manning, Managing Director

EnergyFlex




Garry Harding




Craig Phasey




Taylor Woods

Company and Innovator Overview

EnergyFlex developed Energy Value Proposition (EVP) to understand the impact of variable energy on operations, and act as the measure of trapped energy value that can be realised when constant operations become fully flexible. EVP provides a lever to monetise the energy value of flexible industrial production, and carbon reduction.

Garry Harding leads EnergyFlex with a passion to create a sovereign capability to simultaneously fix the energy grid and environment.

Craig Phasey is focused on energy transformation i.e. bridging the gap between a fossil-fuel based economy to a renewables based economy.

Taylor Woods envisions a world where technology led innovation drives sustainable, and economic energy stability. into the future.

Contribution

EnergyFlex have challenged the S&A cohort to consider the ongoing viability, and carbon footprint, of continuous mining operations under a wholly renewable's based energy system. To quantify this approach, focussed on industrial flexibility, EnergyFlex introduced EVP to assess, monetise and manage the impact of variable energy supply on constant operations. Throughout the challenge, EnergyFlex helped iterate the energy/operations interaction so that the mine could reliably and profitably operate within the renewable's energy envelope.

Watch their interview



“ The highlight has been the opportunity to collaborate with the cohort and with OZ Minerals. As systems integrators, having access to such a broad set of experts has been outstanding. ”

– Craig Phasey, Solutions Lead

Mathworks

Challenge Support




Wilco Volwerk

Company and Innovator Overview

MathWorks is the leading developer of mathematical computing software including MATLAB and Simulink. Engineers and scientists worldwide rely on MathWorks to accelerate the pace of discovery, innovation, & development.

Wilco Volwerk, Energy and Mining Industry Manager for MathWorks Australia. He has been with MathWorks for over 20 years, working with customers in a variety of industries.

Peter Brady, Senior Application Engineer at MathWorks Australia. Since joining in 2019, he strives to accelerate our customers' engineering and scientific computing workflows across maths, statistics and machine learning.

Ruth-Anne Marchant, Engineering Manager at MathWorks Australia. Since joining MathWorks in 2015 her focus is on supporting customers adopt Model-Based Design with Simulink.

Contribution

MathWorks supported Inspire Resources through regular, collaborative sessions with MathWorks product specialists to uplift and enhance the team in their delivery of the Mining Simulation Framework. This included detailed advice on code and tools, through to conceptual simulation approaches via requirements analysis. As the project progressed to completion we also collaborated on cloud scale-up to enable the required parameter sweeps. We are excited that our support allowed to see this simulation through to delivery.

“ It has been a pleasure to support Inspire Resources and to see how a group of mine suppliers came together as one to build a whole-system mine model. ”

– Wilco Volwerk, Energy and Mining Industry Manager



Appendix



A1 | Disclaimer & References



A.1 | Disclaimer & References

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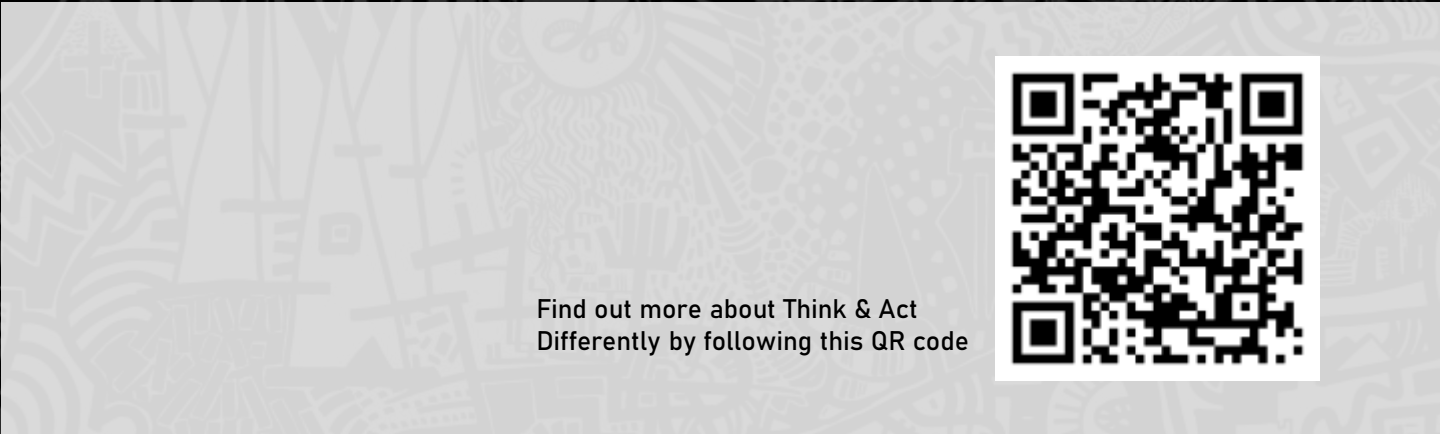
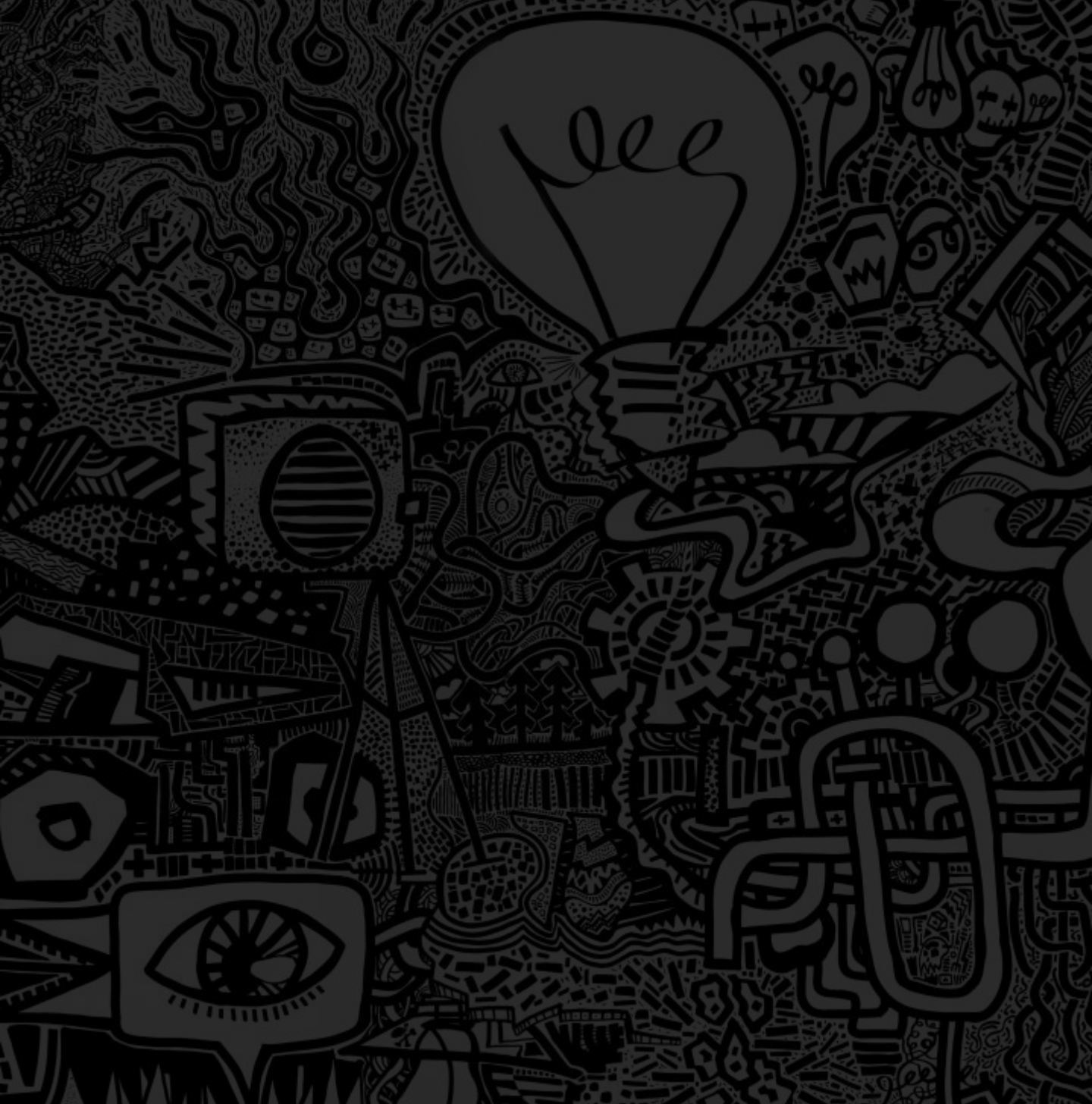
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