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SAIMM

THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

VOLUME 121 NO. 12 DECEMBER 2021


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More research and funding needed for mineral processing

Mining is essential to our life on Earth, but our mineral resources are not renewable and are being depleted rapidly. We will need to recycle more and more minerals and move towards a circular mining economy, in order to meet future demand. This is easy to state but very difficult to achieve in practice, and will need global coordination in a world where we are sadly becoming more polarized and radical.

It is well known that mineable mineral deposits are becoming deeper, more remote, and with lower grades. On the positive side the 4th and 5th Industrial Revolutions will benefit the mining industry the most as we design, build, and operate in 'naturally variable and failed' material (rock). Real-time monitoring, automation, artificial intelligence, and robotics will help make mines much safer as people will be removed from the advanced faces, and much more productive. The skills levels required will also increase dramatically as the mining industry will need computer scientists, mechatronic engineers, instrumentation designers, and technicians to name just a few. Cyber-security will become absolutely essential due to the potential dangers of robotic equipment being hacked.

The resolutions and emission goals for 2030 and 2050 proposed at the recent Conference of the Parties (COP 26) in Glasgow, Scotland, while essential for the global environment, will enormously increase the demand for mainly battery minerals such as copper, nickel, lithium, and graphite. No consideration has been given to how these demands will be met, and the lead time for new mines is 5 to 10 years at least.

Considerable research is being undertaken in the fields of 'green' and 'smart' mining, but I believe that not enough is being done in the field of mineral processing. Specialized metallurgical engineering programmes are being closed globally and absorbed into mainly chemical engineering programmes. This makes financial sense due to low enrolments in metallurgy programmes, but specific and focused courses are essential for at least postgraduate studies and upskilling.

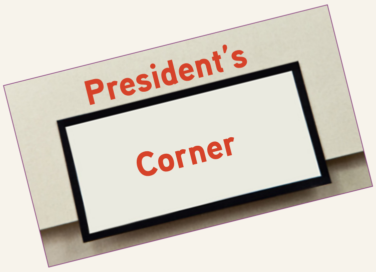
Research areas that I think need more research and implementation include:

- *Grade control* (geometallurgy) – the benefits can be achieved in the short term and can have an immediate effect on most metal mines. It is strange that few mines have investigated the potential real benefits of this.
- *Urban mining* – specifically of electronic devices, in which the gold and rare earth grades are higher than most orebodies. This also carries significant environmental benefits.
- *Water conservation and protection* – reducing fresh water use is essential and can be achieved by more recycling, lower tonnages processed, and the development of less water-intensive processes.
- *Dry processing* – water is a scarce resource and mining competes with other industries, agriculture, and domestic use. Is an important research field that is not a simple task, but should be an area of research focus due to the massive benefits.
- *Energy conservation* – mines are traditionally energy-intensive, especially for ore comminution. Efforts must be made to reduce total energy consumption and use more green energy.
- *Waste reduction and repurposing on surface* – mining produces the largest amount of waste of any industry, and this must be significantly reduced. This can be achieved by maximizing backfilling underground and trying to repurpose the remainder of the waste.

Most of the above are obviously interrelated.

For the mining industry to succeed and help meet the demands of society, more investment into processing is required. International research cooperation is also vital as it tends to generate solutions faster, more efficiently, and at a lower cost.

Prof A.J.S. (Sam) Spearing
School of Mines China University of Mining & Technology



Capaci occasio

Nurturing the future leaders of Southern Africa's mineral's industry is one of the key pillars of the Institute's value proposition and it is understandably highlighted in the opening statements of the new SAIMM brochure[1]. The sentiments and the purpose statements encapsulated in the brochure are the outcome of an intense period of introspection. This self-analysis was sparked by financial sustainability concerns, dwindling volunteerism and participation by members in committees and on organizing committees for technical events, and while there has not been a mass exodus, membership numbers have stagnated, with fewer employers sponsoring individual professionals to join the Institute.

The SAIMM's office team has adapted methods, implementing numerous changes to the internal structure and workings of the Institute, and in response to the impact of the pandemic, shifted completely to a remote working model. But a change in tactics requires more than just polishing the silver, and in this context, the Institute is refocusing on maximizing the value to our membership. And, of course, being financially sustainable, and relevant in fast-changing times.

Although many things have changed over the past few decades, and most particularly the past two years, the need for professional development remains a constant. Throughout this period of reflection, the Institute's purpose has withstood, and is withstanding, the test of time. A glance at the SAIMM's coat-of-arms reminds us of the SAIMM motto, *Capaci occasio* which means '*To the capable the opportunity*'. Therefore, developing and nurturing capable leaders for the minerals industry, because the capable create opportunities, is still one of the key pillars of the SAIMM's purpose. The coat-of-arms, which was adopted in 1965, has become closely associated with the SAIMM brand of professionalism and quality technical events, and the motto is probably more relevant today than ever and is entrenched in what the Institute delivers.

As an Institute, we have emerged with a renewed focus on the core of our existence, strongly underpinned by our history, and the capabilities to deliver on this core purpose. The rapid increase and availability of digital content has created a smorgasbord of options for all. We are flooded with digital content, a trend that accelerated throughout the pandemic. It is also common knowledge that the global mining and minerals community is facing a retirement tsunami, as people with decades worth of expertise wind down their professional activities.

When we think about professional development and growth, it is often in terms of continuing education, job-related skills, or job responsibilities, but we don't necessarily associate professional development with volunteerism. You may think of volunteerism as one more thing you need to juggle in a busy schedule. But volunteerism can provide personal growth, satisfaction, learning opportunities, development of new skill sets, professional and ethical development, and through volunteer activities one can build a new group of friends or colleagues. The SAIMM is at its core a voluntary association of professionals, that exists for our members, through our members, and acts as a vehicle through which members can share knowledge and enable professional development. The SAIMM only exists because of our membership.

As we near the end of another tumultuous year, it is a good time to reflect on the year ahead and how we plan to spend our valuable time. With these thoughts in mind, the definition of volunteerism is quite powerful, and inspiring.

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[1]The link to the SAIMM brochure is https://saimm.co.za/news

President's Corner *(Continued)*

Volunteering is a form of helping in which people actively seek out opportunities, and involves making considerable ongoing commitments to sustain these involvements over extended periods, often at a considerable personal cost, usually time. Volunteering is not the same as helping though. Helping occurs spontaneously in response to an emergency or unwelcome situation, while volunteering requires seeking out opportunities to help. Finally, and this is the aspect that perhaps makes volunteerism particularly powerful at the personal growth level, volunteers typically do not know those they help in advance and have no prior bonds of obligation to help them.

Volunteerism is an act of giving towards a greater cause.

Volunteering is not a one-way street. Through active involvement in voluntary associations, the volunteer also gains from this process. In the SAIMM, volunteering enhances the value of your membership while your time and efforts help others. The feedback loop is positive and personal and professional growth follows. Young or established professionals find that they stay up to date with developments in their industry by being involved in technical events or reviewing papers. As we engage in these types of activities we constantly add to our continued professional development. For some, their involvement with Institute matters leads to new opportunities, and even new career paths; but, most importantly, professionals, through volunteering, build their formal and informal networks, which in turn strengthen their professional capacity.

The formal and informal relationships built through active involvement in a voluntary activity contribute to a healthy society and healthy individuals living in such a society do better in moving forward to meet common aspirations. Many volunteers do it to give something back ('paying it forward') to their profession, especially since someone did it for them earlier in their careers. Volunteer activities can range from serving as a moderator on a webinar session to being an officer of the Institute through Council and Office Bearers. Volunteers could be involved as committee members, serving as committee chair, acting as a liaison with another professional organization, reviewing papers for the Journal, judging student presentations, facilitating panels at technical events, or presenting a webinar or technical talk at a branch meeting. The volunteering opportunities are numerous, and each small act contributes towards the development of capable professionals and a sustainable Institute. The SAIMM is a living institute, and member involvement is the fertile ground in which the Institute and the members flourish.

In conclusion, while any organization ought to be introspective and sharpen its tools, an entity such as the SAIMM relies on membership for content and direction, and growth. It is easily overlooked that the SAIMM can exist only if members are willing to volunteer their precious skills and time in an act of giving towards the greater good of the mining and metallurgy industry.

In the coming year, may the SAIMM and our members find a new and stable footing in a world, where predicting the next wave has nothing to do with surfing. May all our members have a safe and restorative holiday season this summer.

May the road of opportunity rise to meet you in 2022.

I.J. Geldenhuys
President, SAIMM

Effects of *Searsia lancea* hydrochar inclusion on the mechanical properties of hydrochar/discard coal pellets

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Synopsis

The utilization of biomass as a solid fuel for co-firing has received great attention from boiler manufacturers as a clean coal technology (CCT) option. This research aimed to produce biocoal pellets, as a clean energy fuel, using hydrochar from trees planted to rehabilitate acid mine drainage (AMD) water and fine coal discards. The hydrochar was synthesized by hydrothermal carbonization of *Searsia lancea* harvested from AMD-contaminated land at a temperature of 280°C and a residence time of 90 minutes. It was blended with discard coal (–1 mm) at ratios of 25% and 50% hydrochar to produce different forms of solid pelletized biocoal (BC). The physicochemical and mechanical properties of each of the biocoal pellet blends were determined. The 100% hydrochar had the highest calorific value of 29.99 MJ/kg, while the raw discard coal had a calorific value of 16.73 MJ/kg. The ash content decreased from 42% in the discard coal to 25% in the blend of 50% coal and 50% hydrochar biocoal pellets. Biocoal pellets comprising 25% hydrochar and 75% discard coal ($BC_{25\ HC/75\ COAL}$) displayed the best mechanical properties (compressive strength 3.06 MPa) of all the fuels, but the physicochemical properties were inferior to the $BC_{50\ HC/50}$ COAL pellets. This research has demonstrated that hydrochar synthesized from a tree species planted for hydraulic control of AMD has the capability to act as a binder for improving the mechanical properties and energy characteristics of fine discard coal.

Keywords

acid mine drainwwage, co-fired feedstock, discard coal, hydrochar, hydrothermal carbonization, pellets, *Searsia lancea*.

Introduction

The world population in 2017 was estimated to be around 7.3 billion and is projected to increase to 10.5 billion by the year 2040 (EIA, 2016; Saba, Sha, and Reza, 2017). Security of global energy supply is an absolute necessity for sustaining modern life because of the increasing demographic and socioeconomic needs of developing countries. The increase in human population will inevitably require an increase in energy production, necessitating more fossil fuels and biomass to be added to the global energy mix.

The South African energy landscape is still largely based on fossil fuel. That is, the economy still relies heavily on coal for power generation, and its contribution to the total South Africa's energy mix is expected to be 59% till 2030 (Department of Energy, 2018). However, there is a public outcry regarding the increasing emissions from some of the power plants in the country, which are due to the poorer quality of the coal being utilized. Since South Africa is now obliged to use its remaining low-grade coal, the use of biomass as a clean co-fired fuel is an attractive option for use in these power plants in order to meet the stipulated emission standards. The utilization of biomass and refuse-derived fuels (RDF) for co-firing has received great attention from researchers and boiler manufacturers as a clean coal technology (CCT) option worldwide (Rousset *et al*, 2011; Kerina, and Bada 2020). Such products are seen as potential alternative renewable energy sources for electricity generation, with low emissions and low ash contents among other beneficial fuel characteristics (Teixeira *et al*, 2012; Ndou, Bada, and Falcon, 2020).

The continued use of coal depends primarily on (i) advances in CCT with specific respect to the reduction in greenhouse gases (GHG), as well as (ii) answers to allied factors such as the use of coal discard and refuse dumps, low water usage, and management of acid mine drainage (AMD). Gaqa and Watts, (2018) reported that at present, South African energy and liquid fuels are produced primarily from bituminous coal; however, the quality of coals for these applications is rapidly deteriorating and no plan is in place for the use of the abundant discard coal available in the country. Nearly 100% of the fines generated during mining and beneficiation discards from washing plants) is stored in long-term dumps (Bada *et al*., 2016). Well over 2 billion tons of discarded coal of various grades has accumulated in South Africa due to the lack of practical and feasible methods to use this resource, either as sole products or as co-fired fuel in existing power plants. This research seeks to demonstrate that pelletized hydrochar-infused biocoal ('hydrochar/coal blend') can be produced as a new solid fuel for use in existing coal-fired power plants.

In this study, a new solid pelletized fuel was produced by mixing different parts from *Searsia lancea*, a Southern African indigenous semi-hardwood tree, and fine discard coal. *Searsia lancea* is one of the tree species planted in the woodlands project for phytoremediation and control of groundwater pollution from gold and uranium mine tailings dams in southern Africa (Weiersbye, 2007; Botha and Weiersbye, 2010). The woodlands project is part of a mine closure plan for the control of AMD, but there was concern regarding the harvesting of these trees after maturity as firewood by the community. This would undermine the potential of these trees as an alternative energy source. A recent study (Ndou *et al*., 2020) has demonstrated that *Searsia lancea* and discard coal could be co-fired. The authors showed that the raw *Searsia lancea* biomass has a higher combustible reactivity than coal, and the addition of Tamarix usneoides biomass to coal resulted in reduced NO_X and CO_2 emissions.

In the current project, further investigations were undertaken through the process of hydrothermal carbonization (HTC) of this tree species. The aim was to improve the energy content of this biomaterial by producing pellets containing different ratios of hydrochar and biocoal. According to previous reports, HTC enhances the plasticity of biomass (Kudo *et al*., 2014) and promotes particle coalescence or fusion during the briquetting of such biomass. The process has also been found to remove highly volatile cellulosic material, *i.e*. cellulose and hemicellulose, thereby converting the biomass into a solid that is composed mainly of lignin (Kudo *et al*., 2014). The lignin present in the raw biomass can be recovered and used as the binder for different hydrochar and fine coal pellet products. In this investigation, *Searsia lancea* was used as the HTC binder for pelletizing typical high-inertinite, low-grade South African fine coal, and the physiochemical and mechanical properties of the pellets were assessed.

Materials and methods

Materials and sample preparation

The biomass utilized in this study was obtained from *Searsia lancea* trees planted in 2003 and 2004 for phytoremediation trials on a groundwater-polluted gold and uranium tailings dam at the AngloGold Ashanti Limited West Wits and Vaal River mine in South Africa. The biomass materials from *Searsia lancea* (trees S11 and S12) included leaves, twigs, wood, dead wood, stump, root ball (coarse root), and root (fine-medium root). The different materials were milled in a Retsch SM 200 mill to –1 mm and –212 µm size fractions. The –1 mm fractions were subjected to hydrothermal carbonization while the –212 µm fractions were analysed for physicochemical characterization. The combination of tree sections from two trees (S11 and S12) from the same trial site for producing hydrochar was based on the ash content of the individual compartments.. The coal used was fine coal discard obtained from a coalfield in the Mpumalanga Highveld.

Analytical techniques

Proximate analyses were conducted on all samples in accordance with ASTM D-5142, with approximately 1 g used for determining the inherent moisture, ash content, and volatile matter present. The fixed carbon content for all samples is expressed as 100% – (ash content + volatile matter + moisture content). The calorific value was determined on all samples using a Leco AC 500 calorimeter in accordance with ASTM D5865-04.

Hydrochar production and pelletization

Hydrochars were produced in a laboratory-scale high-pressure stirred Berghof BR-1500 reactor. For each experiment, 100 g of air-dried biomass was mixed with 800 ml of deionized water and fed into the stainless-steel vessel. The vessel contents were then purged using argon gas at an initial pressure of 20 bar for each run, followed by agitation of the mixture at 200 r/min for the full length of the test. After each test, the hydrochar slurry was filtered and oven-dried at 105°C for 24 hours, and then stored in plastic containers for characterization tests. The BC pellets were produced by blending hydrochar and discard coal at ratios of 25% to 75% and 50% to 50%. The samples were mixed using a Kenwood type KVL40 (Chef XL) mixer. The mixer was first run empty, then the hydrochar was slowly added. This was done to break up the lumps that formed during the drying stages of hydrochar formation. After the hydrochar lumps had disintegrated, the required amount of discard coal fines was added and the mixture was then blended for five minutes. The blended samples were formed into pellets using a Specac manual hydraulic laboratory pellet press. All the pellets produced at the two different blending ratios were subjected to proximate analysis, calorific value, and various mechanical tests. The results obtained from the combustion and chemical elemental composition of the pellet samples were reported previously (Setsepu *et al*., 2021).

Compressive resistance

The compressive resistance of the pellets was determined following ISO 4700:2007 (E), which stipulates a method that measures the compressive load attained before breakage of the pellets. A load cell of 1000 N was used as the maximum load for the crushing of the pellets. Initially, the pellets were placed flat onto the crushing surface of the compression machine and the load cell applied. However, it was found that this method simply densified the pellets rather than crushing them. Hence, all pellets tested in the study were placed on the side and subjected to the crushing force while aligned. The compressive strength of the pellet was calculated using Equation [1]:

$$\sigma = \frac{2F}{\pi d l} \qquad [1]$$

where F represents the maximum compressive force, d and l represent the diameter and length of the pellet respectively, and σ is the compressive strength.

Impact resistance index

The drop durability method employed in this study is a slight variation on that used by Kambo and Dutta, (2014), who applied the impact resistance test to densified and pre-treated *Miscanthus* feedstock. In this study, the drop durability of the samples was determined by first taking the mass of each pellet, then dropping it onto a steel plate from a height of 1.0 m, and then weighing the resulting pellet. The impact resistance index (IRI) was calculated according to Equation [2].

$$\%\ weight\ loss = \left(\frac{Initial\ mass - Final\ mass\ after\ 10\ drops}{Initial\ mass}\right) \times 100 \qquad [2]$$

Water resistance index

The moisture uptake or water resistance index was determined by submerging the pellet in a 200 ml container filled with tap water. The pellet was weighed and the mass recorded as the initial mass. The pellet was then placed inside a metal basket which was immersed in tap water for 30 minutes. At the end of the submersion period, the pellet was removed and placed on a paper towel to air out the surface moisture for 2 minutes before taking the final mass. The moisture uptake was determined according to Equation [3]:

$$\%\ Moisture\ Uptake = \left(\frac{Final\ mass - Initial\ mass}{Initial\ mass}\right) \times 100 \qquad [3]$$

After the moisture uptake test was completed, a water resistance index (Equation [4] was determined using the results from Equation [3] as follows:

$$WRI = 100 - Mass\ \%\ of\ water\ after\ 30\ minutes \qquad [4]$$

According to Richards (1990), a WRI greater than 95% should be obtained after 30 minutes. This figure is used as the standard for comparisons.

Results and discussion

Physicochemical characterization

The proximate analyses and calorific value results obtained from the discard coal, hydrochar, and biocoal pellets are presented in Figure 1. The discard coal had an ash content of about 42%. This high percentage is due to the inorganic minerals in the coal reporting to this fraction after beneficiation, with the clean fraction composed of the organic component. The increase in the percentage of incombustible minerals in the biocoal will lead to a delay in the ignition of the product and reduce its quality. The biocoals made from the blend of 50% hydrochar and 50% coal are denoted as ($BC_{50\ HC/50\ C}$), whereas the 25% hydrochar and 75% coal blend is denoted as $BC_{25\ HC/75\ C}$. The ash contents in the pellets were found to be considerably lower than that of the discard coal, being 35% and 25% respectively for $BC_{25\ HC/75\ C}$ and $BC_{50\ HC/50\ C}$ pellets. The 100% hydrochar possessed the lowest ash content (3%) and the highest total moisture (10%), as expected. Furthermore, as the percentage of the hydrochar in the blend increased, fixed carbon also increased; with the 100% hydrochar having the highest fixed carbon content because of the sample's almost pure, coal-derived carbon-rich nature. As has been shown by Bada *et al*. (2018) and Zhu *et al.* (2018), thermal treatment and HC of plant-derived biomass results in the restructuring, modification, and concentration of the aromatic carbon molecules, thereby increasing the fixed carbon and calorific values of the heat-treated hydrocarbon products.

Regarding the commercial value of the products, an increase in the percentage of hydrochar added to discard fine coal resulted in an increase in the product's commercial grade. The pure discard fine coal is categorized as commercial Grade D3 with a calorific value of 16.73 MJ/kg, whereas the hydrochar presents with a calorific value of over 29 MJ/kg. By increasing the hydrochar proportion in the mix to 50%, the pellet's grade increases to commercial Grade C (25.5 to 26.5 MJ/kg for the $BC_{50\ HC/50\ C}$ pellets. In accordance with the South African coal classification standard, solid fuels with calorific values of over 28.5 MJ/kg are considered to have the highest heating value and are classified in a category known as Special Grade Coal.

Mechanical properties

Effect of hydrochar inclusion on compression strength of pellets

The results obtained from the compression strength tests carried out on the pellets made from the 100% discard coal, 100% hydrochar, and coal/hydrochar blends at two different ratios are depicted in Figure 2. The compression strength denotes the maximum strength a pellet can withstand before shattering or disintegrating and provides an indication of the bonding strength between the hydrochar and the coal.

The hydrochar produced at 280°C at a residence time of 90 minutes with a biomass-to-water ratio of 1:8 was utilized in the strength tests. Pellets of 2 g were produced from each sample using a 20 mm die, with a higher volume of hydrochar required to meet the 2 g requirement in the 100% hydrochar sample and the blended samples. The $BC_{25\ HC/75\ C}$ sample was found to exhibit the highest compressive strength of 3.06 MPa, and the $BC_{50\ HC/50\ C}$ pellets a slightly lower compressive strength of 2.67 MPa. Both the 100% hydrochar and the discard fine coal pellets were found to have lower compressive strengths (1.71 MPa

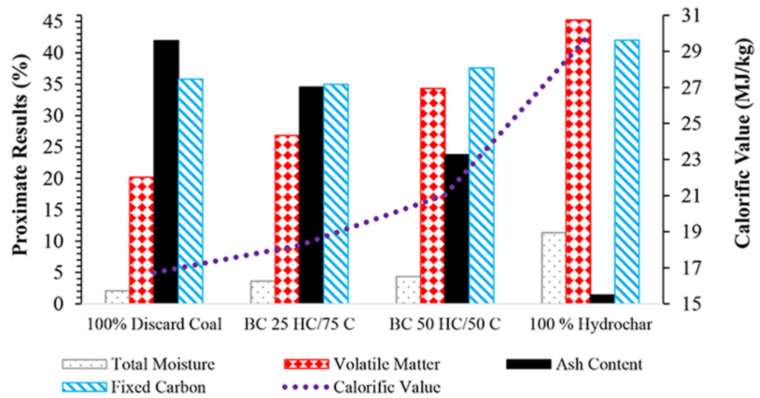


Figure 1—Physicochemical analysis results and calorific values of the discard coal, biocoal blends, and hydrochar

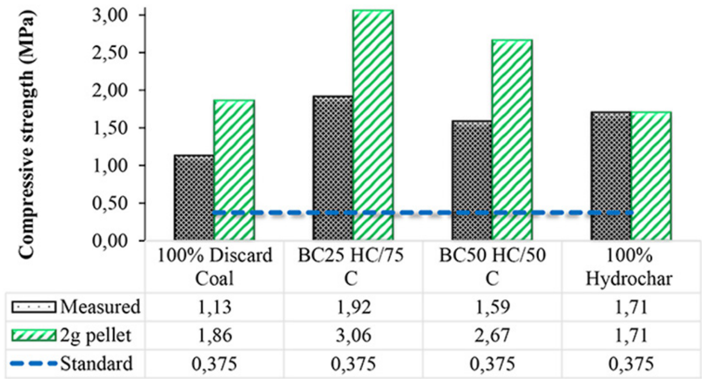


Figure 2—Effect of hydrochar inclusion on the compression strength of pellets

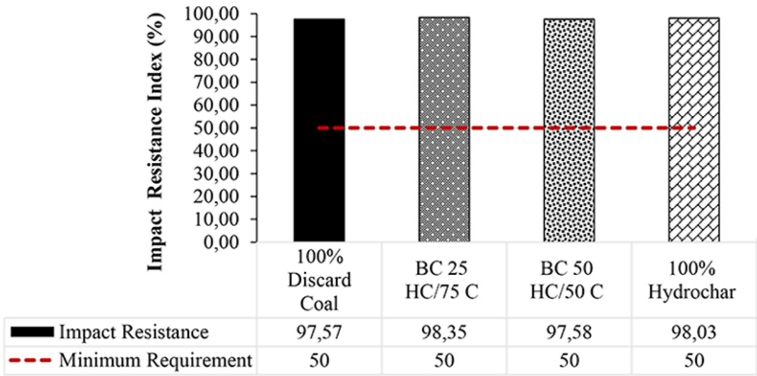


Figure 3—Effect of hydrochar inclusion on the impact resistance of pellets

for the 100% hydrochar and 1.86% MPa for the coal fines discard). On a pellet-to-pellet basis, the 2 g pellets outperformed the volume 'measured' pellets.

The high compressive strength obtained from the $BC_{25\ HC/75\ C}$ is considered to be the result of the interaction between the lignin content of the hydrochar (natural binder) and the minerals (35% ash) and organic matter (35% fixed carbon) components present in the high-ash discard fine coal utilized. In addition, fine coals are usually high in vitrinite and liberated fine clays. This attribute could aid in the softening and fusing of the hydrochar (more in $BC_{25\ HC/75\ C}$) supported by the minerals (ash) to create a strong pellet.

From these results it will be noted that all the samples tested clearly meet the standard compressive strength (0.38 MPa) required for pellet storage and handling. Although fuel with a higher ash content is not desirable for electricity generation, the results from the study suggest that for pellets with the highest compressive strength, a relatively high proportion of coal discard fines is required.

Effect of hydrochar inclusion on impact resistance of pellets

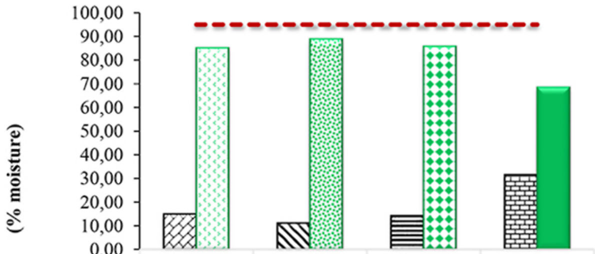
The drop durability test conducted in this study utilizes a similar method to that described by Kambo and Dutta, (2014). The samples were dropped from a height of 1.0 m onto a steel plate and the impact resistance index (IRI) determined using Equation [2]. The impact resistance durability (IRD) of all the pellets was over 97%, with the 100% hydrochar pellet reported to be 98.03% and the $BC_{25\ HC/75\ C}$ pellet slightly higher (98.35%). The results for the discard coal and sample $BC_{50\ HC/50\ C}$ were only marginally lower (both 97.5%). The similarity of the durability results for all samples indicates that all samples meet the acceptable standard for storing and handling pellets.

Effect of hydrochar inclusion on moisture resistance of pellets

The water-resistance index (WRI) is proportional to the moisture uptake by a pellet, with lower quantities of water being absorbed leading to higher WRI values. In the current investigation, the quantities of water absorbed by the pellets after immersion in water for 30 minutes varied significantly, ranging from 11.13% to 31.53% as shown in Figure 4. None of the samples met the WRI standard of 95%.

In the current investigation, sample $BC_{25\ HC/75\ C}$ absorbed the least amount of water at 11.13% and, by extension, recorded the highest WRI of 88.87 % of the four samples tested. It was also observed that the 100% discard coal pellets and the $BC_{50\ HC/50\ C}$ samples both exhibited similar and relatively higher water uptakes (14%) with marginally lower WRIs (85%), whereas the 100% hydrochar absorbed much more moisture (31%) and had the lowest WRI (68%). This sample exhibited the highest level of disintegration relative to the other three samples.

These results present an interesting phenomenon in that despite none of the samples meeting the WRI criterion, the presence of coal discard fines in the 100% discard and in both biochar-coal blend samples reduced the water uptake to a significant degree while also increasing the resistance to disintegration to an equally notable level, *i.e.*, all three- samples that contained discard coal presented relatively high WRI values of over 85%. A possible reason for the high moisture uptake and level of disintegration in the 100% hydrochar pellets lies in the potential level of porosity in the carbon structure of that material.



	100% Discard Coal	BC 25 HC/75 C	BC 50 HC/50 C	100% Hydrochar
Moisture uptake	14,90	11,13	14,23	31,53
Water Resistance Index	85,10	88,87	85,77	68,47
WRI Standard	95	95	95	95

Figure 4—Effect of hydrochar inclusion on the water resistance index of pellets

When blended with coal fines, it is likely that many of the pores and voids in the hydrochar would be filled by variety of ultrafine inorganic components (clays) in the coal sample. A further possible reason could be the fusion and/or agglomeration of mineral (ash)-hydrochar components together, thereby blocking pores and reducing the water intake. Investigation into such aspects is planned in future research.

Conclusion

The results of this investigation show that the hydrochar, as produced, is of higher quality (lower ash and higher calorific value) than the fine discard coal. It has also been shown to possess an acceptably strong binding capacity, capable of creating pellets when mixed with coal fines that possess characteristics eminently suitable for use in power generation.

Biocoal pellets with a 75% coal blend displayed better mechanical, physical, disintegration resistance, and water uptake properties than the other three forms of pellets. Furthermore, pellets of this blend also possessed chemico-physical properties and calorific values indicating that they would be an acceptable substitute fuel for Eskom coal-fired power stations using coals with ash contents ranging from 34 to 42%.

In comparison to other grades of coal products currently being sold in the South Africa marketplace (local grades B to D), the $BC_{50\ HC/50\ C}$ pellet is shown to be of equal or superior quality (Grade C). Pure hydrochar pellets are classified as Grade A in terms of calorific value and ash content.

In summary, this research has led to the production of a new biomass- and coal-based solid fuel suitable for heat and power generation, with the added advantages of:

- Lower CO_2 emissions
- A use for fine discard coal, for which no practical, economic, or feasible method of utilization has been found to date
- The opportunity to develop new skills and employment opportunities in the cultivation and manufacture of such products for those employed across the coal and fuel production and power generation value chain.

Acknowledgement

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SAMCODES NEWS (November 2021)

Please go to www.samcode.co.za to read these and other items of interest to the CP/CV/QRE communities

- **The SAMCODES Virtual Conference 2021** was successfully held over five mornings during the week of 25–29 October 2021. It included papers and presentations on Mineral Resource and Mineral Reserve aspects related to SAMREC as well as a number of presentations on mineral asset valuation. (SAMVAL). The conference was held online and attended by some 40 people on each day. The intention was to provide an opportunity for industry experts, emerging Competent Persons, and sector investors to share and explore developments in the application of the Codes, in particularly since the last conference in 2016 and the launch of the SAMREC and SAMVAL Codes in 2016. The presentations and papers certainly met this objective.
  If you missed the event, you may purchase the recordings from Camielah Jardine at camielah@saimm.co.za
- The **Annual CRIRSCO meeting** took place as a virtual event during October 2021. The written report-back will be placed on the SAMCODES website during January 2022.
  The agenda included updates from all 14 of the National Reporting Organizations. Notably, a significant amount of training is being undertaken internationally. A Code revision has been conducted by PERC and a revision is being undertaken by JORC.
  CRIRSCO was able to participate in the PDAC Conference in March when it hosted a panel discussion on the relevance of the CRIRSCO Codes. ESG continues to be an important point of discussion. No formal approach has been determined although a subcommittee has been appointed to look at the details and implications for CRIRSCO. The ICMM gave a presentation to the meeting emphasising the importance attached to transparent mineral reporting.
- The SAIMM hosted the **Mineral Project Valuation School** in late July through August – a series of three webinars with a broad range of valuation-related issues. The webinars provided attendees with insight into a range of current issues and some interesting case studies. The organizing committee, the SAIMM, and SAMCODES hope that the attendees were motivated to join in the activities of the SAMCODES (especially the SAMVAL Committee) and contribute actively to the body of knowledge in South African mining.
- The GSSA hosted a **two-day ESG Inquisition webinar** event in the second week of August 2021. The main objective of the event was to gather industry views and input regarding the potential ESG reporting requirements when disclosing Mineral Resource and Mineral Reserve estimates in Competent Persons reports and also in the annual Mineral Resource and Mineral Reserve reports published by mineral companies.
  The results of this event can be accessed at https://www.samcode.co.za/codes/category/31-general?download=271:esg-inquisition-summary-2021
  If you missed the event, you can catch up on the GSSA YouTube channel
  Day 1. https://www.youtube.com/watch?v=HAbuwYqxx2o
  Day 2. https://www.youtube.com/watch?v=jqRXJ1O7LWM
- SAMCODES have launched an App that allows one to access and search the SAMREC, SAMVAL and SAMOG Codes, the JSE Section 12 Listing Rules, as well as SAMESG and the Diamond/Precious Stones Reporting Guidelines. Download it from your preferred App Store (2022 Android version update now available).
- If you wish to view a **FREE introductory short course** (2.5 hours) on the SAMCODES presented by Professors Steven Rupprecht, please follow the link. https://youtu.be/MRlhpDBl7J8
- As of December 2021, the GSSA has put the 2020 recordings of the 4-day **Introduction to the SAMCODES and JSE Listing Requirements** course on open access. Please access these recordings at http.5s://www.youtube.com/playlist?list=PL-MPMaHidsW1Vc6ZPwCq5-e76wfQywPPt
- During July 2021, in an online event hosted by the Investment Analysts Society of South Africa (IASSA), Impala Platinum Holdings was awarded the SAMREC/IASSA Squirrel for the best Integrated Annual Report (in terms of compliance with the SAMREC Code). This is the third year in a row that Impala has won this accolade.
- There is a digital suggestion box on the home page of the SAMCODES website. Please let us know how you think we can improve our service to you and/or how to improve public reporting practices in general.
- Your contributions in terms of photos, articles, and content are welcome – please send to sam@saimm.co.za

T.R. Marshall

Risks and challenges affecting opencast pillar mining in previously mined underground bord and pillar workings

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Synopsis

South Africa is one of the leading producers and exporters of coal globally. A significant amount of the country's production is obtained from previously mined underground bord and pillar workings. This coal is in the form of pillars and remnants on the roof and floor of the old workings. The good quality coal pillars were left behind as primary support during underground bord and pillar mining operations. Due to the depletion of virgin coal reserves, the pillars and remnant coal are now removed using opencast mining rather than underground methods. However, the secondary extraction of pillars and remnant coal from the old workings using opencast methods entails some serious challenges that have a negative impact on the safety and productivity of the operations, affecting both personnel and machinery. If these risk factors and challenges are managed properly, then the opencast mining operations could remove the pillars safely at recoveries competitive with those of virgin coal operations. In this study we review the recurring challenges affecting opencast pillar mining by means of field investigations and consultations with experts at five opencast pillar mining operations, and evaluate the best practices used to combat these challenges. It was found that each mine has its own unique conditions and challenges.

Keywords

opencast pillar mining, spontaneous combustion, bord collapse, bord and pillar collapse, bord voids, sinkholes.

Introduction

Coal was discovered and first mined in South Africa in the 1850s and continues to play a critical role in today's economy and energy supply (Hanconx and Gotz, 2014). According to the Energy Information Administration (2020) and Schernikau (2010), coal will remain a key global economic driver for some years to come. The demand for coal is expected to increase at least until the 2040s, especially in emerging economies such as India and China. During the early years of coal mining, over 90% of South Africa's coal was produced by underground bord and pillar mining (Figure 1) (Mohutsiwa and Musingwini, 2015). However, one of the biggest disadvantages of this method is its relatively low extraction ratio – an average of just less than 50% across all collieries in South Africa (Madden *et al*., 1995). A higher extraction ratio is possible in the case of smaller pillars, but these have a low factor of safety (Wagner, 1980). With increased pillar dimensions, the extraction ratio in bord and pillar mines can be as low as 36%, as shown in Table I.

In bord and pillar mining, a valuable amount of coal is left behind in standing pillars as primary support. According to van der Merwe and Mathey (2013), up to 9.55 Gt of coal has been mined in South Africa, of which approximately 53% came from bord and pillar mines. Moolman and Canbulat (2003) assert that approximately 1.1 Gt of potentially mineable pillar coal remains in the ground in the form of remnant pillars, mostly from mining operations dating to between 1970 and 1997. The amount of coal left behind continues to increase at a rate of 110 Mt per year. In 2003, the total number of pillars left underground was estimated to be over 1.7 million since 1970 (Moolman and Canbulat, 2003). In 1996, between 100 000 and 150 000 intact pillars were formed during bord and pillar mining operations (Madden, Canbulat, and York, 1998), and this figure has been estimated at 3 million by 2006 (van der Merwe, 2006).

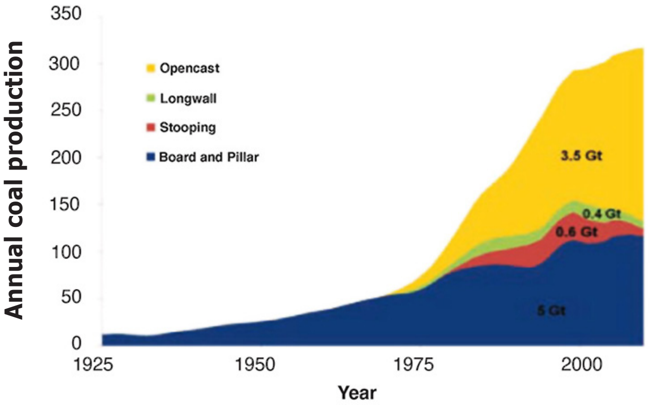

Figure 1—Coal production in South Africa by different mining methods (van der Merwe and Mathey, 2013)

Table I

Relationship between pillar size and extraction ratio

Pillar width (m)	7	9	13	15	18	28
Extraction ratio (%)	75	68	58	53	48	36
Average depth (m)	50	80	120	130	160	180

According to Moolman and Canbulat (2003), only pillars with a safety factor of at least 1.8 can be safely extracted using underground methods. Nonetheless, greater safety risks and low recovery rates are among the disadvantage of sunderground pillar extraction methods. Furthermore, the secondary extraction of old pillars using underground mining methods can be constrained by geotechnical, geological, environmental, and economic factors. Extracting old pillars which have reduced in size due to spalling and deteriorated in strength is more difficult than the extraction of newer pillars.

Due to the safety concerns and low recovery rates associated with underground pillar extraction, opencast pillar mining became a viable option. This method has also been extensively used in countries such as India (Panigrahi, Sinha, and Singh, 2013; Mahto, 2015). In this study, it has been shown that opencast pillar mining operations can compete with virgin coal operations (Table II).

The secondary extraction of pillars from previously mined underground bord and pillar operations dates back to the early 1990s. However, opencast pillar mining is a complex method and entails multiple challenges compared to virgin coal mining, which can adversely affect the process if control measures are not properly implemented (Clough and Morris, 1985; Laybourne and Watts, 1990). Nonetheless, opencast pillar mining has been preferred over underground pillar extraction due to the safer working environment, higher extraction and recovery rates, flexibility, reduced coal losses, and increased productivity of surface methods. Figure 2 shows the layout of a typical opencast pillar mining operation:

Despite its complex challenges and difficulties, opencast pillar mining is expected to play a critical role in the supply of coal due to the good quality coal in standing pillars remaining underground (Ngwenyama, de Graaf, and Preis, 2017). This is due to the fact that virgin coal reserves in South Africa have continued to diminish and are nearing depletion (Hartnady, 2010). The effective utilization of pillar coal reserves in previously mined areas is therefore required (Schalekamp, 2006; Ngwenyama, de Graaf, and Preis, 2017). The purpose of this study was to identify the major challenges and risks associated with opencast pillar mining in order to improve the effective utilization of coal reserves remaining in pillars and remnant coal.

Field investigations

This study was conducted through field investigations and consultations with mining experts from five opencast pillar mining operations. These operations together produce an average of 60 Mt good quality coal per annum for both the export and domestic markets. Table II gives some production details for the five operations.

Risks and challenges affecting opencast pillar mining

Opencast pillar mining has been practiced since the early 1990s in South Africa, and earlier than this in other countries such as Scotland. However, despite all efforts to improve the process, this method is still experiencing continued and unresolved challenges which are detrimental to production, productivity, and health and safety. Through the field investigations, this study was able to identify the major challenges encountered during opencast pillar mining, and review the recurring challenges and best practices among the mines facing similar conditions.

Lack of information on the old workings

One of the biggest risk factors in opencast pillar mining is the paucity of information regarding the state of the old pillars and the general conditions of the workings. In some of the mines visited, it was found that information regarding the old

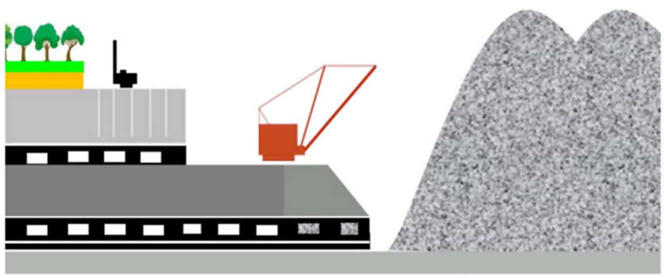

Figure 2—Typical layout of an opencast pillar mining operation

Table II

Opencast pillar mining operations visited during field investigations

Mine	U/G mining start date	OPM start date	Mining method	Waste removal equipment	Coal extraction equipment	ROM production (Mt/a)
A	1890s	2015	Bench mining	Truck and shovel	Excavator and trucks	3.9
B	1890s	1980's	Double bench	Dragline	Truck and shovel	19
C	920s	1990's	Strip mining	Dragline	Truck and shovel	7
D	1950s	2000's	Double bench	Dragline and truck-and-shovels	Front end loader and trucks	16
E	1940s	1990's	Strip mining	Dragline	Truck and shovel	12.5

workings is not available or only partially understood. The partially available information is extrapolated from old mine plans, which are less accurate than modern plans. This is because the old mine plans were constructed manually due to the lack of advanced survey technology at the time. The unavailable or partially known information includes the exact positions of the pillars, their centres, pillar dimensions, bord width, and roof undulation and thickness. To overcome this challenge, Govender (2018) conducted a study to evaluate techniques that can identify underground coal pillars from surface. A cavity auto-scanning laser system was found to be effective in determining sufficient information about the pillars in the old workings. The risk factors associated with old workings across the visited mines are evaluated in Table III.

Spontaneous combustion and its control measures

Spontaneous combustion is one of the most common challenges experienced across all the opencast pillar mines visited. Although the risk may differ in magnitude from mine to mine, it is still an ongoing and unresolved problem. One of the biggest risks of spontaneous combustion is premature detonation of blasts, which can easily result in multiple fatalities and/or damage to equipment. Extensive research pertaining to spontaneous combustion has been conducted (Eroglu, 1999; Eroglu, Uludag, and Thyse, 2002; Stenzel, 2002; Eroglu and Moolman, 2003; Phillips, Uludag, and Chabedi, 2011; Genc and Cook, 2015; Gemmell, 2016). Spontaneous combustion is common not only in South African mines, but across the world in countries such as India and the USA (Panigrahi, Sinha, and Singh, 2013; Sloss, 2015). Several techniques have been developed to minimize and potentially mitigate the effects of spontaneous combustion. Some of these techniques and their advantages are described in Table IV.

The spontaneous combustion combating techniques in Table IV have a common goal, which is to eliminate at least one of the three constituents of the 'fire triangle'; namely fuel, heat, and oxygen. Spontaneous combustion cannot occur when one (or more) of these constituents is absent. Some of the spontaneous combustion control techniques have proven to be effective and are used extensively in the mines, while some have not. Different mines have their own preferred techniques. The selection of

Table III

Risk factors due to the unavailability of information regarding the old workings

Risk factor	Mine A	Mine B	Mine C	Mine D	Mine E
Exact positions of pillars known	No	No	No	No	No
Sizes and shapes of pillars known	No	No	No	No	No
Pillar centres known	No	No	No	No	No
Pillars still intact in the old workings	Yes	Yes	Yes	Yes	Yes
Pillar scaling has occurred	Yes	Yes	Yes	Yes	Yes
Thickness of roof coal known	No	No	No	No	No
Undulation of seam known	No	Yes	No	No	No
Pillars are robbed or semi/fully collapsed	Yes	No	No	Yes	Yes
Pillar strength has decreased	Yes	Yes	Yes	Yes	Yes
Cave-ins have occurred in the old workings	No	No	Yes	No	Yes
Tramp material in the old workings	Yes	Yes	Yes	Yes	Yes
Excessive water in the old workings	No	Yes	No	Yes	Yes

Table IV

Techniques for mitigating or minimizing spontaneous combustion

Technique	Description and advantages
Cooling agents	Cooling agents are chemical substances used with water to reduce the temperature of hot holes to workable levels. Holes less than 40°C are charged as normal. Holes between 40 and 60°C are treated to reduce the temperature to 40°C or less before charging, and holes 80°C or more are closed off immediately.
Sealing agents	This method is used to prevent coal from coming into contact with air. Materials such as calcium chloride and bentonite are used to coat the coal surface exposed to air.
Inert gas	Used to flush combustible gases. This technique is not economically viable for most mines.
Water cannons	Highwalls exposed to the surface are sprayed with high-pressure water using water cannons. Only the fires exposed are extinguished, while internal combustion may continue.
Drill diameter	Air was found to be penetrating into the old workings through drilled holes. Reducing the drill diameter is one way of reducing the amount of air entering the old workings, in conjunction with sealing off where possible.
Buffer blasting	Sufficient explosive energy is used to heave the overburden such that the blast collapses the pillars. This allows the underground voids to be sealed off, preventing the ingress of air.
Cladding	Overburden or topsoil material is pushed over highwalls to prevent air from entering the old workings. This technique is effective in sealing off highwall voids, but may result in increased dilution.
Buttress blasting	Cast blasting is used to seal off voids in the highwalls. This technique requires sufficient explosive energy to cast the blast and may also result in dilution and re-handling of material.
Bord-only collapse	Only the overburden is blasted, with the old workings being preserved. The blasted overburden is allowed to collapse the roof coal and fill the bord voids. This prevents air from entering the old workings.
Bord and pillar collapse	The overburden and pillars are blasted simultaneously. The presence of voids is reduced by the pillars falling into the bord voids. This technique reduces the occurrence of sinkholes and prevents dilution

a technique is influenced by the unique conditions of the old workings at that specific operation. Table V and Figure 3 show the usage of the spontaneous combustion combating techniques by the opencast pillar mining operations. This gives an indication of which of the techniques are more effective and practical to implement. As well as the practicality and effectiveness, the cost-effectiveness is a contributing factor to the usage of these techniques.

Cooling agents are commonly used for treating hot holes due to their practicality and cheapness. The other techniques are used selectively by specific mines. Despite all the efforts, spontaneous combustion remains an ongoing and complex problem. According to Stenzel (2002), spontaneous combustion and its mitigating measures are still poorly understood despite it being a wellknown phenomenon. Spontaneous combustion can result in the loss of coal reserves and has a negative impact on production, productivity, and health and safety (Panigrahi, Sinha, and Singh, 2013). Some of the common effects of spontaneous combustion in opencast pillar mining operations include:

➤ Devolatized coal or reduced quality of coal, and direct coal losses
➤ Decreased production rates
➤ Slope and highwall instability and sloughing
➤ Damage to property – tools, machines, and equipment
➤ Subsidence and sinkholes due to beam failure and collapse of burnt-out pillars
➤ Increased sulphur emissions
➤ Increased occurrence of hotholes
➤ Adjacent communities affected by increased emissions and dust.

Table V

Spontaneous combustion control measures in use

Control measure	Mine A	Mine B	Mine C	Mine D	Mine E
Cooling agents	Yes	Yes	Yes	Yes	Yes
Sealing agents	No	No	No	Yes	No
Inert gas	No	No	Yes	No	No
Water cannons	No	No	No	Yes	Yes
Reducing drill diameter	Yes	No	Yes	No	Yes
Buffer blasting	No	Yes	Yes	Yes	Yes
Cladding	No	Yes	Yes	Yes	Yes
Buttress blasting	No	Yes	Yes	No	Yes
Bord-only blasting	No	No	Yes	Yes	No
Bord and pillar blasting	Yes	Yes	Yes	No	Yes

Sinkholes and surface subsidence in the old workings

Some of the mines visited were found to be severely affected by sinkholes and surface subsidence. Surface subsidence remains a concern in coal mining and has also been reported in virgin coal mining operations in South Africa and countries such as Australia, China and Indonesia (Peng, 2020; Cui *et al.*, 2020; Han *et al.*, 2019; van der Merwe, 2018; Sasaoka *et al.*, 2015). The major factors contributing to surface subsidence include poor geotechnical conditions as well as the presence of voids due to mining. Sinkholes constitute a risk to people, machines, property, and the environment. Several incidents in which machines have fallen into sinkholes have been recorded. These sinkholes are initiated by the presence of voids in the old workings and propagate all the way to surface due to caving of the overlying strata into the bord voids. Sinkholes are approached and treated differently from mine to mine. Sinkholes are often invisible and may form unexpectedly while people and equipment are working directly above them.

Figure 4 shows the surface appearance of sinkholes of different sizes. The size and severity of a sinkhole, and the rate at which it propagates to the surface, depends on a number of factors, including:

➤ *The thickness of the overlying strata*: The thickness of the overburden from the old workings to the surface has an influence on the distance of propagation. Sinkholes are likely to propagate and reach surface quicker in shallower overburden.
➤ *The strength and ability of the rock to resist weathering over time*: Competent rocks are less affected by sinkholes than weaker rocks, especially in oxidized areas such as the upper portion of the overburden and topsoil. This is due to weaker rocks being more affected by weathering. Sinkholes propagate faster in weaker rock than in competent rock due to the faster rate of weathering.

Figure 4—Formation and propagation of sinkholes from old workings voids (visited mine)

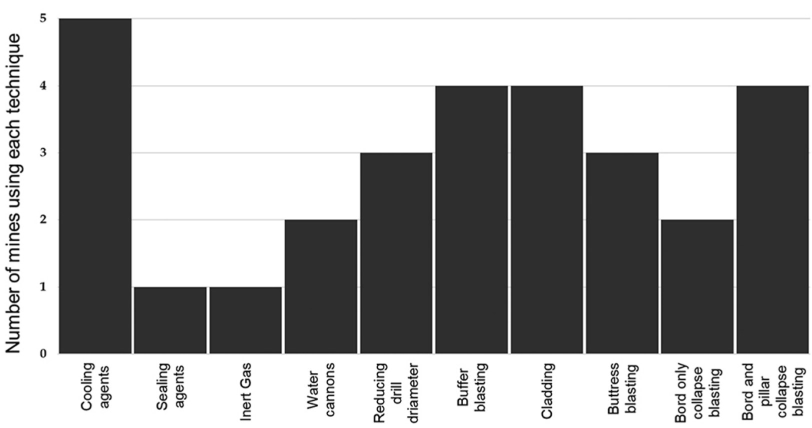

Figure 3—Number of mines using a specific spontaneous combustion combating technique

- *Load on the surface*: The presence of heavy equipment working above a sinkhole may result in a collapse. This is also dependent on the maturity of the sinkhole.
- *The position of the coal seam in relation to the old workings*: The closer the seams are to the old workings; the quicker sinkholes can propagate to the surface.
- *The moisture content of the rock*: Wet areas in oxidized rock are more prone to sinkholes. Moisture reduces the strength of the material in oxidized zones and this can result in higher propagation rates.
- *General geology of the area*: The presence of faults, sills, and dykes in the surroundings or directly above the old workings, as well as natural or mining-induced cracks, can influence the rate of propagation of sinkholes to surface.

Incompetent roof beam and highwall

The safety of people and equipment working above the old workings depends on the conditions and competency of the overlying strata (beam layer) and highwall stability. The beam, as shown in Figure 5, is the immediate overlying stratum (layer) above the roof coal and the pillars. The competency of the beam layer is crucial for the stability of the working area. However, this is not critical in mines where buffer blasting is used. Incidents of machines falling into the bord voids have been reported. This is mainly due to the thickness and consistency of the beam being poorly understood or unknown. Furthermore, there are several restrictions regarding highwall stability, especially at shallower depths. Opencast pillar mines should be designed such that the highwall is always supported by pillars and does not hang over the bord voids, as demonstrated in Figure 6. Thompson (2005) suggested that the mining direction should be orientated at an angle relative to the pillars of the old workings, as shown in Figure 7. This is to ensure that pillars are always present at the edge of the highwall.

Excessive dilution

Excessive dilution is one of the major challenges in opencast pillar mining. In principle, only the bord should collapse and the bord and pillar collapse techniques are designed to prevent spontaneous combustion. However, this can result in excessive dilution. The bord-only collapse technique was designed to incur an excessive amount of dilution for the sake of avoiding or preventing spontaneous combustion. This dilution is due to the waste material (overburden) which is blasted to collapse the roof coal and fill the bord voids. The purpose of this is to prevent the ingress of air or oxygen into the old workings. This method has been effective in preventing spontaneous combustion in some of the mines where it is employed. On the other hand, the bord and pillar collapse technique is expected to incur less dilution. In this case, the pillars are collapsed first to fill in the bord voids and thus preventing the ingress of air into the old workings.

The amounts of dilution incurred by each mine with the different blasting techniques employed are depicted in Figure 8. It is clear that the bord-only collapse method incurs higher dilution than bord and pillar collapse. In Mine A, the amount of dilution is relatively low even with the bord-only collapse technique because the waste material around the pillars is loaded separately from

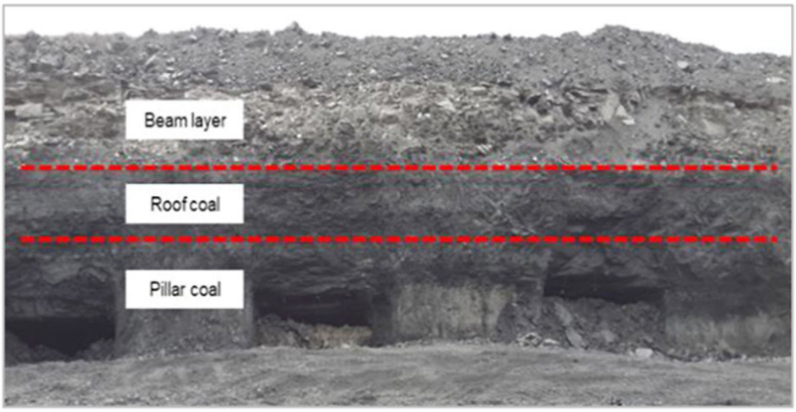

Figure 5—Typical layout of the beam above old workings and the edge of the highwall supported by pillars

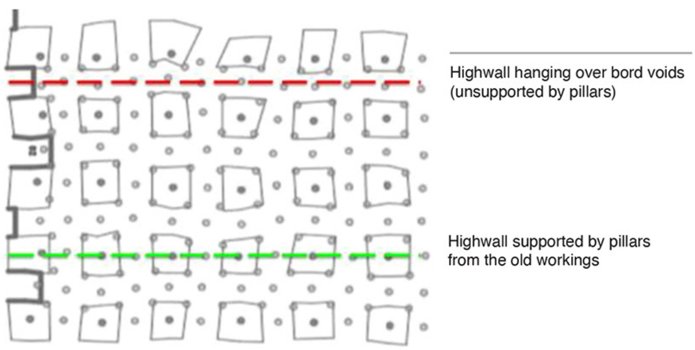

Figure 6—Highwall supported by pillars *vs* highwall hanging over bord voids

pillar material. For example, an excavator would be used to clean waste material around the pillars. In Mine C and Mine D, the pillars are loaded together with the waste material, hence resulting in higher dilution. Mine B and Mine E have always employed the bord and pillar collapse technique, while Mine D utilizes the bord-only collapse technique. Figure 9 illustrates how the bord-only collapse technique incurs higher dilution than bord and pillar collapse.

Pit flooding

Opencast pillar mining operations are also heavily affected by large quantities of water, which result in the pit being flooded as can be seen in Figure 10. According to the experts in this field, the flooding is caused by water that was pumped back into the old mines when they ceased operation. This water needs to be pumped out before the pillar coal can be extracted. However, it was observed that spontaneous combustion starts to occur after pit dewatering. This was also noted by Philip, Uludag, and Chabedi (2011).

Highly undulating coal seams

One of the operations visited was found to be severely affected by excessively undulating coal seams. These undulating coal seams also contain some old workings. This makes the opencast pillar mining process even more complex. Figure 11 shows a stratigraphic section of the undulations.

Drilling and blasting technique

There are two main types of drilling and blasting techniques in opencast pillar mining; bord-only collapse and bord and pillar collapse. These drilling and blasting techniques are aimed at preventing the ingress of air into the old workings, stabilizing the beam, and eliminating the occurrence of sinkholes. During the field investigations it became apparent that opencast pillar mining operations often struggle to identify the most suitable technique. The mines visited were found to have switched between the two blasting techniques as shown in Table VI.

The changes in Table VI are a result of several factors such as dilution, coal losses, and health and safety. For example, Laybourne and Watts (1990) conducted a study in which a mine switched from the bord-only collapse to the bord and pillar collapse technique with the aim of minimizing excessive dilution.

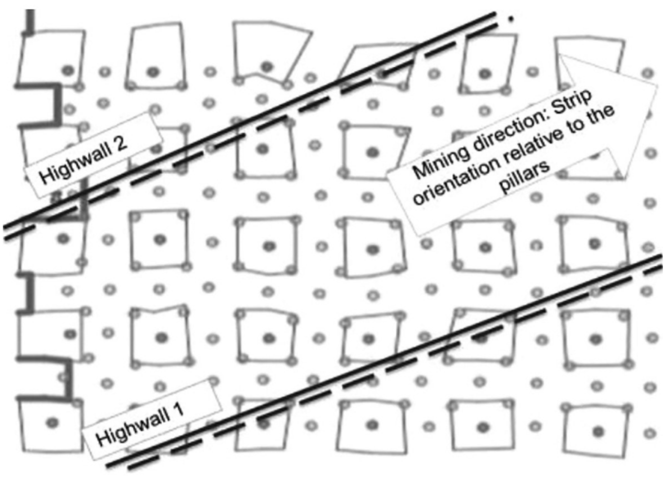

Figure 7—Orientation of opencast mining strips relative to the pillars in the old workings

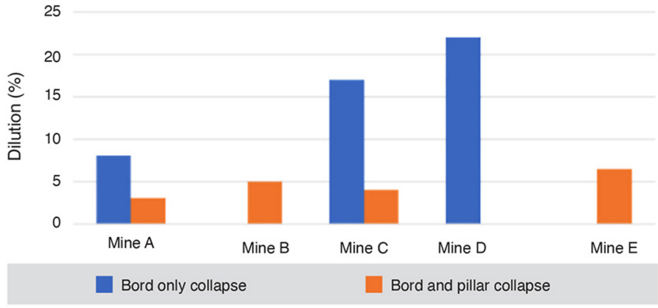

Figure 8—Comparison of dilution between the bord collapse and the bord and pillar collapse techniques

Figure 9—Amount of dilution between pillars due to the bord collapse blasting technique

Figure 10—Water inundation in two of the opencast pillar mines visited

However, converting from one technique to the other has an effect on the drilling and blasting processes. The changes that can be expected when converting from the bord-only to the bord and pillar collapse technique are shown in Figure 12 and Table VII.

With the bord-only collapse technique, the pillars remain intact (standing) or semi-collapsed after blasting. This results in waste material (blasted overburden) falling and filling the bord voids around the standing pillars. This technique may result in excessive dilution and minimal coal losses due to top-ofcoal scalping. On the other hand, the bord and pillar collapse technique results in good segregation between the pillar coal and waste material. This is due to the simultaneous blasting of the pillars and the overburden. Although dilution is significantly reduced, this technique may result in an interlock of roof coal and waste. Minimal dilution may still be experienced on the borderline of the roof coal and the overburden. The expected outcomes of the two blasting techniques are shown in Figure 13.

Deciding between the bord-only collapse and the bord and pillar collapse blasting techniques can be difficult, not only for new mines but also existing mines that seek to convert. In general, the major challenges expected were identified as spontaneous combustion, sinkholes, incompetent roof strata, excessive dilution, pit flooding, and tramp material. Any opencast pillar mining operation can expect to encounter one or more of these challenges. These challenges were found to originate from

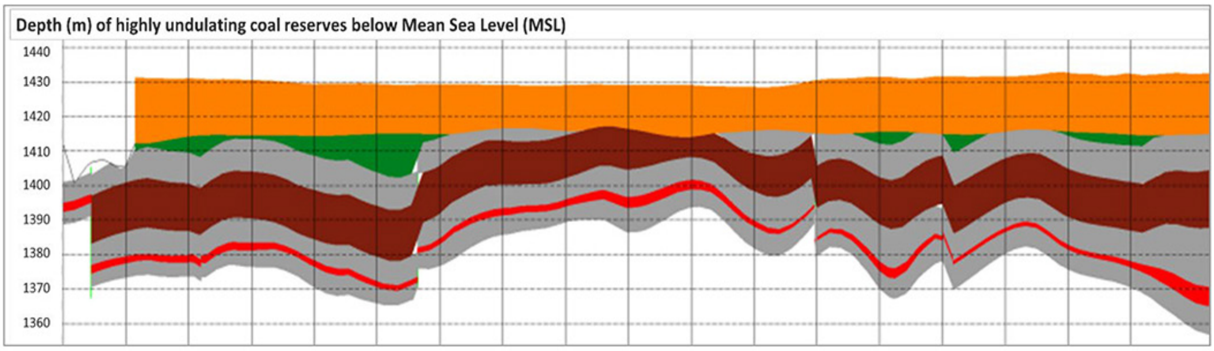

Figure 11—Stratigraphic section depicting excessive undulation of coal seams in an opencast pillar mining operation

Table VI

Changes in drill and blast technique

Mine	Number of pillar seams	Average thickness of pillar seams	Initial blasting technique	Current blasting technique	Reason for the change
A	1	3 m roof and 4 m pillars	Bord-only collapse	Bord and pillar collapse	Failure of the beam strata above old workings – machines falling into bord voids
B	3	8.5 m, 7 m and 5.8 m pillars	Bord and pillar collapse	Bord and pillar collapse	Highly undulating coal seams
C	1	3.2 m pillars only	Bord and pillar collapse	Bord-only collapse	Machines falling into sinkholes originating from bord voids
D	3	1.5 m roof, 4 m pillars, and 1 m floor	Bord-only collapse	Bord-only collapse	Excessive dilution incurred
E	2	Unspecified	Bord and pillar collapse	Bord and pillar collapse	Excessive spontaneous combustion

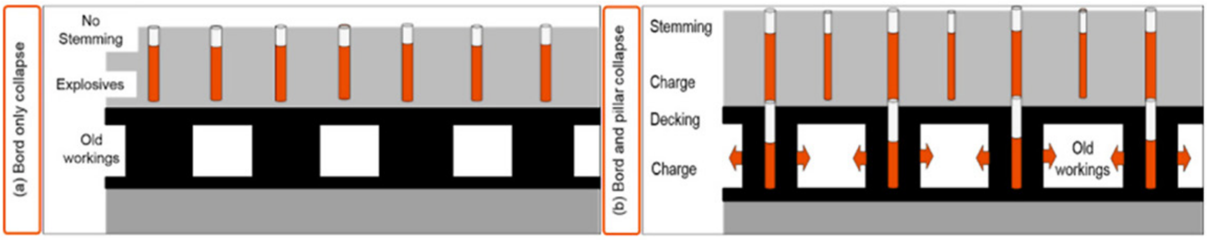

Figure 12—Drilling and charging patterns for (a) bord-only collapse and (b) bord and pillar collapse

Table VII

Comparison of the drilling and blasting changes when converting between the bord-only collapse and the bord and pillar collapse techniques

Parameter	Bord-only collapse	Bord and pillar collapse
Number of drilled holes	Unchanged	Increased (pillar centre holes)
Total drilled metres	Unchanged	Increased (drilling to pillar floor)
Duration of drilling	Unchanged	Increased
Total explosives per delay	Unchanged	Increased
Total blasting accessories used	Unchanged	Increased
Stemming length	No stemming (hot holes)	Stemming required
Stemming material	No stemming	Chippings or slag
Hole diameter (mm)	250 to 311	127 to 165

risk factors associated with the old workings. The three main risk factors are (1) unknown conditions of the old workings, (2) partially known conditions of the old workings, and (3) inaccurate information on the pillars in the old workings. When the conditions of the old workings are unknown or only partially known, detailed information such as pillar dimensions, pillar centres, roof thickness, and coal seam undulation are unavailable.

As such, a process flow chart for selecting the most suitable blasting technique based on the availability of information is proposed. The flow chart (Figure 14) consolidates the findings from the mine visits and provides a guideline for the selection of the most appropriate blasting technique. This flow chart takes into consideration the risk factors and the possible challenges that can be experienced during operation, which are influenced by the availability of information regarding the old workings. Based on this information, the appropriate blasting technique can be selected.

Health and safety

As opencast pillar mining is a complex and challenging undertaking, health, safety, and the environment are other major aspects for consideration. A number of unique incidents and accidents have been reported from the opencast pillar mines which were visited. These incidents were found to be directly related to the risk factors and challenges associated with the old workings. A total of 21 incidents were identified. These incidents include first aid cases, lost time injuries, recordable injuries, and fatalities, and involved both machines and persons. The major and frequently occurring incidents are summarized in Figure 15. All these incidents can be seen to be directly associated with the challenges and risk factors identified. Examples of these accidents include premature detonation of explosives due to hot holes, damage to trucks loading and transporting burning coal, and machines falling into sinkholes.

Conclusion

The extraction of pillars and remnant coal in previously mined underground bord and pillar operations using opencast mining methods involves some serious challenges. These challenges are mainly due to risk factors associated with the absence or partial availability of information pertaining to the old workings. The major challenges affecting opencast pillar mining were investigated. These challenges and risk factors need to be managed very well as they can have an adverse impact on productivity and safety.

A significant and valuable amount of coal can be effectively extracted from pillars in old workings. This requires the risk factors and challenges associated with opencast pillar mining to be managed properly. These challenges are managed differently by each mine as the conditions differ depending the way in which the underground mines operated. This requires a good understanding and management plan to deal with the challenges and risk factors. Drilling and blasting techniques and can be selected based on the conditions of the old workings.

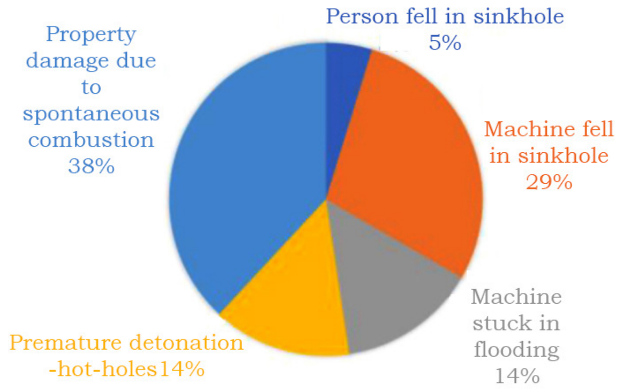

Figure 15—Incidents related to the risk factors and challenges associated with opencast pillar mining

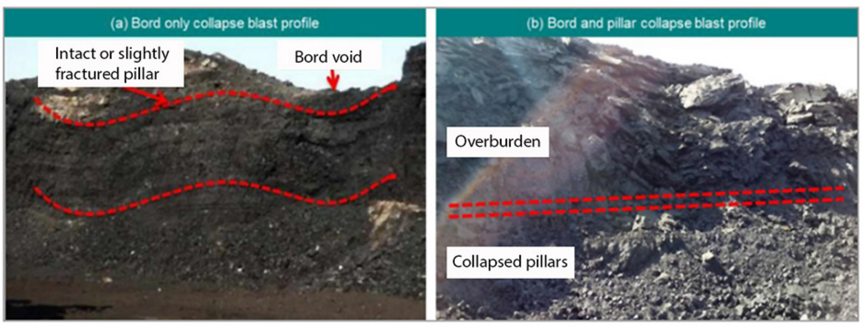

Figure 13—Comparison of blast profiles between (a) bord-only collapse and (b) bord and pillar collapse

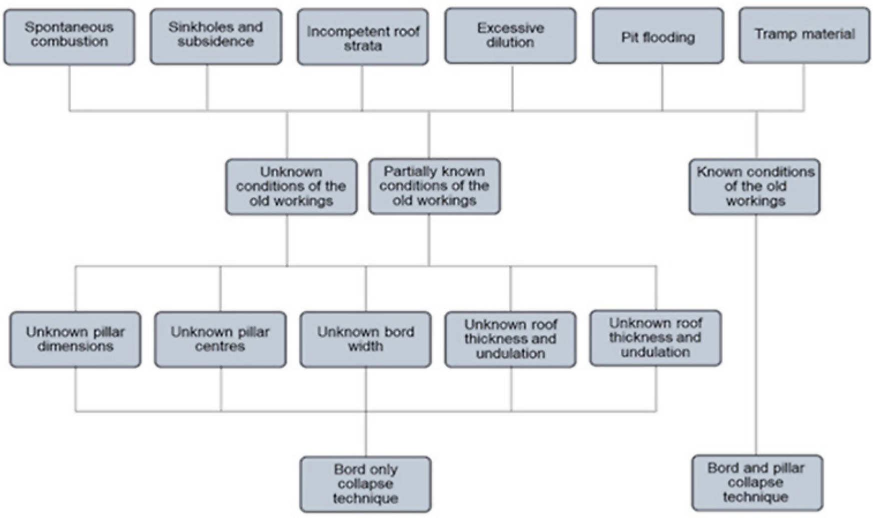

Figure 14—Guideline for selection between the bord-only collapse and the bord and pillar collapse techniques

Suggestions for further studies

- ➤ A significant amount of coal continues to be lost due to spontaneous combustion. However, no study has been able to quantify the amount of coal lost due to spontaneous combustion in opencast pillar mining operations. Therefore, some method of quantifying thee losses needs to be developed.
- ➤ The biggest risk factor in opencast pillar mining is the paucity of information regarding the old workings. Therefore, a study of the feasibility of locating and assessing the condition of pillars in the old workings should be conducted to obtain the essential information required. This information can be used to extrapolate the parameters of the pillars and bords.
- ➤ The amount of water being pumped out from the old workings is still unknown. A study should be conducted to quantify the amount of water present in the old workings.
- ➤ An investigation into the effects of spontaneous combustion on the health and safety of employees and the nearby communities. This can be conducted through measuring the amount of emissions due to spontaneous combustion.

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South African mining and metallurgy researchers ranked in the 2021 listing of the world's top 2% scientists

A recently updated database1 from Stanford University lists the top 2% of science researchers in the world. This year, 26 South African scientists are recognized in the sub-discipline of Mining and Metallurgy, up by 24% from the previous rankings. It is also gratifying to see a significant increase in the number of women represented, as well as a wider range of academic institutions and commercial entities.

The research team, led by Professor John Ioannidis, created a database that includes the best scientists in the world, using standard citation indicators. The indicators take a range of factors into account, including the number of citations, h-index, citations of papers in different authorship positions, and a composite indicator. The database categorizes 186 000 scientists in 22 scientific fields and 176 sub-fields.

The South African scientists who featured in the Mining and Metallurgy ranking according to career-long citation impact are as follows.

Name	Institution	No. of papers	Ranking
Frank Crundwell	CM Solutions	67	13
Sue Harrison	University of Cape Town	174	28
John Preston	Mintek (retired)	51	49
Dick Stacey	University of Witwatersrand	104	71
Jochen Petersen	University of Cape Town	91	84
Dee Bradshaw (deceased)	University of Cape Town	156	99
Leon Lorenzen	Stellenbosch University	86	109
Michael Moys	University of Witwatersrand	89	116
Cyril O'Connor	University of Cape Town	186	135
Kathy Sole	University of Pretoria	43	139
Dave Deglon	University of Cape Town	53	192
Jan Svoboda	De Beers Group (retired)	33	199
Steven Bradshaw	Stellenbosch University	100	227
Mariekie Gericke	Mintek	30	237
Sehliselo Ndlovu	University of Witwatersrand	69	252
Geoff Hansford	University of Cape Town	54	257
S. Ramazan	AngloGold Ashanti Limited	16	315
J.-P. Franzidis	University of Cape Town	98	415
Tunde Ojumu	Cape Peninsula University	59	439
Megan Becker	University of Cape Town	67	485
Victor Ross	Mintek (retired)	24	494
Rob van Hille	University of Cape Town	55	526
Johan de Villiers	University of Pretoria	58	565
J. van der Merwe	University of the Witwatersrand	39	572
Andrie Garbers-Craig	University of Pretoria	44	630
Gloria McDougall (deceased)	NCP	16	667

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The South African mining royalty regime: Considerations for modifying the system to balance its competing objectives

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Synopsis

Mineral royalties are one of the oldest forms of mining taxation, and were initially introduced to extract economic rents from mining. Over time, the royalty regime has become more complex as it was identified as an important policy instrument that can achieve more multi-faceted outcomes. Such a multi-tiered approach in the use of the royalty instrument is also the case with South Africa. With South Africa's new mineral royalty regime now in place for ten years, it is perhaps time to assess its impact and effectiveness.

To carry out this assessment, an econometric evaluative study was undertaken using four major commodities in South Africa, namely gold, platinum, iron ore, and coal. The study explored five different policy options for government to consider and tested them to determine the most favourable one that will realize the regime's policy objectives. After the assessment, two major options stood out. Hence, this paper seeks to highlight which of the two options is the most favourable for consideration by policymakers. Based on that study, we find that the current structure is effective, but also recommend that the factors in the formula for refined minerals be 'modified' to reduce the capped profitability ratio from the current 60% to 30% and the maximum royalty rate for refined minerals from 5% to 3%. The minimum rate of 0.5% during times of depressed mineral prices and no or low profitability will not be affected.

Keywords

mineral royalty, beneficiation, policy option, royalty formula, royalty regime, policy objectives.

Introduction

There is a significant variety of fiscal instruments available for policymakers to select from in the international resource taxation policy field. Mineral royalties fall in a category called 'special taxes', along with other instruments available to governments when they exercise national sovereignty over natural resources within their territories. Otto *et al*. (2006) summarized and discussed the range of royalty instruments and quasi-taxes encountered internationally and how these affect investors, government, and civil society. Many jurisdictions, including South Africa, have since then updated their royalty regimes to align the fundamental royalty principles with national policy imperatives (Cawood, 2010). Mineral royalties are usually charged on some definition of turnover value, which results in a small percentage change translating into a big change on the actual royalty amount. Royalties therefore could affect mining pay limits and consequently, influence investor decisions on where and when to invest. This makes mineral royalties a controversial topic. Otto *et al*. (2006) observed that 'across the globe, no type of tax on mining causes as much controversy as a royalty tax'. The role of public policy is to optimize mineral resource development by balancing investor interests with the need to utilize sovereign assets in the best interest of society, while still allowing investors a fair return on their investment.

Mineral royalties in South Africa are governed by the Mineral and Petroleum Resources Royalty Act (MPRRA, Act 28 of 2008) and by its Administration Act 29 of 2008. The two Acts were implemented in 2010, which year was the first time that royalties were governed by the national revenue authority (South African Revenue Service – SARS). Before 2010, mineral royalties were set, administered, and collected by the department responsible for mineral development and not by the more efficient revenue services parastatal. Recently, the Davis Tax Committee (DTC) reviewed the efficiency of the corporate income tax structure in South Africa. The DTC also considered the competitiveness of the mining tax regime, including the relatively new mining royalty system that was introduced in 2010. Several concerns were raised during the investigation, with most of them being about the complexity of the MPRRA rather than the competitiveness or affordability of the royalty system. The DTC commented that the mineral royalty regime 'is very new and that there is little by way of data to measure its success at this stage' and that 'the Treasury benchmarks the design of the royalty to best international practice'. The final recommendation was to retain the current royalty dual formulae structure, allowing for future refinement of the factors in the royalty formula, but only after '… a rigorous economic analysis by the National Treasury' (DTC, 2016).

Having the recommendation of the DTC in mind and accepting the structure of the royalty formulae as leading practice, there is therefore a need for further analysis of the factors used in the two formulae to establish if refinement thereof is required and how such changes will affect the policy objectives of the royalty system. In this regard, Oshokoya (now Akinseye) investigated the policy implications after econometric analysis of the factors within the two formulae (Akinseye, 2019).

In conducting the econometric analysis, the methodology used in the 2019 study involved the econometric evaluation and analysis of five different policy options. To facilitate this investigation, four major commodities in South Africa (gold, platinum, iron ore, and coal) were selected. After testing the five different policy options, two main beneficial options for the government were identified, but one of them stood out as the most desirable for achieving the regime's major policy objectives. The approach used was special because it demonstrated how the use of mining/refining companies' financial information can econometrically allow for the modifying of various parameters of the royalty formulae, thereby resulting in several policy options for consideration.

In this paper, which is mainly based on the findings of the Akinseye (2019) study, as well as previous studies by Oshokoya (2012) and Cawood and Oshokoya (2013a, 2013b), we aim at providing South African policymakers with a desirable option for 'modifying' and improving the current mineral royalty system in order to achieve its intended goals. The various sections of the paper reflect the process that leads up to the policy option that is proposed. The beginning sections give a description of the royalty regime, examine whether or not the system has been successfully implemented, and state the reason why modification of the system could be considered. The latter sections discuss the policy options that could be available for 'modifying' the regime, and finally present the recommended policy option that is most likely to facilitate the realization of the policy's objectives.

The South African royalty regime for mining

More than ever, the capture of a greater direct share in the wealth potential of mineral development, along with obtaining more socio-economic linkages, has topped the agenda of many mineral-rich countries. This re-emergent drive has instigated many governments to revise mineral policy and fiscal instruments as well as renegotiate contractual terms, to ensure the realization of more economic linkages from their mineral resources.

With the South African government not being left out of this initiative, one of the ways that it aimed at effectively obtaining more benefits from the development of its natural resource endowments for present and future generations was through the enactment of the MPRRA (Oshokoya, 2012). Based on the provisions of South Africa's Minerals and Mining Policy 1998 and the Mineral and Petroleum Resources Development Act, 2002 (MPRDA), as well as 'a most informative internal economics analysis…', the National Treasury designed the mechanism of the MPRRA to satisfy some criteria (Department of Minerals and Energy, 1998; MPRDA, 2002; DTC, 2016). These criteria are economic efficiency, rent collection and government risk, as well as administration and compliance costs. Hitherto, the main objectives of the MPRRA are generally as follows:

1. To compensate the State for the permanent extraction of the country's non-renewable mineral resources through royalty payments for the benefit of the National Revenue Fund (PwC, 2009a).
2. To target mineral rents.
3. To facilitate the achievement of the government's objective of promoting local beneficiation of its minerals (Akinseye, 2019).

The MPRRA specifies that royalty payments are to be charged when [mineral and petroleum] resources are transferred or sold in accordance with the MPRDA's provision for State custodianship over its mineral resources (National Treasury, 2008). The royalty payments collected by this instrument represent an additional revenue stream to the government in conjunction with corporate income tax (CIT) receipts, because both payments are collected in the same time cycle. With the royalty regime being designed to collect both royalties and mineral rents during times of profitability, this avails more opportunity for the mining sector to contribute to the enhancement of the socio-economic wellbeing of citizens. Also, this royalty instrument was viewed by National Treasury as one of the ways by which the government could achieve its beneficiation objective, so that industrialization and economic growth and development could be linked to mineral extraction.

The MPRRA stipulates that royalties are charged *via* a dual ad *valorem*, sliding-scale formula[1] method, after a distinction is made between 'one of two physical conditions – after some processing (unrefined minerals) or after the "final" refined condition (refined minerals)' (National Treasury, 2008). In this regard, the condition of the mineral as either refined or unrefined is specified in either Schedule 1 or 2 of the Act. In addition to this, the Act makes provision for cases in which a mineral resource can potentially/valuably be transferred either as a Schedule 1 product or Schedule 2 product (*idem*). Those types of minerals are listed under both Schedules. Dual-listed minerals are viewed as 'refined' only if they are produced to the 'refined' or beyond the 'refined' condition specified in Schedule 1. On the other hand, dual-listed minerals that fail to meet Schedule 1 specifications are viewed as unrefined (*idem*). Hence, the rates for refined and unrefined minerals are calculated thus:

Refined minerals:

$$\text{R\%} = 0.5 + \left(\frac{\textit{Earnings before interest and taxes}\ \text{(EBIT)}}{\text{Aggregate gross sales in respect of refined mineral resources} \times 12.5}\right) \times 100$$

or

$$\text{R\%} = 0.5 + \left(\frac{\text{X}}{12.5}\right); \qquad [1]$$

and

Unrefined minerals:

$$\text{R\%} = 0.5 + \left(\frac{\textit{Earnings before interest and taxes}\ \text{(EBIT)}}{\text{Aggregate gross sales in respect of unrefined mineral resources} \times 9}\right) \times 100$$

or

$$\text{R\%} = 0.5 + \left(\frac{\text{X}}{9}\right) \qquad [2]$$

[1]This dual sliding-scale formula mechanism imposes no specific royalty rates for any mineral, instead, it allows for self-adjusting royalty rates for minerals, according to the level of refinement and profitability (MPRRA, 2008)

where

- R% = Royalty rate.
- Minimum royalty rate payable for all minerals = 0.5%. This minimum royalty charge ensures that the government (as custodian) always receives some level of royalty payments for the depletion of non-renewable resources, even in times of low profitability (Strydom, 2012).
- Maximum royalty rates payable at maximum profitability (100%) are 5% and 7% of gross sales for refined and unrefined minerals respectively, in that year of assessment. The reduced royalty rate of 5% is a reward for incurring additional costs on value addition (Oshokoya, 2012).
- X = profitability indicator (ratio) *i.e* $\left(\frac{\text{EBIT}}{\text{Aggregate gross sales}}\right) \times 100$.
- Maximum value of *X* for both refined and unrefined mineral producers ≈ 60% per year of assessment.
- F (factor) = 12.5 and 9.0, which determine maximum rates for refined and unrefined minerals respectively.
- EBIT = Earnings before interest and taxes. It is realized from the sum of gross sales after adding recoupments under the Income Tax Act 1962 (ITA) less operating expenditure less capital expenditure in the year incurred and any other amounts that are deductible in terms of the ITA.
- Aggregate gross sales: This is the royalty base and is defined as arm's length gross sales value in the transfer of all mineral resources, as defined in Schedule 1 and 2 of the Act (PwC, 2009b). As with EBIT, various inclusions and exclusions are applicable.
- The royalty rate determined in terms of the formula for refined minerals must not be below 0.5% nor exceed 5%, while the royalty rate determined in terms of this formula for unrefined minerals must not be below 0.5% nor exceed 7%.
- Royalty amount = Royalty base x R%.

Payments of royalties are due semi-annually and are estimated on a basis similar to provisional tax for income tax purposes (PwC, 2009b). It is noteworthy that these mineral royalties are deductible for income tax purposes (Strydom, 2012).

It is important to note that the formula provisions of the Act automatically recognize downstream beneficiation of mineral products. This is because the Act allows for the reduction of royalty rate as beneficiation increases in order to compensate for the significant additional costs that are incurred as a mineral is refined, even though a refined product has higher sales value, which leads to a higher tax base than that of an unrefined mineral. Hence, through the Act's definition of value, acknowledgment of profitability, and automatic recognition of the downstream mineral beneficiation, this further indicates that the royalty system aligns with the government's objective to promote local beneficiation of South Africa's minerals (Cawood and Minnitt, 2001: Portfolio Committee on Finance, 2008). As indicated previously, the design of the regime and its provisions bring South Africa's mining legislation in line with prevailing international norms, in which taxation instruments are used not only for revenue collection but also to encourage or discourage the promotion of various economic sector initiatives (PwC, 2016).

With the regime being in existence for about 10 years and knowing that a country's legal/regulatory environment is a key determinant for investors when considering investment destinations, it was deemed necessary to assess whether its implementation has been successful (or not). This would also give an indication of the impact of some of its policy intents on investment decisions. The next sections consider the success (or otherwise) of the implementation so far and give a lead as to whether the system requires some adjustments to achieve better results.

Considerations for modifying the system

The authors (Oshokoya, 2012; Cawood and Oshokoya, 2013a, 2013b) carried out studies using data from Statistics South Africa (Stats SA) of mining taxes that included royalty payments in the years 2004 to 2009 (before 2010, when the royalty regime became effective) to 2011 to measure and monitor the success of the system. Akinseye (2019) expanded these studies up to 2017, as indicated in Figure 1.

The deductions from the assessments indicated that the mining fiscal flows to South Africa's economy were significant in comparison to other sectors. Additionally, data showing the tax to turnover contributions of the mining sector and all other economic sectors in general, presented in Table I, indicated that the royalty regime has resulted in mining companies paying more

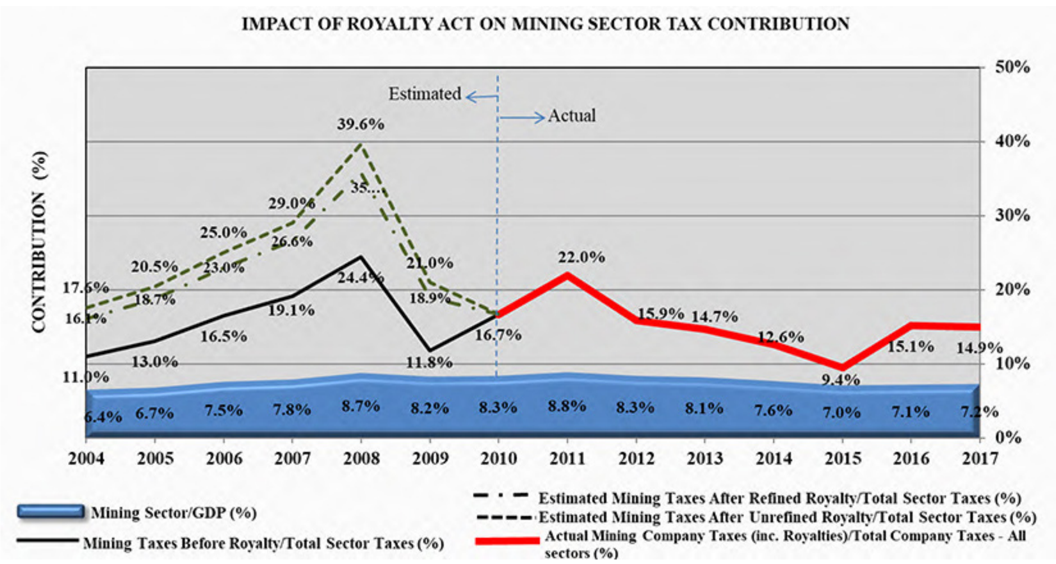

Figure 1—Impact of the new royalty on mining taxes. Source: Stats SA (2018a, 2018b)

Table I

Comparison of profitability and tax-take between mining companies and the total economy

	All sectors													
Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
EBIT/Revenue (%)	11%	12%	13%	14%	15%	11%	11%	11%	11%	10%	10%	9%	10%	11%
Tax/Turnover (%)	1.8%	2.2%	2.6%	2.6%	2.6%	1.8%	2.0%	2.0%	2.0%	2.0%	1.6%	1.5%	1.3%	1.4%
	Mining sector													
Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
EBIT/Revenue (%)	18%	24%	29%	31%	41%	18%	23%	24%	17%	7%	11%	-3%	11%	5%
Tax/Turnover (%)	4.3%	5.5%	7.2%	7.6%	8.1%	3.2%	4.6%	5.7%	4.5%	4.0%	3.0%	2.1%	2.9%	3.1%

taxes than other economic sectors, with the combination of income tax and mining royalties. This deduction was supported by the fact that the tax to turnover contributions of the mining sector in all the years (2010–2017) were almost twice as much as the tax to turnover contributions of all other sectors. Even in the year 2015, when the mining sector generally functioned at no profitability[2] (as depicted by the 'negative' profitability ratio – EBIT to Revenue), the mining sector was still a major tax contributor to South Africa's economy in comparison to all the other economic sectors.

These deductions highlighted that the rent collection aspect of the royalty regime appeared to be effective (especially in times of good commodity prices). Also, the deductions indicated that the regime did not necessarily deter investment because it allowed for equitable sharing of economic benefits between the State and mining companies. This was because royalties are charged in-sync with economic cycles and the ability to pay is taken into consideration

With the equitability, economic efficiency, neutrality, and rent collection characteristics of the royalty regime proven as being effective, investigations on the regime's beneficiation (refining) policy objective were conducted. In summary, the findings of those investigations by these authors were that:

- ➤ The economic linkage objective of the regime was in line with global trends of using fiscal instruments to encourage or discourage private sector initiatives[3]
- ➤ The MPRRA's beneficiation incentive was insufficient and not likely to encourage miners to become refiners.

Conclusively, Cawood and Oshokoya (2012, 2013, 2013b) recommended that even though the beneficiation provisions appeared to be unable to realize the mineral beneficiation objective of the South African government, the initiative should not be terminated. Instead, further studies should be carried out to investigate ways of improving the design of the regime to achieve its policy objectives. Their recommendations tallied with the recommendations of the interim report of the DTC (2016), that '...various aspects of the mineral royalty regime still needed to be improved...'. The possibility of modifying some of the parameters of the royalty regime presented a way of making headway to obtain optimal results[4].

These findings and recommendations, along with the continued indication that one of the ways that the South African government planned on encouraging the establishment of more beneficiation companies/projects through incentives like lowering royalty rates for such projects, indicated the need for modifying the MPRR system. The next section, which is largely based on Akinseye's 2019 study, describes the methodology used for modifying the system and the resultant policy outcomes available for consideration.

Policy options for modifying the system

According to the DTC (2016), '...three alternative options to the existing royalty regime were discussed as feasibilities, using a combination of proposals and options developed in the International Monetary Fund report and by the National Treasury'. Hence, in alignment with these initiatives, Akinseye carried out a follow-up study[5] to her 2012 study to contribute to the discussion around finding alternative ways of modifying the royalty regime. The investigation[6] that was conducted in 2019 resulted in the development of five policy options for the purpose of proposing 'pragmatic' and 'realistic' solutions/adjustments that could be applied to the regime in order to realize policy objectives.

One of the major focus themes of the 2019 research was to find better ways to optimize the beneficiation objective of the MPRRA by checking how its parameters could be adjusted to incentivize the cost side of mineral developers. This was proposed based on the reality that mineral producers are largely price-takers (because the prices received for their products are generally set by global market dynamics), coupled with the difficulty they face with regard to reducing production costs. Another focal issue of the 2019 study was how to use the MPRRA's rent-collection feature to establish a most favourable system of management and use of the rents collected. The expected result of this assessment was to highlight which of the MPRRA parameters could be readjusted/modified for government to effectively realize its intended goals.

To adequately carry out the assessment, the methodology of this study aimed at addressing some of the shortcomings of the 2012 study. Some of these shortcomings included the type of financial data that was obtained and used, as well as the financial/accounting calculations that were conducted. It was expected that the confidentiality issues encountered in 2012 study would be resolved at the beginning stages of the 2019 study, so that actual

[2]According to Rossouw (2015), 'financial performance for the South African mining industry in 2015 was extremely challenging and downcast'. This challenging performance, which resulted in shrinking margins and impairment provisions, was largely due to 'local cost pressures, labour action, a continuing downswing in commodity prices and declining trend in market capitalization' (Cornish, 2015).

[3]An example is the Scandinavian case of using policy instruments to promote the transition of their economies from raw-materials based to industrialized.

[4]Expected optimal results are that increased benefits accrue to South Africa from mineral beneficiation [even in times of poor prices], thereby possibly increasing revenue from mining taxes plus royalties.

[5]Some of the 'problematics' of the Act informed the rationale for this follow-up study (Akinseye, 2019).

[6]This assessment was done irrespective of the fact that the realization of the positive influence of the beneficiation objective on mineral investments has been widely debated over time.

financial data for revenue, costs, and new processing facility capex could be obtained and used to portray a more realistic picture of the actual financial positions of producers. To this end, both the Department of Mineral Resources and Energy (DMRE) and SARS were approached between January and March 2017. They declined to release financial information of the mining companies and the researcher was advised to use relevant information available in the public domain. Therefore, the limitation imposed by confidentiality issues, which was experienced in the 2012 study, was also encountered in the 2019 study. Information for this study had to be obtained from the public domain (Integrated Annual Reports, analyst books *etc*.) as directed by SARS. For the purpose of this study, the analysis was carried out using models created in Microsoft Excel and IBM SPSS Statistics.

Based on the data obtained as at the time of the 2019 study involved carrying out econometric analysis[7] in two phases. Both phases were applied to three other mineral sectors – gold, iron ore, and coal – as well as the PGM sector (as in the 2012 study)[8]. This was done to determine whether the conclusion of the 2012 study was PGM sector-specific or also applicable to the entire South African mining industry.

The application of these econometric procedures involved conducting tests of statistical significance and 'Realized Beneficiation incentive' (or royalty savings) on the current MPRR regime (hereinafter referred to as policy option 1). After testing this policy option, the general observation from the sectors' assessments in terms of Realized Beneficiation incentive was that only the steel/iron ore sector appeared to attain such royalty savings. For all other sectors assessed (except the peculiar case of gold), the application of the dual royalty formula showed mixed performance in terms of the Realized Beneficiation incentive. However, the mixed performance tended more towards the absence of any royalty savings for the minerturned- refiner (refiner) as the producer paid more royalties than the miner-only in the majority of the years that were assessed. The general observation that refiners appeared to pay more royalties than miners-only, despite the royalty regime's incentive of a lower royalty rate for refiners, was largely a function of the 'better' profitability of refiners compared to that of the miners-only. Hence, the implication was that the royalty formulae are at best a revenue-generating and rent-collection instrument. This result was supported by another assessment conducted under policy option 1, where only the royalty formula for refined minerals was applied to the gold sector. These deductions led to the generation of other policy options for the government to explore for modifying the formulae. These options, which involved the reduction of the maximum rate for refined minerals, and/or manipulating the F-factor of 12.5, are as follows:

1. Leaving the current royalty formulae as they are, despite the apparent inequity. This inequity, however, is by design so that miners are motivated to become refiners;
2. Reducing the royalty rate for refined minerals to increase its Realized Beneficiation incentive portion, thereby allowing the miner-only to continue to bear royalty penalty (as per the Act's specifications) in the current poor economic climate generally and for minerals in particular;
3. Using only the royalty formula for refined minerals for both classes of producers;
4. Using only the royalty formula for unrefined minerals for both classes of producers; and
5. Using a modified version of the royalty formula for unrefined minerals for both classes of producers (Akinseye, 2019).

These various policy options were examined to ascertain the most optimal way of adjusting the parameters of the royalty regime. The next sub-section gives details about the specific structures of the five policy options.

The structure of the five policy options

Policy option 1

This option involved the application of the two current royalty formulae to the financial information of the two classes of producers in each of the four selected commodity sectors of the study. For the application of these formulae in this policy option, none of the parameters of the formulae were changed. The parameters of the formulae used in this option are as per the MPRRA (formulae 1 and 2).

Policy option 2

With the policy objective of incentivizing refiners in mind, this option involved modifying only the current royalty formula for refined minerals while leaving the current formula for unrefined minerals unchanged. Before statistical tests were carried out on this option, different aspects/parameters of the royalty formula for refined minerals that could yield more royalty savings were explored[9].

In seeking to modify this royalty formula for refined minerals, the maximum profitability ratio (X-factor) was changed from 56.3% (approx. 60%) (which is the specified maximum profitability ratio in the current MPRR regime) to 30%, and the F-factor for refined minerals was changed from 12.5 to 12. This modified maximum profitability ratio was based on the deductions from the comparisons between the maximum profitability ratios and the corresponding resultant maximum royalty rates of all the refined mineral producers in all the four commodity sectors that were assessed in the Akinseye (2019) study. The purpose of that comparative assessment was to determine the optimal profitability ratio or maximum royalty rate by which the formula was to be modified. After averaging the maximum royalty rates that were generated based on these maximum profitability ratios, the final optimal maximum royalty rate of 3% for refined minerals was selected. This was in line with the Competitive Investment Framework (CIF) study by Cawood (1999). This implied that by substituting the realized optimal maximum royalty rate of 3% and the modified maximum profitability ratio of 30% (which was a more realistic maximum profitability ratio for the mineral producers), along with the minimum royalty rate of 0.5% in the current royalty formula for refined minerals (*i.e.* formula 1), a new F-factor was obtained. This new F-factor was derived as follows:

By substituting new values for maximum Yr and X in the restated formula (Equation [1]):

$$\text{Maximum Yr }\% = 0.5\% + \left(\tfrac{30}{F}\right)\% = 3\%$$

[7]The specifics of how the econometric analysis of the 2019 study was modified to differ from that of the 2012 study are stated in chapter 5 of Akinseye (2019).

[8]These four commodity sectors were identified as being substantial contributors to the South African economy and with the imposition of the MPRRA, their importance to the fiscus and the economy has become even greater. The major players in each selected commodity sector that possessed mining-only operations or both mining and refining operations in South Africa were presented as suitable representatives of the dual stages of processing per sector required in this study.

[9]The details of how the parameters of the MPRRA formula for refined minerals were adjusted for this policy option can be found in chapter 8 of Akinseye (2019).

$$F = \frac{30}{(3\% - 0.5\%)}$$
$$= 12$$

Hence, the formulae for policy option 2 are stated as follows:
For refined mineral resources:

$$\text{Royalty rate} = 0.5 + \left[\frac{\textit{Earnings before interest and taxes (EBIT)}}{\text{Gross sales in respect of refined mineral resources x 12}}\right] \times 100$$

or

$$R\% = 0.5 + \left(\frac{X}{12}\right)$$

or

$$R\% = 0.5 + \left(\frac{30}{F}\right) \quad [3]$$

where

$$\text{Profitability ratio (X)} = \frac{\textit{Earnings before interest and taxes (EBIT)}}{\text{Gross sales in respect of refined mineral resources}};$$

Formula constant (F-factor) = 12

The royalty rate determined in terms of this formula must not be below 0.5% nor exceed 3%.

For unrefined mineral resources:

$$\text{Royalty rate} = 0.5 + \left[\frac{\textit{Earnings before interest and taxes}}{\text{Gross sales in respect of unrefined mineral resources x 9}}\right] \times 100$$

or

$$R\% = 0.5 + \left(\frac{X}{9}\right); \quad [4]$$

where

$$\text{Profitability ratio (X)} = \frac{\textit{Earnings before interest and taxes (EBIT)}}{\text{Gross sales in respect of unrefined mineral resources}};$$

Formula constant (F-factor) = 9

The royalty rate determined in terms of this formula must not be below 0.5% nor exceed 7%; with maximum profitability ratio remaining at 60%.

Policy option 3

Based on the deduction from the assessment of policy option 1 that the royalty formulae are at best revenue-collection instruments, one of the policy options available to the government is to charge royalties using only one of the current formulae. The implication of this is that the current beneficiation intent of the Act would be forfeited. In this regard, policy option 3 involves charging mineral royalties by applying only the current formula for refined minerals (*i.e.* Formula 1, with none of its parameters changed) to both classes of producers. Choosing this option potentially has both positive and negative connotations for both government and investors. To fruitfully establish its impacts, it was important to test the option just like the other options.

Policy option 4

In this option, only the current formula for unrefined minerals (Formula 2) was applied to financial information of the two classes of producers in each commodity sector. None of the parameters in the current formula for unrefined minerals were changed in its application in this model. It should be noted that if government chooses this option, it will have to forfeit the beneficiation intent of the current Royalty Act, just like in option 3. Also, the choice of this option potentially has both positive and negative connotations for both government and investors. To fruitfully establish its impacts, it was important to test the option just like the other options.

Policy option 5

This option involved applying only one formula (a modified version of the formula for unrefined minerals) to both classes of producers. However, it should be noted that if government chooses this policy option, it will have to forfeit the beneficiation intent of the current Royalty Act, as in the case of policy options 3 and 4. To obtain this modified version of the royalty formula, the adjustment of some aspects/parameters of this royalty formula had to be explored[10]. The formula is stated as follows:

For all mineral resources,

$$\text{Royalty rate} = 0.5 + \left[\frac{\textit{Earnings before interest and taxes (EBIT)}}{\text{Gross sales in respect of refined/unrefined mineral resources x 4}}\right] \times 100$$

or

$$R\% = 0.5 + \left(\frac{X}{4}\right); \quad [5]$$

where

$$\text{Profitability ratio (X)} = \frac{\textit{Earnings before interest and taxes (EBIT)}}{\text{Gross sales in respect of refined/unrefined mineral resources}};$$

Formula constant (F-factor) = 4

The royalty rate determined in terms of this formula must not be below 0.5% nor exceed 7%; with maximum profitability ratio being 26% (instead of 60%).

After the final modified formula was realized, statistical tests were carried out on this option just like the other options, to fruitfully establish its impacts.

Discussion of results

The outcomes of the tests conducted on these policy options are as follows:

- *Policy option 1*: The major result of assessing this policy option was that, if the South African government decides to keep the regime unchanged, there would be no 'loss' to the government. This is because the MPRRA in its current state would still effectively collect compensatory revenues for the exploitation of the country's non-renewable resources, as well as additional economic rents when the profitability of mining and refining companies is high.
- *Policy option 2*: To test this option, the modified formula for refined minerals based on the new parameters was applied to financial information on the refined mineral producers in those commodity sectors (except for the peculiar case of the gold sub-sector), just like policy option 1. On the other hand, the current formula for unrefined minerals (formula 2) was applied to the financial information of the miners-only in those sectors. The results indicated that the application of the dual royalty formula showed mixed performance for different commodities. As in option 1, the mixed performance tended more towards the absence of any Realized Beneficiation incentive for the miner-turned-refiner

[10]The details of how the parameters of the MPRRA formula for unrefined minerals were tweaked for this policy option can be found in Akinseye (2019).

as the refiner paid more royalties than the miner-only in the majority of the years assessed, except for the steel/iron ore sub-sector, which appeared to obtain these savings. However, the royalty burden on the refiner in this option was much less than that in option 1. Hence, the implication is that although the royalty formulae appeared to be revenue- generating and rent-capturing instruments, option 2 was likely to provide more beneficiation incentives than option 1.

➤ *Policy option 3*: As with the assessment of policy options 1 and 2, only the current formula for refined minerals was applied to financial information on the two classes of producers in each commodity sector. The observation from this assessment was that even though no Realized Beneficiation incentives accrued to the refiner in general, the magnitude of the royalty burden on the refiner was more than that of option 2 but the same as option 1. On the other hand, the royalty burden on the miner-only was less than that of options 1 and 2.

➤ *Policy option 4*: From the assessment on this option, it was observed that in addition to the fact that no royalty savings accrued to the refiner in general, the magnitude of the royalty burden on the refiner was more than that of options 1 to 3. On the other hand, the royalty burden on the miner- only remained the same as in options 1 and 2.

➤ *Policy option 5*: From the assessment of this option, it was observed that no Realized Beneficiation incentive accrued to the refiner generally. Also, the magnitude of the royalty burden on both classes of producer was more than that of options 1 to 4. This was due to the reduced maximum profitability ratio (from 60% to 26%) and maximum royalty rate parameters of option 5.

These results are summarized in Table II.

After making econometric evaluations of the five policy options, Akinseye (2019) carried out additional assessments and observations with respect to the value-added to the miner-turned-refiner, using different proportions of refinement costs as a percentage of sales price. These assessments were based on unpublished work by Cawood in which he sought to check the effect of different proportions of refinement cost (as a percentage of sales price) in terms of value-added (as deduced from Bradley's 1986 model) in the context of the peculiar provisions of the MPRRA. From the additional assessments, it was clear that of all the five options assessed in terms of Cawood and Bradley's model specifications/recommendations, option 2 stood out as the most satisfactory.

Implications of the policy options in terms of government imperatives

From the evaluations carried out on the five policy options for modifying the MPRRA, the study reiterated that the regime functioned more as a revenue-collection instrument than a beneficiation-fostering instrument. The implication of this is that from the perspective of the representative mining/refining companies used in the study (except the steel/iron ore sector), if the regime's current reduced rate provision for refined products is retained and is the only incentive given to motivate miners to become refiners, the Act's beneficiation objective would generally not be achieved.

Given a situation whereby the South African government was flexible about the topmost priorities/imperatives that the MPRRA is intended to satisfy, the options available for consideration can be summarized as follows.

1. If the most important purpose of the mineral royalty is to earn economic rent, then the government should leave the royalty system as it is currently (*i.e.* policy option 1). This is due to the fact that the revenue-collection benefit of this option to the government and the economy would hold irrespective of whether or not the royalty regime successfully motivates miners to become refiners.
2. If the most important purpose is to motivate miners to become refiners, then the government should leave the royalty formula for unrefined minerals as it is currently, but change the F-factor for the formula for refined minerals from 12.5 to 12 and cap the maximum royalty rate for refined production at 3% (as per policy option 2). It should be noted that, as highlighted in Table II, if the government chooses to adopt this policy option, it stands a chance of motivating more mining companies to move up the mineral value chain by carrying out more mineral beneficiation than with option 1. This will hold because of policy option 2's beneficiation incentive of a reduced maximum royalty rate, from 5% to 3%, that refiners would be charged. Additionally, this policy option could potentially enable the collection of more royalties from refiners using the maximum royalty rate because more refining companies are likely to realize a maximum profitability ratio of 30% per period of assessment (specified by policy option 2) as opposed to a maximum profitability ratio of 60% per period.
3. If the most important purpose of the mineral l royalty is to earn more economic rent than is currently received, while relieving South Africa's primary mining sector in order to ensure its continued existence, then the government should to apply the royalty formula for refined production only (policy option 3) to both classes of mineral producers. As highlighted in Table II, if the government chooses to adopt this policy option, its application to both mining and refining companies would effectively still collect compensatory revenues for South Africa's non-renewable resources and economic rents for the government. Additionally, this policy option proposes to provide a 'gain' to the government due to the lesser royalty burden on the miner-only compared to policy options 1, 2, 4, and 5, because of the reduced maximum royalty rate (5% instead of 7%), thereby aiding the continued existence and survival of South Africa's primary mining sector. However, it is recommended that policy collected might be less than that under policy options 1, 4, and 5 because of the reduced maximum royalty rate (5% instead of 7%). Additionally, the downside of choosing this policy option would be that the government would have to forfeit its intent to use the MPRRA to encourage mining companies to engage in more mineral beneficiation activities.
4. If the most important purpose of the mining royalty is to earn much more economic rent than is currently received (more rent than policy option 3), then the government should to apply the royalty formula for unrefined production only (policy option 4) to both classes of mineral producers.
As indicated in Table II, if the government chooses to adopt this policy option, its application to both mining and refining companies would effectively still collect compensatory revenues for South Africa's non-renewable resources and economic rents for the government. Also,

Table II

Summary of deductions from the five econometric policy options

	Policy option 1	Policy option 2	Policy option 3	Policy option 4	Policy option 5
Formula specifications	Refined minerals: $R\% = 0.5\% + [\frac{x}{12.5}]\%$ Where, Minimum royalty rate = 0.5% Maximum royalty rate = 5%. Unrefined minerals: $R\% = 0.5\% + [\frac{x}{9}]\%$ Where, Minimum royalty rate = 0.5% Maximum royalty rate = 7%	Refined minerals: $R\% = 0.5\% + [\frac{x}{12}]\%$ Where, Minimum royalty rate = 0.5% Maximum royalty rate = 3%. Unrefined minerals: $R\% = 0.5\% + [\frac{x}{9}]\%$ Where, Minimum royalty rate = 0.5% Maximum royalty rate = 7%	For all minerals: $R\% = 0.5\% + [\frac{x}{12.5}]\%$ Where, Minimum royalty rate = 0.5% Maximum royalty rate = 5%.	For all minerals: $R\% = 0.5\% + [\frac{x}{9}]\%$ Minimum royalty rate = 0.5% Maximum royalty rate = 7%	For all minerals: $R\% = 0.5\% + [\frac{x}{4}]\%$ Minimum royalty rate = 0.5% Maximum royalty rate = 7%
Revenue-collection capability	A functional instrument	A functional instrument, but magnitude of collection could be potentially **less than** options 1, 3, 4 and 5.	A functional instrument, but magnitude of collection could be potentially **less than** options 5, 4 and 1.	A functional instrument, but magnitude of collection could be potentially **more than** options 1 – 3	A functional revenue-collection instrument, but magnitude of collection could be potentially **more than** options 1 - 4.
Compensatory charge-collection capability	Yes	Yes	Yes	Yes	Yes
Rent-capturing capability	Yes, the magnitude of revenue receipts flows is in sync with profitability performance.	Yes, the magnitude of revenue receipts flows is in sync with profitability performance.	Yes, the magnitude of revenue receipts flows is in sync with profitability performance.	Yes, the magnitude of revenue receipts flows is in sync with profitability performance.	Yes, the magnitude of revenue receipts flows is in sync with profitability performance.
Tax on beneficiation capability	It appears to be a 'tax on beneficiation'.	It could **potentially reduce** 'tax on beneficiation' as the royalty cost penalty on refiners is reduced as compared to options 5, 4, 3, 1.	It **does not increase or reduce** 'tax on beneficiation' as the royalty cost penalty/burden on refiners continues as per current terms. However, it could potentially reduce royalty cost burden on miners-only as compared to options 1, 2, 4 and 5.	It **increases** 'tax on beneficiation' than options 1 – 3, as the royalty cost penalty/burden on refiners increases more than current terms. Royalty cost burden on miners-only remains like options 1, 2 and 5.	It **increases** 'tax on beneficiation' than other models as the royalty cost refiners and miners-only increases more than current terms.
Complexity of formula(e) specifications	The formulae's of dual formula's specifications are complex.	The formulae's of dual formula's specifications are complex like option 1.	The complexity of calculations associated with dealing with two formulae is reduced as compared to options 1 – 2.	The complexity of calculations associated with dealing with two formulae is reduced as compared to options 1 – 2.	The complexity of calculations associated with dealing with two formulae is reduced as compared to options 1 – 2.
Probability ratio trigger for maximum royalty rate of the formula	The maximum royalty rate of the formula for refiners is triggered when X ≈ 60% or more.	The maximum royalty rate of the formula for refiners is triggered when X ≈ 30% or more. 30% is a more realistic and achievable profitability ratio by more refiners than the X value of the other options.	The maximum royalty rate of the formula for refiners is triggered when X ≈ 60% or more like option 1.	The maximum royalty rate of the formula for refiners is triggered when X ≈ 60% or more like option 1. The combination of increased maximum royalty rate on refiners and maximum X value, makes this model to potentially collect revenues from same number of refiners and miners-only as in the case of option 1.	The maximum royalty rate of the formula for refiners is triggered when X = 26% or more. The combination of increased maximum royalty rate for all producers and acceptable lower maximum X value, enables this model to potentially collect revenues from much more refiners and miners-only than in the case of any of the options.

the magnitude of revenue collection might be greater than that of policy options 1, 2, and 3 because of the high maximum royalty rate of 7% that applies to all mineral producers. However, although this policy option would provide a monetary 'gain' to the government, the downside would be that the royalty burden on refiners would be greatly increased and government would have to forfeit its intent to use the MPRRA to encourage mining companies to engage in more mineral beneficiation activities.

5. If the most important purpose of the mining royalty is to earn much more economic rent than is currently received (more rent than under policy options 1 to 4), then the government should to apply the modified royalty formula for unrefined production only, which specifies that the F-factor for the formula be changed from 9 to 4, and cap the maximum royalty rate for refined production at 7% (policy option 5) for both classes of mineral producers. This implies that if government chooses this policy option, it can expect more mining companies and refining companies to pay royalties using the maximum royalty rate of 7% per year. However, with this policy option, government can still compensate the already 'penalized' refiners due to the added costs of refinement they incur as well as the downward pressure on revenues that they have been experiencing of recent, by allowing the royalty base to have more refinement costs deducted before applying the royalty rate.

Comparing these policy options to the findings and recommendations of the DTC and IMF, as stated in the DTC (2016) report in this respect, the following can be observed:

- Policy option 1 is in line with the DTC's '...preferred alternative of broadly retaining the current royalty system...'
- Policy option 2 is in line with the DTC's '...favour of a hybrid of the 1st and 2nd [IMF] options with an overall preference for option 2...'
- Policy options 3 to 5 are in line with the IMF's option 3 (except for changing the F-factor to 10.5); the DTC did not favour the IMF's option 3.

Conclusion and recommendation

This paper has highlighted the South African government's expectation from the enactment of the MPRRA, *i.e*. that more benefits should be realized from mineral development. Although revenue collection for depletion of renewable natural resources remains the primary objective, another benefit is mineral beneficiation – whereby more mineral producers would become mineral beneficiators/refiners. In deciding how successful the implementation of the regime in realizing its objectives has been so far, this paper suggests that the equitability, economic efficiency, neutrality, and rent collection aspects of the royalty regime are effective. However, the investigation of the regime's beneficiation (refining) policy objective indicated that the system requires some adjustment.

This paper presents different policy options that could be available for adjusting/improving the current mineral royalty regime for the achievement of its intended goals. Therefore, in maintaining its imperative of keeping to the dual formulae and all three main policy objectives of the MPRRA, it is recommended that policy option 2 is the most ideal option for consideration by NT. This option specifies that the current formula for unrefined minerals remains unchanged, while the parameters for the formula for refined minerals be changed to:

$$\text{Royalty rate (\%)} = 0.5\% + \left(\frac{30}{F}\right)\%;$$

where the maximum profitability ratio (X-factor) is 30%, the F-factor for refined minerals is 12, and minimum and maximum royalty rates are 0.5% and 3% respectively-

Furthermore, in choosing this option for 'modifying' the system, government should take note of the following impacts.

- SARS will collect less royalties from companies that are already refining to levels specified in the MPRRA because of the lower maximum rate of payment (from 5% to 3%). Notwithstanding this apparent loss to government, a greater number of refiners would be paying royalties at the maximum royalty rate than is currently the case. This is because refiners will reach the maximum rate much quicker.
- The reduced maximum royalty rate for refiners will encourage more miners to become refiners, which will support for the government's beneficiation objective.

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Integration of strategic open-pit mine planning into hierarchical artificial intelligence

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Synopsis

The mine production scheduling problem (MPSP) has been studied since the 1960s, and remains an active area of computational research. In extending the concepts of the MPSP, the automated mine may now be regarded as a hierarchical intelligent agent in which the bottom layer consists of distributed robotic equipment, while strategic functionality occupies the higher layers. Here we present a disambiguation of artificial intelligence, machine learning, computational optimization, and automation within the mining context. Specifically, the Q-learning algorithm has been adapted to generate the initial solutions for a high-performing strategic mine planning algorithm, originally developed by Lamghari, Dimitrakopoulos and Ferland, based on the variable neighbourhood descent (VND) metaheuristic. The hierarchical intelligent agent is presented as an integrative conceptual platform, defining the interaction between our new Q-learning adaptation and Lamghari's VND, and potentially other hierarchically controlled components of an artificially intelligent mine, having various degrees of automation. Sample computations involving Q-learning and VND are presented.

Keywords

open-pit strategic mine planning, artificial intelligence, machine learning, metaheuristics, Q-learning, variable neighbourhood descent.

Introduction

Solving the mine production scheduling problem (MPSP) consists of identifying which blocks should be mined during each period within the life-of-mine to maximize the total net present value (NPV). This problem is divided into block-level resolution and aggregation methods (Campos, Arroyo, and Morales, 2018) and deterministic and stochastic versions (Lamghari, Dimitrakopoulos, and Ferland, 2014a; 2014b). Finding the optimal schedule is a complex task, and a significant amount of research is indeed oriented towards developing methods to solve more detailed and realistic models (Huang *et al.*, 2020; Lamghari and Dimitrakopoulos, 2016; Villalba and Kumral, 2019). Unfortunately, this complexity involves high computation times, which has led some scholars to deal with this challenge by developing solutions under the aggregation approach (Mai *et al.*, 2019; Tabesh and Askari-Nasab, 2019). However, the block-level resolution presents advantages such as considering the temporality of the problem, opportunity cost when sequencing blocks, and the possibility of obtaining a production plan in a few steps (Campos, Arroyo, and Morales, 2018). On the deterministic side, researchers have developed efficient deterministic algorithms to manage over 1 000 000 blocks and, thus, to tackle realistic-size mines (Rezakhah, Moreno, and Newman, 2020; Rivera *et al.*, 2020; Muñoz *et al.*, 2018). Nevertheless, for open-pit mining, managing stochasticity has shown significant improvements in expected NPV, increasing of the likeliness of meeting production forecast, and finding pit limits larger than those found by deterministic approaches (Lamghari, Dimitrakopoulos, and Ferland, 2014b). This is the main reason why stochastic optimization continues to be an active area of research (Navarra, Grammatikopoulos, and Waters, 2018a).

In the context of open-pit mines, researchers have devised constraints for this type of problem, thereby defining a constrained optimization, as an increasing number of features are considered. Among these formulations, it is possible to find reserve, slope, mining capacity, processing capacity, and stockpiling constraints (Lamghari *et al.*, 2014a; Lamghari and Dimitrakopoulos, 2016). The features include metal uncertainty (Lamghari Dimitrakopoulos, and Ferland, 2014b), geometallurgical modelling (Navarra, Grammatikopoulos, and Waters, 2018a), supply uncertainty (Goodfellow and Dimitrakopoulos, 2016; Senecal and Dimitrakopoulos, 2020), the actions of mineral concentrators (Navarra *et al*., 2017), prevention of excessive movement of mining equipment between benches (Gholamnejad, Lotfian, and Kasmaeeyazdi, 2020), and commodity price uncertainty (Rimélé, Dimitrakopoulos, and Gamache, 2020).

Montiel and Dimitrakopoulos (2015) have extended their focus beyond a single mine and consider the production planning of a 'mining complex'. The authors indicate that a mining complex can be interpreted as a supply chain system where the material is transformed from one activity to another. Any change in the sequence of extraction of the mining blocks modifies the activities downstream, including blending, processing, and transporting the processed material to output stockpiles or ports. This work seeks to extend the paradigm of the MPSP into a broader holistic view (Levinson and Dimitrakopoulos, 2019; Saliba and Dimitrakopoulos, 2019).

Diverse methods have been used to solve the open-pit MPSP, including the Bienstock-Zuckerberg approach, which is based on integer programming with special decomposition techniques (Bienstock and Zuckerberg, 2010; Muñoz *et al*., 2018). However, metaheuristics provide a useful platform for global optimization because of their ability to handle large-scale nonlinear optimization models and fast resolution times. Even though they do not necessarily provide the optimum solution (Navarra *et al*., 2018b), they are extendable to incorporate critical features, including geometallurgical modelling and concentrator actions. Simulated annealing (Mousavi *et al*., 2016; Sari and Kumral, 2016), Tabu Search (Lamghari and Dimitrakopoulos, 2020; Senecal and Dimitrakopoulos, 2020), variable neighbourhood descent (VND) (Navarra *et al*., 2017), and colony optimization (Sattarvand and Niemann-Delius, 2013) are only a few of these metaheuristic approaches used. The VND algorithm developed by Lamghari, Ferland and Dimitrakopoulos (2014a) is among the most effective approaches, giving good performance on realistically sized data-sets, even on a standard desktop computer. Moreover, this approach does not depend on extraneous computation parameters such as the 'temperatures' that are required for simulated annealing (Navarra, Montiel, and Dimitrakopoulos, 2018b).

Given the absence of the extraneous computing parameters, Lamghari's VND is an appropriate metaheuristic algorithm to be hybridized into artificial intelligence (AI) frameworks (Poole and Mackworth, 2017). Indeed, the following development will introduce three new computing parameters related to learning, and it will be beneficial for these parameters not to be confounded with metaheuristic parameters. More broadly, AI-based approaches are gaining interest throughout the mining industry, as evidenced by the demand for practitioners (World Economic Forum, 2018). Besides, AI has been included as part of virtual reality applications in mining (Mitra and Saydam, 2014), considered in mine modernization processes (Jacobs and Webber-Youngman, 2017), and provided advances in mining geomechanics (McGaughey, 2020). The notion of a mine (or mining complex) that can behave as an intelligent agent is appealing, although there does not seem to be a convincing treatment of this notion in the literature.

For instance, McCoy and Auret (2019) describe AI and machine learning in the mineral processing field. One of their conclusions is the identification of a domain knowledge problem, *i.e*. an interdisciplinary gap between data scientists and the current generation of experts in the mineral processing field. The authors state that plant metallurgists may not be the best choice to construct and analyse complex machine-learning models, unless they have a sufficiently broad training in modern quantitative methods. Conversely, data scientists may be equipped to run the analyses but may not be prepared to deal with mineral processing data and systems. This conclusion can be extended upstream into the mining operations, as indicated by Ali and Frimpong (2020); they conducted a study to review and analyse recent automation-related work in different sectors of the mining industry. Despite the papers they found dating between 2008 and 2019 related to AI in mine planning, Ali and Frimpong conclude that there has not been a general approach for critical tasks such as re-optimizing a shift plan of mine activities, predicting activities that can become bottlenecks, and finding patterns in productivity variance.

The authors of the present work strongly believe that a systematic view based on AI is necessary to simulate the behaviour of mining systems when working under a stochastic environment. Therefore, the objective of the study is to reduce the aforementioned interdisciplinary gap by providing the theoretical background to properly extend AI approaches to the mining context. A computational framework will be presented to illustrate the application of the concepts to mine planning and optimization problems, incorporating Lamghari's VND algorithm as a high-level function within an intelligent agent. Under this same approach, an AI algorithm is introduced as a part of the computational framework, opening the discussion about how these algorithms contribute to finding the best way of solving complex problems, extending beyond the relatively nondescript MPSP.

AI and the concept of agents

AI definitions are not unique and have been categorized into four groups: those which are related to how humans think, how human acts, how to think rationally, and how to act rationally (Russell and Norvig, 2016). For this research, an acting rationally approach will be considered, as it is more amenable to scientific development than the other categories (Russell and Norvig, 2016). Some works have used the terms AI and machine learning interchangeably; however, it is essential to clarify that machine learning is a branch of AI concerned with systems that can learn from data in a manner of being trained (Bell, 2014). Actions that are informed from previous training are indeed rational.

The concept of 'agent' is fundamental in the AI field, and is defined as something that acts in an environment (Poole and Mackworth, 2017). As shown in Figure 1, an agent is represented as a combination of a controller and a body by which it perceives stimuli, generates percepts, and gives commands to be performed through actions. A controller is the intelligence (or mind) of the agent that provides the commands, yet it has limited memory and computational capabilities. In contrast, the body is implemented either physically or computationally based on the environment in which the agent may interact.

It is relevant to mention that an agent is autonomous; therefore it is not only constrained to compute online, but it can also perform activities offline (Poole and Mackworth, 2017). Online computation means that organizational tasks are done between observing and acting in the environment, similar to a standard program that gets data, processes it, and then gives the corresponding answer when interacting with a user. In contrast, offline computation is done before it is deployed, not necessarily triggered by an interaction with the environment; however,

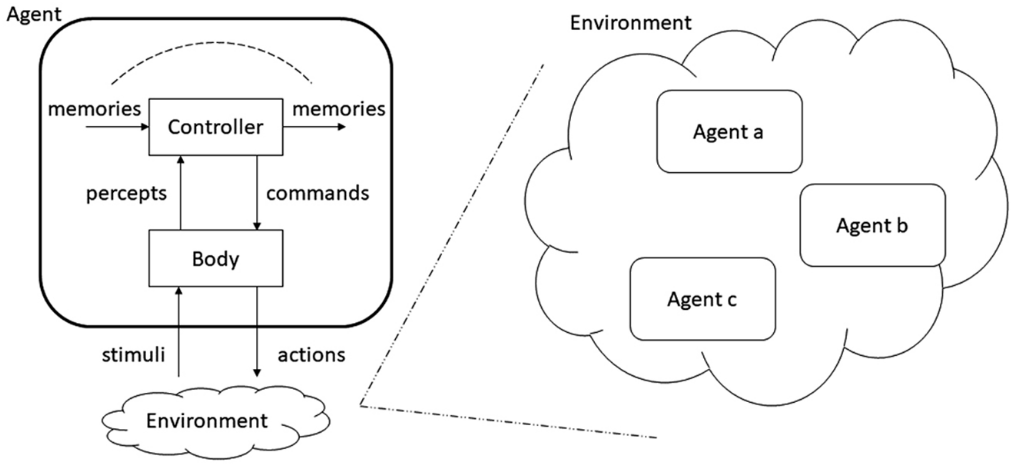

Figure 1—Parts of an agent and its relationship with the environment (adapted from Poole and Mackworth, 2017)

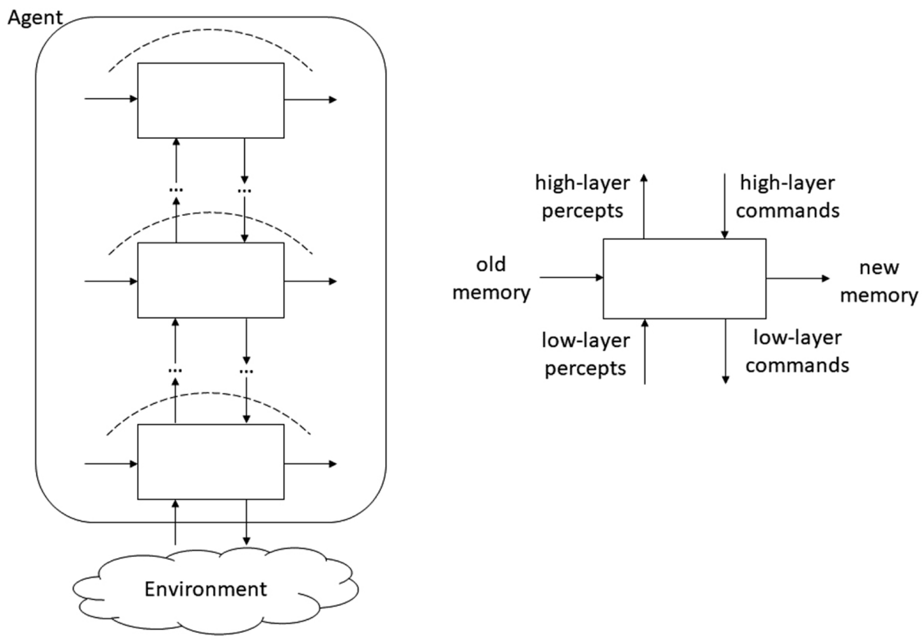

Figure 2—An agent can be seen as a hierarchy of control layers (adapted from Poole and Mackworth, 2017)

these offline computations typically alter how the agent will later respond when it is ultimately deployed in the environment. For instance, machine learning computations are typically done offline, to predetermine how the agent would eventually respond to a set of stimuli when it is online.

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Relying on the definition given, an agent can represent any complex decision or task within a mine or mineral processing plant. The environment may be comprised of other agents, which allows interaction between the agents in a competitive or collaborative manner. Agents enable the modelling and simulation of mining systems, including what-if scenarios that clearly extend the paradigm of MPSP into a holistic view. This is critical due to the suboptimization principle of the general system theory, stating that 'if each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency' (Skyttner, 2001).

The concept of 'agent' generally considers a hierarchy of control layers (Figure 2). Each layer has its own memory and sees the layer below as a virtual body from which it gets percepts and sends commands. Likewise, each layer sees the layer above as a virtual controller where to send percepts and from which to receive commands. This flexibility allows an agent to distribute its reasoning among its layers, reaching specializations, and thus to add more details and complexity as needed.

Strategic mine planning should be understood as a high-layer functionality that parameterizes decisions and actions carried out by lower layers. To represent industrial systems, including mining systems, it may be helpful to decompose the individual layers to represent distributed control systems (Eloranta *et al.*, 2014). Figure 3 illustrates a fully automated mine, in which the centralized strategic planning may consist of one or more layers; the lower layers make decisions within shorter timeframes based on tactical data, whereas the bottom layer consists of automated equipment that is distributed throughout the mine and which can even perform *in-situ* geomechanical analysis (McGaughey, 2020). The individual equipment items (*e.g.* robotic trucks) are equipped with sensors to adjust their immediate actions (*e.g.* a small course correction to avoid debris on the haul road). The sensor data for immediate action is not generally transmitted all the way up to the strategic planning layers, although unexpected incidents can be relayed part-way (*e.g.* sending a signal for another item of equipment, such as a road cleaner to clear the debris).

Open-pit mine plan optimization using Lamghari's VND

Stochastic mine plan optimization involves determining which blocks should be excavated during each period of the mine life, so as to maximize the expected (NPV) of the blocks to be mined. Following the development of Navarra, Grammatikopoulos, and Waters (2018), the expected NPV can be expressed as:

$$f(x) = -c^{Mining}(x) + \frac{1}{n_G}\sum_{g=1}^{n_G} v_g^{Process}(x, y_g(x)) \qquad [1]$$

where

x: The strategic plan that lists which blocks are to be excavated in which time period (longterm decisions)

$yg\,(x)$: Given strategic plan x, describes how and when exactly the blocks are processed if scenario g is realized (short-term decisions)

$c^{Mining}\,(x)$: Discounted mining cost

$v_g^{Process}\,(x, y_g\,(x))$: Discounted value obtained under scenario g as incurred by long-term plan x, and short-term processing decisions $y_g(x)$

n_G: The number of geological scenarios.

The optimization of $f(x)$ is considered to be a two-stage optimization, since $y_g(x)$ is itself the result of a decision-making process,

$$y_g(x) = \underset{y\in\mathcal{Y}_g(x)}{\operatorname{argmax}}\left(v_g^{Process}(x, y)\right) \qquad [2]$$

in which $\mathcal{Y}\,g(x)$ is the set of feasible short-term decision values under geological scenario g and strategic mine plan x. Thus y_g is adjusted in function of the incoming short-term geological information that constitutes the geological scenario. Assuming that the n_G scenarios are equi-probable and generated from the same underlying geological samples, the optimization of f results in a mine plan x that is expected to perform well for the entire distribution of possible scenarios (Navarra, Grammatikopoulos, and Waters, 2018a).

By considering a distribution of geological scenarios, the resulting mine plan ensures enough flexibility to perform effective short-term decisions in the lower layers, even those which are not explicitly characterized by y_g. In practice, n_G is between 10 and 20 scenarios, and each additional scenario has a diminishing impact on the final result.

The strategic mine plan x is a list of block sets x = $[B_1\,B_2 \ldots B_{nT}]$, in which B_t is the set of blocks to be mined in period t, and n_T is the number of periods under consideration within the mine plan. Given a feasible initial solution, Lamghari's VND algorithm

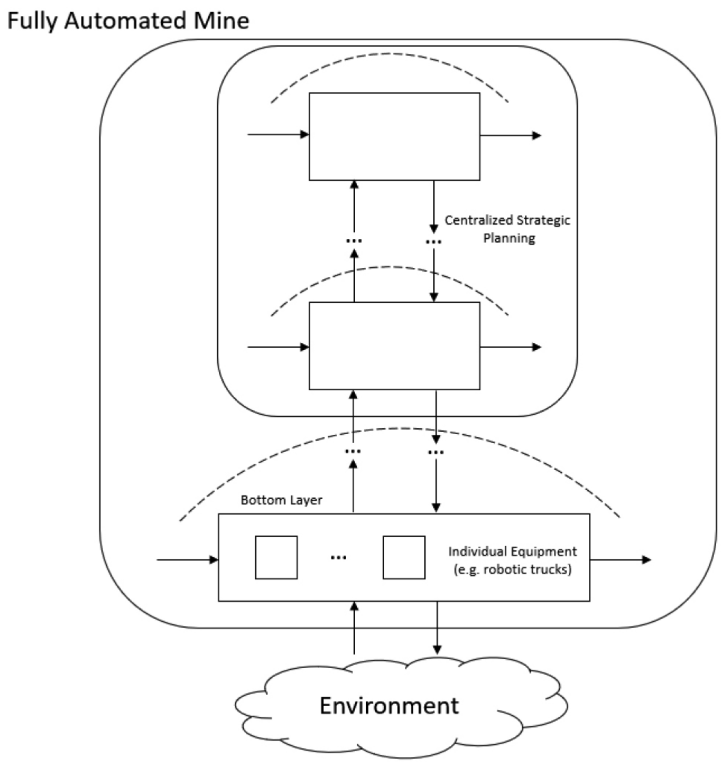

Figure 3—Fully automated mine. Equipment in the bottom layer is physically distributed throughout different sectors of the mining system

performs numerous modifications in which blocks are transferred between the sets B_t. The algorithm considers three types of modifications: Exchange, Shift-After, and Shift-Before. Given a particular period *t*,

- *Exchange*: swaps pairs of blocks that are scheduled to be mined in periods *t* and *t*+1
- *Shift-After*: transfers a block and its successors extracted during the same period *t*, to the subsequent period *t*+1
- *Shift-Before*: transfers a block and its predecessors mined in the same period *t* to the preceding period *t*-1.

Each of these types of movements define a different type of 'neighborhood' within the solution space of feasible mine plans, hence the name 'variable neighborhood descent' (Hansen and Mladenovic, 2001). In traversing from one solution to the next, the algorithm only accepts movements that result in an improvement in the objective *f*, and which are feasible.

Feasibility implies satisfying mining capacity constraints and block precedence constraints. The mining capacity limits the number of blocks that can be excavated within a single period; in general, the capacity is expressed as a maximum tonnage of rock within a given period, considering that each block may consist of a different tonnage of rock. In the open-pit context, the block precedence constraints usually relate to the maximum slope angle required to safely access a given block; for instance, Figure 4 illustrates a 45° maximum slope, such that the grey block cannot not be excavated in period *t* until the white blocks (the predecessors) are excavated in period $t' \leq t$.

Lamghari's VND algorithm is remarkably fast, capable of obtaining near-optimal solutions for industrial-scale problems on a standard laptop within a matter of hours (Lamghari, Dimitrakopoulos, and Ferland, 2014a; Navarra *et al*., 2018b). Nonetheless, the original algorithm was not designed to support detailed descriptions of downstream operations, including mineral processing. In this implementation, any ore that is mined within a given period, and which exceeds the downstream processing capacity, is simply treated as waste rock rather than stockpiled for a future period (Lamghari, Dimitrakopoulos, and Ferland, 2014a, 2014b). However, Navarra, Grammatikopoulos, and Waters (2018) have indicated that strategic stockpiles can be represented within Lamghari's VND through the development of customized data structures. Moreover, the work by Lamghari, Dimitrakopoulos, and Ferland (2014a; 2014b) and Navarra, Grammatikopoulos, and Waters (2018) applies two different approaches to generating an initial solution, as the former uses a linear programming approximation and the latter uses a simplified version of the VND. This aspect of initial solution generation is relevant for other open-pit MPSP metaheuristics, as well as Lamghari's VND. Indeed, the following section presents an entirely different approach to initial solution generation and which has never been published. In principle, there may be several candidates for initial solutions, generated from different algorithms; this motivates a two-layered approach to centralized mine planning depicted in Figure 5, which fits within the larger scheme of Figure 3.

Implementation of Q-learning within the initial solution layer

The inputs into an open-pit mine plan optimization include:

- Geostatistical results from core sampling campaigns to generate scenarios
- Strategic directives that parameterize the broad layout of the expanding open pit, to ensure the safe placement of critical equipment, tailings treatment ponds, *etc*.
- Strategic directives that balance the excavation of different rock types, to ensure favourable ore blends are fed into the process, neutralizing blends of waste rock, *etc*.
- A mechanism to generate an initial solution.

Decisions regarding exploration and sampling campaigns are beyond the scope of the MPSP as developed previously by Lamghari, Dimitrakopoulos, and Ferland (2014a, 2014b), Navarra, Grammatikopoulos, and Waters (2018), and others (Bienstock and Zuckerberg, 2010; Levinson and Dimitrakopoulos, 2019; Montiel and Dimitrakopoulos, 2015; Muñoz *et al*., 2018; Saliba and Dimitrakopoulos, 2019); although they could be part of the future work framed by Figure 3. Moreover, Navarra, Grammatikopoulos, and Waters (2018) give only a cursory discussion regarding strategic directives for linking rock types to concentrator operational modes, identifying data structure development as an avenue for incorporating downstream realism. However, the intelligent generation of MPSP inputs does fit into the hierarchical decomposition of Figure 3. The most basic demonstration of agent-based hierarchization is in the consideration of initial solution generation (Figure 5); the mathematical programming approaches of Bienstock and Zuckerberg (Bienstock and Zuckerberg, 2010; Muñoz *et al*., 2018), and the numerous metaheuristic approaches all rely on *ad-hoc* constructions of initial solutions which undoubtedly affect the performance of the subsequent optimization. The remainder of this section describes a new approach to initial solution generation. This new

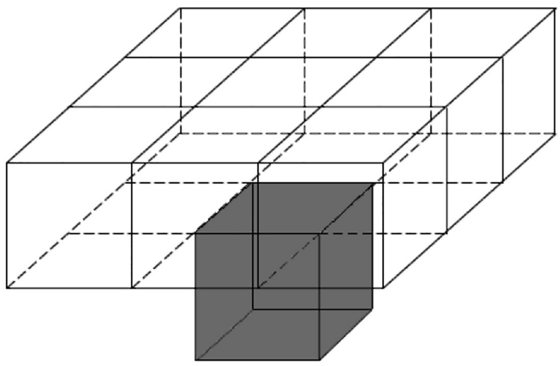

Figure 4—A block may be excavated if its nine overlying blocks have been previously mined (slope constraint)

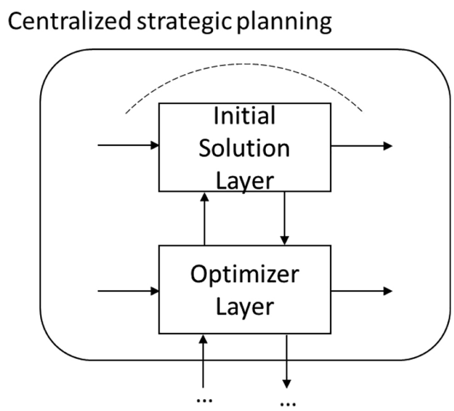

Figure 5—Centralized strategic mine planning, considering distinct layers-for initial solution generation and for optimization

approach has led to unexpected computational results, shown in the following section, regarding what could be the conceptual division between the initial solution layer and the subsequent optimization.

As stated earlier, machine learning is a branch of AI, which postulates that agents behave rationally as a function of what they have previously learnt. There are three main ways by which an agent can do this: unsupervised learning, supervised learning, and reinforcement learning (Russell and Norvig, 2016). In particular, reinforcement learning is a variation of supervised learning, in which the agent 'supervises itself', *i.e.* the agent autosupervises the balance between exploration of new regions of the parameter space and exploitation ('mining') of known regions of the parameter space. In contrast, conventional supervised learning is concerned with the relation of input predictor variables $\mathbf{x}_i$, and output observable variables $\mathbf{x}_i$, and is an extension of classical statistical regression applied to data pairs ($\mathbf{x}_i$, $\mathbf{x}_i$), for observations $i = 1, 2, \ldots n$. The distinction between supervised and unsupervised learning is that the former considers pairs ($\mathbf{x}_i$, $\mathbf{y}_i$) in determining predictive patterns, while the latter foregoes the (human) supervised distinction between predictor and observable variables, effectively incorporating all significant variables into $\mathbf{y}_i$. In addition to the three main categories of machine learning (unsupervised, supervised, and reinforcement), some authors consider a fourth category 'semisupervised learning', which employs a combination of supervised and unsupervised techniques (Russell and Norvig, 2016).

Reinforcement learning is arguably the most appropriate approach in the initial solution layer, since the agent does not initially know the composition of the orebody, relying merely on geostatistical estimations. Reinforcement learning allows the agent to gain knowledge from a series of reward or punishment outcomes each time it acts. The agent is not told which movement to take but instead must discover which actions yield the most reward by trying them (Sutton and Barto, 2018). The concept of a policy emerges, which is the set of rules that tell the agent how to behave given a specific state (Sutton and Barto, 2018). As an agent learns a strategic planning policy, it is enabled to make better decisions and act rationally in the *ad-hoc* construction of a strategic plan.

In this regard, pioneering work was done by Askari-Nasab in developing an intelligent open-pit simulator (IOPS) that comprises algorithms based on reinforcement learning (Askari-Nasab, Frimpong, and Szymanski, 2007, 2008; Askari-Nasab and Awuah-Offei, 2008, 2009). These works are based on the aggregation method, which lacks certain advantages mentioned in the introduction, such as the consideration of the temporality of the problem, opportunity cost when sequencing blocks, and the possibility of obtaining a production plan in a few steps (Campos, Arroyo, and Morales, 2018). The current study is a further incorporation of reinforcement learning, which is better described as a block-level resolution method since the proposed learning process relies on geological scenarios, characterized by scenario-specific attribute values within each mine block, as explained in the previous section.

An orebody is represented by a set of blocks with specific coordinates XYZ. For simplicity, the orebody can be confined to a bounding cube, and each block is an equally sized right-angled prism. Moreover, each of the blocks can be ascribed a state value, *i.e.* a value that describes the extent to which the block data has been learnt by the agent and has hence been incorporated into the agent's policy. In describing these state transitions, a Markov decision process (MDP) is a classical formalization of sequential decision-making wherein actions influence not just immediate rewards, but also subsequent states and indeed the future rewards. Figure 6 presents how an agent interacts with the environment under an MDP approach. When an agent reaches a state S_t in the environment, it obtains a reward R_t, and is enabled to perform an action A_t. This action will take the agent to a state S_{t+1}, earning a reward R_{t+1}, and so on.

The actions taken to discover the patterns in an orebody are to explore north, south, east, west, up, and down as shown in Figure 7. It is important to keep in mind that these movements are not necessarily the way that blocks will be extracted but are only the way the agent is exploring the orebody for learning purposes, *i.e.* in the construction of its planning policy.

Q-learning is an algorithm that allows the agent to learn the optimal policy from its history of querying the environment. A Q-learning agent learns a Q-function, which gives the expected utility of taking a given action in a state, the so-called Q-value or 'quality'. Even though after many iterations the Q-values converge, these values should not be confused with the real utility of the movement; it is only a way of creating a policy based on the expected utility. This approach seems appropriate for the construction of an initial solution for the MPSP, but it is questionable how much subsequent optimization will be required. The basic algorithm is presented in Figure 8.

The outcome of a Q-value is based on the state and the action Q[*s*,*a*], which means that from a state with four possible movements it will consist of four Q-values. The update of the two-dimensional array Q[*s*,*a*] is given by line 16 of the algorithm.

$$Q[s,a] \leftarrow Q[s,a] + \alpha(r + \gamma \max_{a'} Q[s',a'] - Q[s,a]) \quad [3]$$

where *s* is a state, *a* is the action carried out on the state, *s'* is the next state, *a'* is the next action from this next state *s'*, *r* is the reward obtained after being in state *s* and performing action *a*, and finally the parameters α and γ are the learning and discount factors respectively, both of which are in the range 0 to 1. The

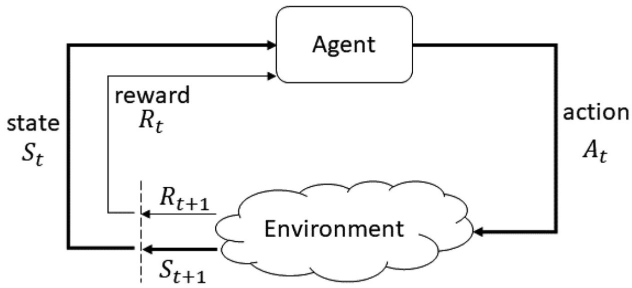

Figure 6—Interaction under an MDP approach (Sutton and Barto, 2018)

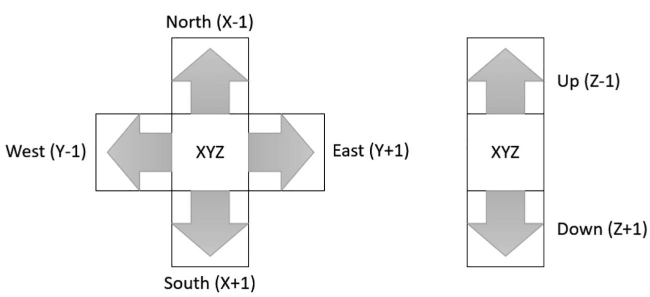

Figure 7—Actions considered in order to learn from the orebody

```
controller Q-learning(S,A,γ,α)
2:      Inputs
3:              S is a set of states
4:              A is a set of actions
5:              γ is the discounter factor
6:              α is the learning factor
7:      Local
8:              real array Q[S,A]
9:              state s, s' ∈ S
10:             action a ∈ A
11:     initialize Q[S,A] arbitrarily
12:     observe current state s
13:     repeat
14:             select and carry out an action a
15:             observe reward r and next state s'
16:             Q[s,a] ← Q[s,a] + α(r + γmax_a' Q[s',a'] - Q[s,a])
17:             s ← s'
18:     until termination
```

Figure 8—Q-learning algorithm (adapted from Poole and Mackworth, 2017)

learning factor α quantifies the contribution of the (modified) difference between the maximum Q-values of the next state and the current Q-value, in updating the Q-value array. The discount factor ϒ measures the extent to which the possibility of future rewards is prioritized at the expense of known short-term gains; if ϒ = 1, the equation favours patience in considering that the motion *s* to *s´* may eventually lead to future possible rewards, whereas ϒ = 0 causes the agent to be greedy for the immediate rewards as it ignores all possible future rewards.

Data scientists consider that an agent must balance short-term exploitation to maximize its immediate reward and exploration to maximize its long-term wellbeing. Pure exploitation risks getting stuck in a rut, whereas pure exploration to improve one's knowledge is of no ultimate use if the learnt knowledge is not implemented in an action plan. An additional parameter ϵ is introduced in line 14 of the algorithm (Figure 8) to select an action based on the following random function.

$$f(\epsilon, s) = \begin{cases} max_a Q(s), \; with\; probability\; 1-\epsilon \\ \quad random\; a, otherwise \end{cases} \qquad [4]$$

Therefore, the current implementation of Q-learning considers three parameters: α, ϒ, and ϵ. However, this is a manageable number since the optimizer layer is based on Lamghari's VND algorithm and thus does not introduce any additional parameters. The tuning of (α,ϒ,ϵ) could in principle be a task that would be part of the initial solution layer (Figure 5), measuring the performance of the subsequent optimization as a function of (α,ϒ,ϵ). However, the following sample computations consider static values of (α,ϒ,ϵ) = (1, 0.7, 0.3), which were deemed acceptable from preliminary computational trials. Additionally, all of the Q-values have been initiated to zero, but different configurations may also be considered as part of future research.

In the following sample computations, the initial mine plan is constructed from the Q-learning algorithm, considering the actions defined by Figure 7. As a first action, the surface block with the highest economic block is found (Z=1) and is selected to be mined in the first period, *i.e.* it is included in B1. In the current scope, each subsequent action is to extract a selected block plus all its predecessors, while respecting the slope (Figure 4) and mining capacity constraints. The actions are north, south, west, east, and down. For instance, Figure 9 presents the blocks that would be mined if the action 'down' were selected.

The following section is the first attempt at developing an automated mine as a hierarchically controlled intelligent agent, which segregates the MPSP optimizer from one of its computational inputs. The computational input is, in this case, the initial solution. Other inputs could be the results of dynamic geological sampling and metallurgical plant tests (Navarra, Grammatikopoulos, and Waters, 2018a), which may be the subject of future work.

Sample computations

An agent described by Figure 5 has been applied to an ore deposit composed of 9953 blocks, in which the initial solution is generated according to the Q-learning algorithm described in the previous section, and the optimization is based on Lamghari's VND algorithm. However, it is relevant to mention that since the agent includes this orebody within a bounding cube, the number of blocks increases to 144 420. The bounding cube includes all potential blocks that would be predecessors of the original 9953 blocks. Conditional simulation has allowed the generation of 20 scenarios for this deposit, 10 of which have been used to construct an optimized mine plan, while the other 10 are used for an a-posteriori construction of cumulative NPV profiles that will be discussed below (Figure 10).

The sample computations are based on the same set of geological scenarios presented by Navarra, Grammatikopoulos,

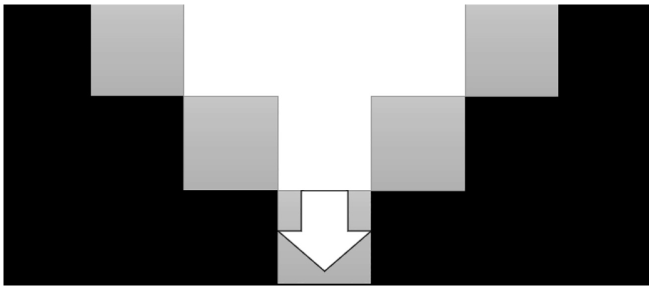

Figure 9—Blocks extracted (in grey) if action 'down' is selected

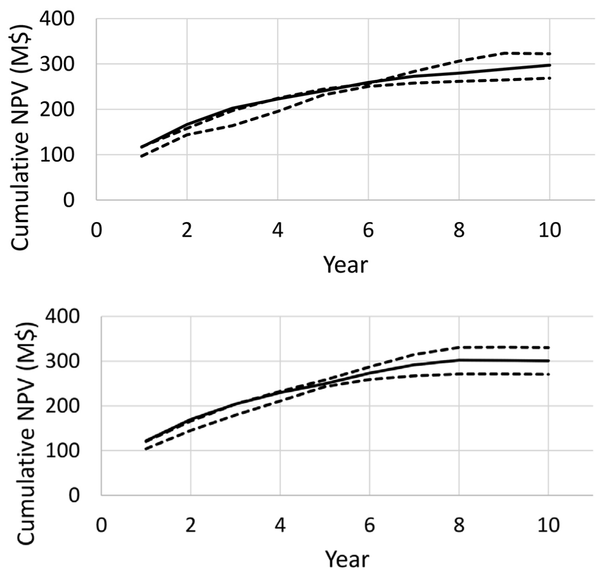

Figure 10—Cumulative NPV. 10th, 50th, and 90th percentiles, (a) before optimization, and (b) after optimization

and Waters (2018) to provide a comparison. Each of the blocks has identical dimensions, 20 m × 20 m × 10 m, and identical weight of 10 000 t. Based on the scenario, the blocks have a higher or lower grade of a certain metal, which varies from 0.01% to 4.14%, with an average of 0.33%. The operational data for this calculation is presented on Table I.

The Q-learning and VND algorithms were programmed in C++ and run on a standard ASUS laptop with an Intel Core™ i5 CPU, and 8 GB of RAM. The total computations were completed in roughly 60 minutes. The previous computations in 2018 apply the VND algorithm and were completed is roughly 90 minutes; this earlier work used a slightly older laptop, having an i3 CPU and 4 GB of RAM. It was surprising, however, that the newer computations devote over 95% of the computation time to initial solution generation, whereas the previous work devoted roughly 50%. This has caused us to reinterpret the potential roles of the initial construction of a plan, *versus* its final optimization (*i.e.* refinement), which will be discussed below.

The learning parameters (α,γ,ϵ) were set to (1, 0.7, 0.3) following preliminary experimentation. For simplicity, the preliminary tests assumed $\alpha = 1$, and $(\gamma + \epsilon) = 1$, and so only the balance between γ ϵ and ϵ was modified. The control of these learning parameters may be a moot point, however, since an initial solution layer can include parallel computing that would simultaneously attempt a spectrum of parameter values (and possibly even several completely different algorithms), transmitting only the most promising ones as candidates for subsequent optimization. Moreover, this balance between γ and ϵ did not affect the outcome in any observable manner.

It was surprising that the initial solution generator produced high-value solutions comparable to those obtained in previous work (Navarra, Grammatikopoulos, and Waters, 2018a), with the life-of-mine NPV of approximately $300 million over ten years (Figure 10a). Furthermore, the subsequent VND optimization was completed in under three minutes, and did not result in a notable increase in the life-of-mine NPV, as the spread between the 10th and 90th percentiles is $269 million to $323 million for the preoptimized (Figure 10a) and $271 million to $330 million for the optimized (Figure 10b); thus the 10th percentile was improved by 1% and the 90th percentile by 2%, which is surprisingly small.

The VND algorithm clearly does have an impact. However, since the optimized plan effectively completes the production in eight years, rather than ten, considering that the curves in Figures 11 and 10b are approximately flat after year 8; for comparison, the pre-optimized solution yields between $261 million and $306 million in the first eight years, whereas the optimized solution yields the complete life-of-mine NPV, between $271 million and $330 million, which is between 4% and 8% higher. Moreover, the optimized solution is observed to be less erratic in the first five years of the mine life, as all three curves follow a gradual attenuation. The optimization also has a noteworthy impact on the shape of the pits, as illustrated in Figure 12; the optimized plan is organized such that only the very bottom of the deposit is excavated after the end of year 8 (Figure 12b), whereas the pre-optimized plan continues a broad advancement into years 9 and 10 (Figure 12a). The same figures also indicate the high number of active benches in the periods, which typically happens in the absence of a dedicated constraint, as developed by Gholamnejad, Lotfian, and Kasmaeeyazdi (2020). In practice this might be fixed in a subsequent step by a postprocessing algorithm that refines the mine plan generated, although approaches similar to Gholamnejad, Lotfian, and Kasmaeeyazdi (2020) may be superior.

The authors were genuinely surprised by the effectiveness of the Q-learning, but refrain from drawing overly broad conclusions. For the given sample calculations, much of the computational effort was consumed by the initial solution generation, which resulted in a high expected NPV. The subsequent application of the VND optimization was comparatively short and did not significantly increase the life-of-mine NPV, but did however enhance the solution by shortening the life of mine and smoothing

Table I

Operational data

Effective metal price	$5000 per ton
Annual discount rate	8%
Maximum pit angle	45°
Mining capacity	15 Mt/a
Mining cost	$1.5 per ton
Processing capacity	6 Mt/a
Processing cost	$6 per ton
Recovery	85%

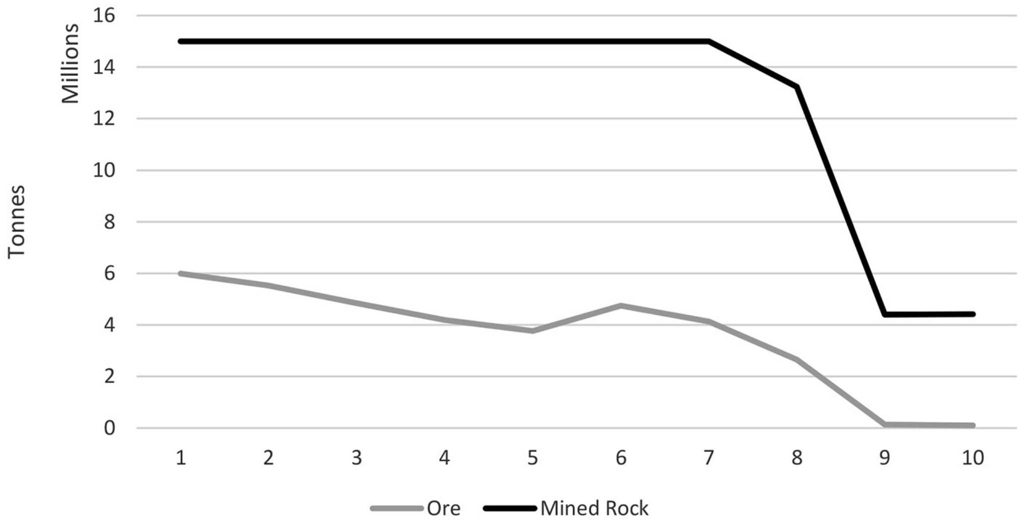

Figure 11—Production chart of the schedule after optimization

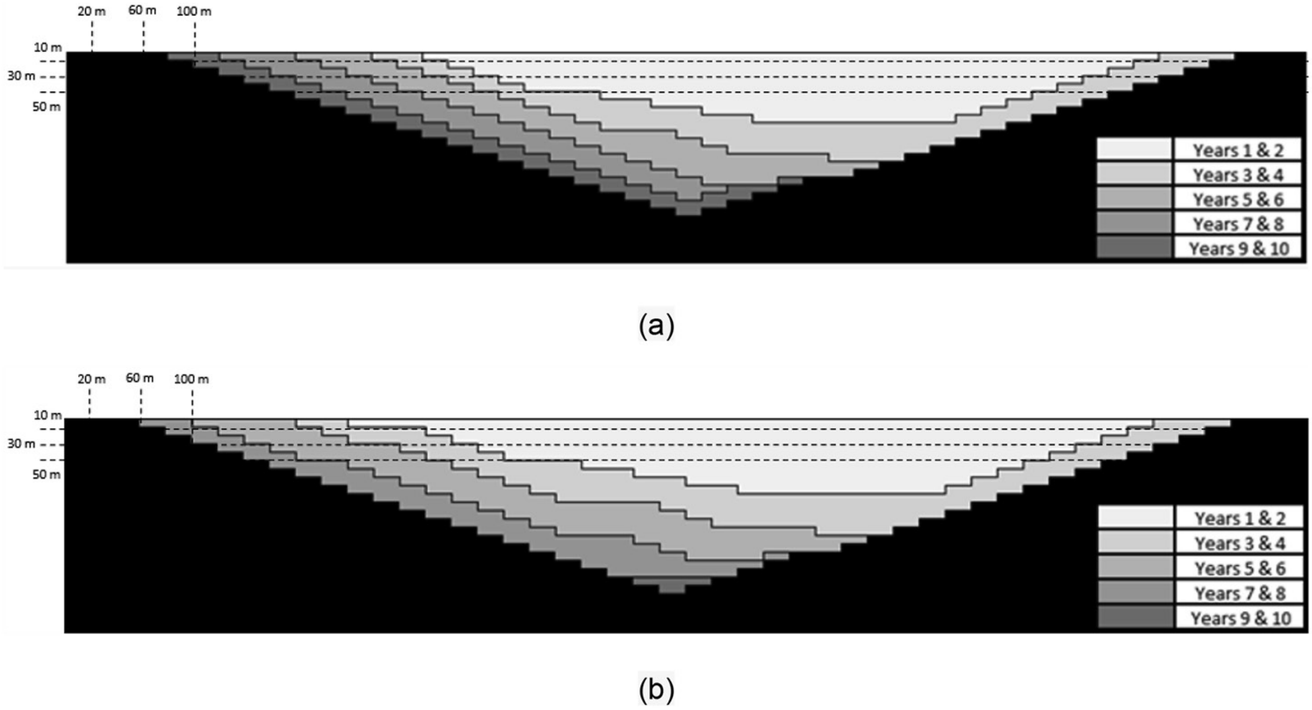

Figure 12—XZ-planar cut along Y = 6 of mine plan (a) prior to optimization and (b) after optimization

the cumulative NPV profiles. Given that the VND algorithm has been previously published and validated, its impact within the current implementation is to refine the plan constructed by Q-learning, as well as creating a final plan that is validated. Indeed, the VND algorithm ensures that the final solution cannot be further improved within the Exchange, Shift-Before, and Shift-After neighbourhoods that were initially conceived by Lamghari, Dimitrakopoulos, and Ferland (2014a). The definition of additional neighbourhoods would allow further avenues of refinement and validation for the results of Q-learning, or potentially any other approach to initial plan generation.

Conclusions and future work

This paper introduced essential notions of AI and machine learning to embed strategic mine planning within the higher layers of an intelligent agent. The intent of this work is to favour future interdisciplinary work. The concepts were demonstrated in the generation of sample computations, showing their suitability in contributing to MPSP research (Navarra, Grammatikopoulos, and Waters, 2018a). Moreover, an agent can be divided into several layers to reach specialization, allowing the hierarchical modelling of complex mine operations problems, thereby extending the scope of MPSP research to consider the tactical coordination of robotic equipment (Figure 3).

Within the sample computations, the policy developed by the Q-learning algorithm explores the orebody successfully, as it identifies those blocks that if excavated sooner will ultimately result in a higher NPV. A similar approach could be adapted for underground mines. Other opportunities for future work include:

- Further comparisons and hybridization of initial solution generation, which could be refined through VND optimization
- Inclusion of more features in the agent such as operational modes, stockpiling, efficient number of active benches, coordination of robotic equipment, *etc*.
- Improvements to deal with more extensive mines (a greater number of blocks)
- Exploration of the collaborative and competitive relation between agents within mining systems
- Finding new ways of applying other AI structures (such as neural networks) to MPSPs.

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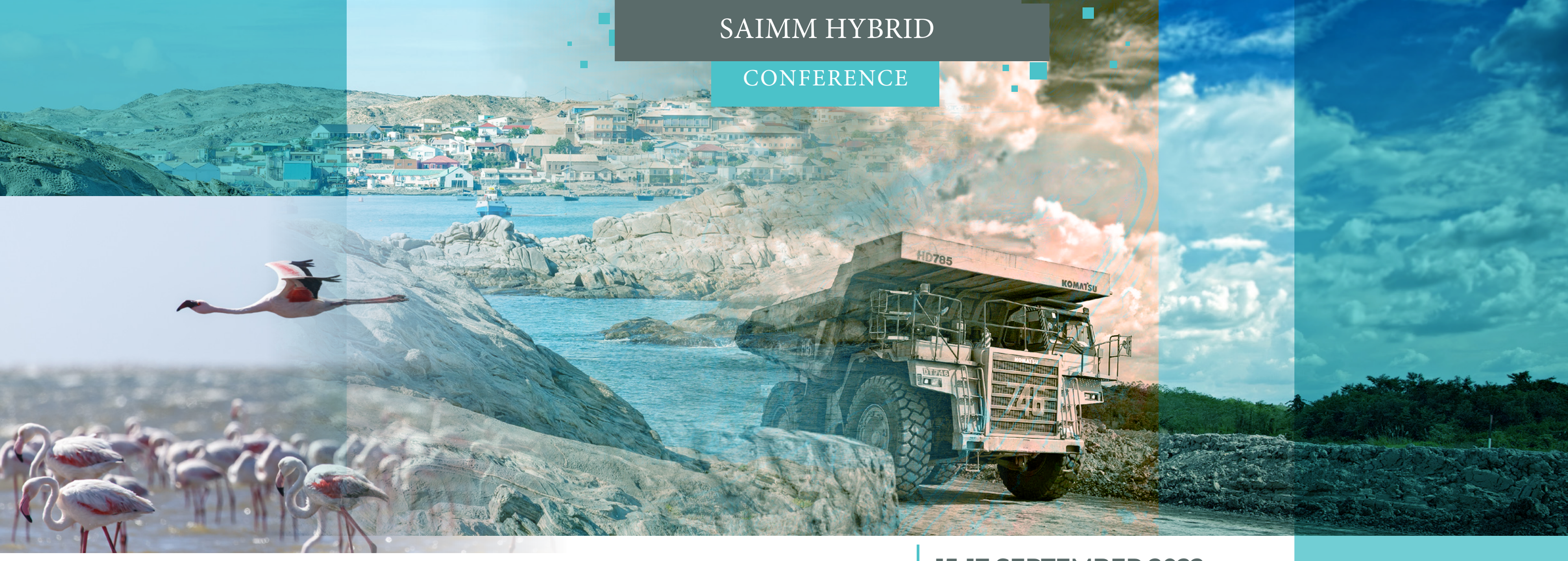
AEL Mining Services Limited
African Pegmatite (Pty) Ltd
Air Liquide (PTY) Ltd
Alexander Proudfoot Africa (Pty) Ltd
AMEC Foster Wheeler
AMIRA International Africa (Pty) Ltd
ANDRITZ Delkor (Pty) Ltd
Anglo Operations Proprietary Limited
Anglogold Ashanti Ltd
Arcus Gibb (Pty) Ltd
ASPASA
Aurecon South Africa (Pty) Ltd
Aveng Engineering
Aveng Mining Shafts and Underground
Axiom Chemlab Supplies (Pty) Ltd
Axis House Pty Ltd
Bafokeng Rasimone Platinum Mine
Barloworld Equipment -Mining
BASF Holdings SA (Pty) Ltd
BCL Limited
Becker Mining (Pty) Ltd
BedRock Mining Support (Pty) Ltd
BHP Billiton Energy Coal SA Ltd
Blue Cube Systems (Pty) Ltd
Bluhm Burton Engineering (Pty) Ltd
Bond Equipment (Pty) Ltd
Bouygues Travaux Publics
Castle Lead Works
CDM Group
CGG Services SA
Coalmin Process Technologies CC
Concor Opencast Mining
Concor Technicrete
Council for Geoscience Library
CRONIMET Mining Processing SA Pty Ltd
CSIR Natural Resources and the Environment (NRE)
Data Mine SA
Digby Wells and Associates
DRA Mineral Projects (Pty) Ltd
DTP Mining - Bouygues Construction
Duraset
Elbroc Mining Products (Pty) Ltd
eThekwini Municipality
Ex Mente Technologies (Pty) Ltd
Expectra 2004 (Pty) Ltd
Exxaro Coal (Pty) Ltd
Exxaro Resources Limited
Filtaquip (Pty) Ltd
FLSmidth Minerals (Pty) Ltd
Fluor Daniel SA (Pty) Ltd
Franki Africa (Pty) Ltd-JHB
Fraser Alexander (Pty) Ltd
G H H Mining Machines (Pty) Ltd
Geobrugg Southern Africa (Pty) Ltd
Glencore
Gravitas Minerals (Pty) Ltd
Hall Core Drilling (Pty) Ltd
Hatch (Pty) Ltd
Herrenknecht AG
HPE Hydro Power Equipment (Pty) Ltd
Huawei Technologies Africa (Pty) Ltd
Immersive Technologies
IMS Engineering (Pty) Ltd
Ingwenya Mineral Processing (Pty) Ltd
Ivanhoe Mines SA
Joy Global Inc.(Africa)
Kudumane Manganese Resources
Leica Geosystems (Pty) Ltd
Longyear South Africa (Pty) Ltd
Lull Storm Trading (Pty) Ltd
Maccaferri SA (Pty) Ltd
Magnetech (Pty) Ltd
Magotteaux (Pty) Ltd
Malvern Panalytical (Pty) Ltd
Maptek (Pty) Ltd
Maxam Dantex (Pty) Ltd
MBE Minerals SA Pty Ltd
MCC Contracts (Pty) Ltd
MD Mineral Technologies SA (Pty) Ltd
MDM Technical Africa (Pty) Ltd
Metalock Engineering RSA (Pty) Ltd
Metorex Limited
Metso Minerals (South Africa) (Pty) Ltd
Micromine Africa (Pty) Ltd
MineARC South Africa (Pty) Ltd
Minerals Council of South Africa
Minerals Operations Executive (Pty) Ltd
MineRP Holding (Pty) Ltd
Mining Projections Concepts
Mintek
MIP Process Technologies (Pty) Ltd
MLB Investment CC
Modular Mining Systems Africa (Pty) Ltd
MSA Group (Pty) Ltd
Multotec (Pty) Ltd
Murray and Roberts Cementation
Nalco Africa (Pty) Ltd
Namakwa Sands(Pty) Ltd
Ncamiso Trading (Pty) Ltd
New Concept Mining (Pty) Limited
Northam Platinum Ltd - Zondereinde
Opermin Operational Excellence
Optron (Pty) Ltd
Paterson & Cooke Consulting Engineers (Pty) Ltd
Perkinelmer
Polysius A Division Of Thyssenkrupp Industrial Sol
Precious Metals Refiners
Rams Mining Technologies
Rand Refinery Limited
Redpath Mining (South Africa) (Pty) Ltd
Rocbolt Technologies
Rosond (Pty) Ltd
Royal Bafokeng Platinum
Roytec Global (Pty) Ltd
RungePincockMinarco Limited
Rustenburg Platinum Mines Limited
Salene Mining (Pty) Ltd
Sandvik Mining and Construction Delmas (Pty) Ltd
Sandvik Mining and Construction RSA(Pty) Ltd
SANIRE
Schauenburg (Pty) Ltd
Sebilo Resources (Pty) Ltd
SENET (Pty) Ltd
Senmin International (Pty) Ltd
SISA Inspection (Pty) Ltd
Smec South Africa
Sound Mining Solution (Pty) Ltd
SRK Consulting SA (Pty) Ltd
Time Mining and Processing (Pty) Ltd
Timrite (Pty) Ltd
Tomra (Pty) Ltd
Traka Africa (Pty) Ltd
Ukwazi Mining Solutions (Pty) Ltd
Umgeni Water
Webber Wentzel
Weir Minerals Africa
Welding Alloys South Africa
Worley



SDIMI 2022

SUSTAINABLE DEVELOPMENT IN THE MINERALS INDUSTRY

10TH INTERNATIONAL CONFERENCE

15-17 SEPTEMBER 2022
CONFERENCE

17-20 SEPTEMBER 2022
TOURS AND TECHNICAL VISITS

WINDHOEK COUNTRY CLUB & RESORT, WINDHOEK, NAMIBIA

Making economies great through sustainable mineral development

It is my pleasure to invite you to **SDIMI (Sustainable Development in the Minerals Industry) 2022**, the 10th of a series of conferences whose objective is to assist the global mining and minerals industries in their transition to sustainable development. The conference will take place from (*15-20 September 2022*) in Windhoek and will run under the theme (Making Economies Great through Sustainable Mineral Development). This will be a **hybrid conference** entailing a real-time, face-to-face component as well as a virtual component.

We celebrate a journey that commenced in 2003 in the historic town of Milos, Greece, when the landmark **MILOS DECLARATION** was adopted. The **MILOS DECLARATION** represents a statement of our collective contribution to a sustainable future using scientific, technical, educational, and research skills and knowledge in minerals extraction and utilization that was endorsed by the leading global professional and scientific organizations and institutes representing the minerals professionals. SDIMI 2022 aims to continue with our noble journey by building on the progress we have made since 2003.

THE CONFERENCE TOPICS ARE AS LISTED BELOW

- Mining industry's response to covid-19 : Impact and learning points
- Artisanal and Small-scale mining
- Mining in Africa and its Unique Challenges
- Social Licence to Operate
- Circular Economy
- Mining in Protected Areas
- Uranium Mining
- Marine Mining
- Mining towards a renewable future – lithium, rare earths, strategic minerals *etc.*
- Precious gems
- Fair Trade of raw materials (Minerals)
- Critical Minerals
- Advances in life cycle and sustainability assessment in the industry
- Integration of sustainability thinking into professional education
- Economic sufficiency
- Water Stewardship
- Policy and Regulatory Framework
- Mine Closure and repurposing case studies
- Tailings management
- Mineral Beneficiation and value chains
- Energy Efficiency
- Space mining

FOR FURTHER INFORMATION, CONTACT:

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SAIMM

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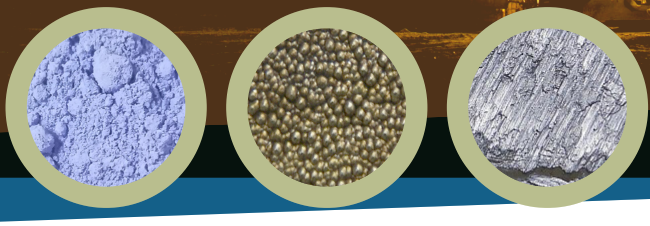
NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

SAIMM
THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

BATTERY MATERIALS CONFERENCE 2022

24-25 AUGUST 2022

MISTY HILLS CONFERENCE CENTRE,
MULDERSDRIFT, JOHANNESBURG



The intensified search over the past decade for alternatives to fossil-fuels as stores of energy has led to an exponential growth in the demand for batteries and research into battery technologies. The largest application by far has been in transportation, followed by electrical distribution grids.

Of the raw materials required for battery manufacture, metals such as cobalt, manganese and vanadium are highly concentrated in southern Africa. The supply of lithium, on the other hand, is concentrated in Australia, Chile and Argentine.

These activities have created both opportunities and challenges. Opportunities such as new value chains for the associated raw materials, with several production companies with battery-material metals in their plant feedstocks undertaking research towards producing battery-grade products. And challenges such as the means for recycling these batteries once they reach the end of their (first) life.

The aim of this conference is to provide the opportunity for thought leaders in the global battery value chain to exchange ideas on recent developments in the fields of:

- Materials and high-purity intermediates for battery components
- Flow-battery electrolytes
- Processes for the recycling of batteries
- Market outlook and legislative implications
- Related case studies.

KEYNOTE SPEAKERS

Prof. Jacques Eksteen
Chair for Extractive Metallurgy,
WA School of Mines: Minerals, Energy and Chemical Engineering & Research Director,
Future Battery Industries Cooperative Research Centre

Dr. Nils Rainer Backeberg
Guest Researcher, Cape Geo

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