Mechanical Rock-cutting Technical Design Study Phase II_(a)

PROGRAMME	Mechanised Mining Systems	**WORK PACKAGE**	**MMS24WP3** Mechanical Rock-cutting Technical Design Study Phase II_(a)

FINAL CLOSE-OUT REPORT

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MINDS FOR MINES

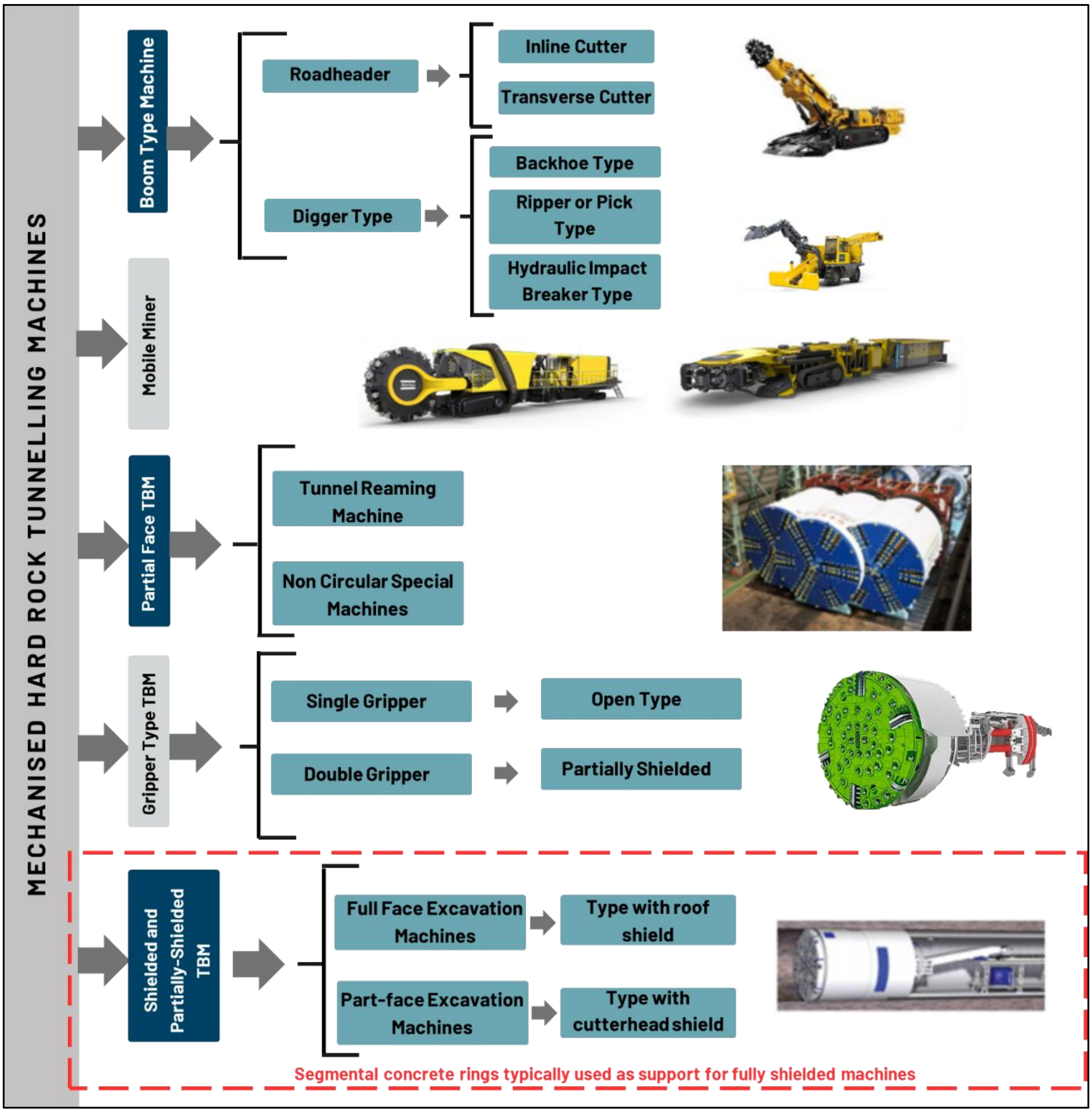
1 EXECUTIVE SUMMARY

Tunnel boring using mechanical rock-cutting is a method employed to construct tunnels through solid rock. Typically, this technique uses specialised machinery called tunnel boring machines (TBMs) equipped with rotary cutters or disc cutters that break and excavate rock by chipping away the rock face.

These machines are designed to handle a very specific set of conditions, meaning that multiple machines with different designs are sometimes utilised or required for a single tunnelling project. The cutting process involves rotating cutters or moving impact positions, which gradually wear away the rock while the rotation allows for simultaneously removing debris. This method is particularly advantageous due to its precision, efficiency and absence of cyclical excavation processes. The excavation also typically has a smoother tunnel surface and potentially faster rates than traditional drilling and blasting techniques. Somewhat different to tunnel excavation is the mechanical cutting of the tabular reefs in South Arica and this is the focus of this report.

The push towards optimised continuous mining was initiated in the 1960's in South Africa. The need for mechanisation and safer operations, coupled with the desire to improve overall mining efficiencies, led to various mining houses, manufacturers and research bodies joining forces to study various mechanised mining systems. The first started in the 1960s with diamond wire cutting (Barnes, 1969) and the development of the first prototype continuous rock cutter developed by COMRO in 1968. Further development of cutter assembly variations ensued with the likes of swing-hammer and impact ripper machines discussed by Joughin (1976). Most of these initial developments happened in the gold mining industry in South Africa with the key shift being the advent of raise boring technology. Reef boring trials is first described by Wilson and Graham (1974).

Although studies in gold mines continued, from the 1980's the trend of technological advancements, especially non-explosive rock-breaking, are noted extensively within the platinum sector of South Africa as this became a means to a survival strategy to combat market factors and labour costs. The CSIR (Miningtek) set out to develop a drum cutter head with disc cutters in the late 1990's and early 2000's, specifically aimed at mining UG2 reef in platinum mines in South Africa. Also developed around that time was the famous ARM1100 hard rock narrow reef miner trialled at Lonmin platinum mines as well as mines of Impala Platinum (see Pickering and Ebner, 2002; Moxham, 2004; Picket et al., 2006). Most of the rock-cutting projects after the ARM1100 to date have been on platinum mines in South Africa, with current projects in Twickenham mine (Anglo American), Modikwa and Bokoni platinum mines (ARM and Impala). The Mobile Tunnel Borer project at Anglo's Mogalakwena mine is believed to have been terminated in 2023 following several challenges such as overall cost incurred, water management, ore handling capability, additional unplanned support requirements (due to blocky ground), low advance rates and breakdowns. The diagram below summarises the technology developed for mechanised hard rock tunnelling.



Considering the operational environment of the SAMI, the Gold and Platinum operations would, typically, not consider a machine that makes use of segmental concrete rings, as this is a very expensive support medium and far exceeds the typical support requirements of a mining operation. The machine selection forms part of the final design before ordering.

Mechanical rock-cutting in South Africa

The study found that mechanical rock-cutting has a rich history in South African mines since the 1950's rock-cutting. Although the technology has been successfully implemented in coal mining, the development and implementation of hard rock-cutting applications have been slow due to the lack of appropriate funding for research in this domain as well as some technological constraints.

Most of the developments in hard rock-cutting were focused on off-reef development such as shaft sinking, decline tunnels, ventilation shafts and box holing. However, there has been studies on on-reef cutting with less success. The key historical studies found for on-reef cutting included:

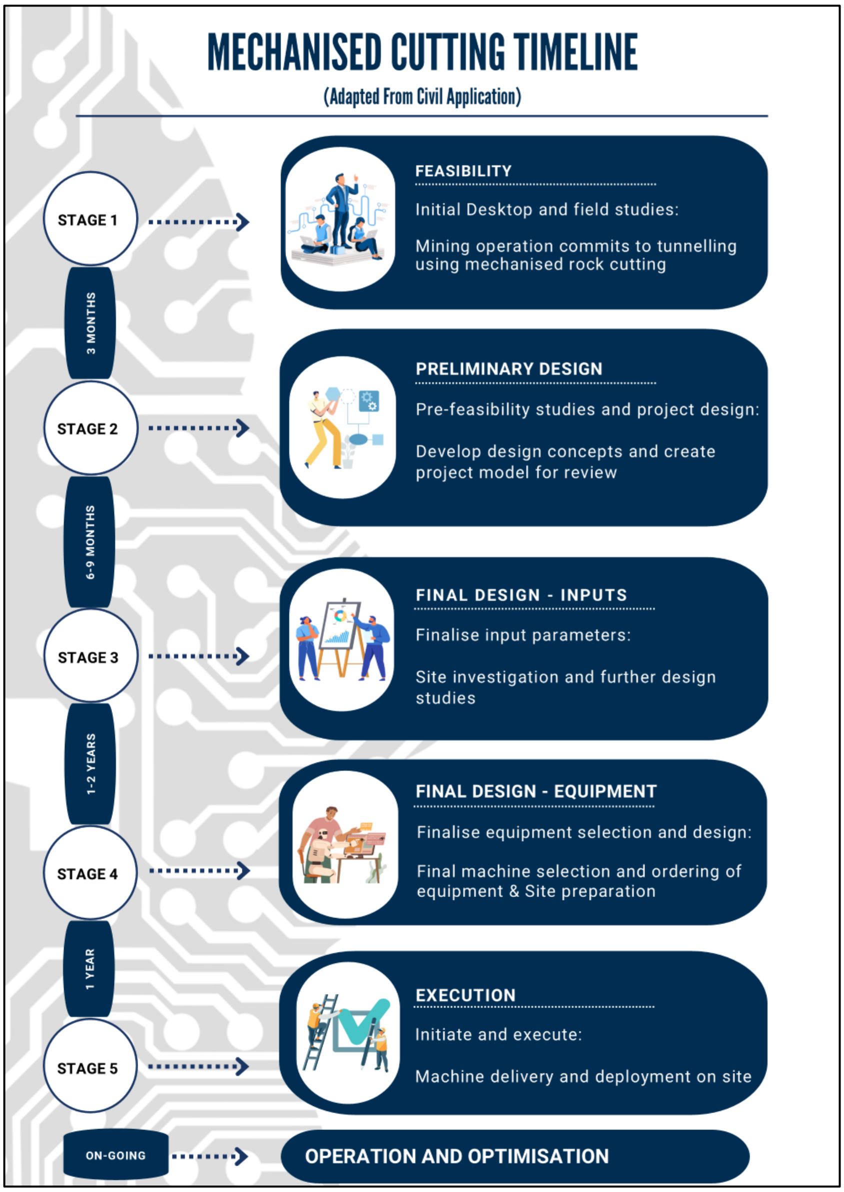
Machine	Location	Reference
Wire Saw	Anglo Gold Ashanti mines	(Barnes, 1969)
Prototype rock-cutting machine (COMRO)	COMRO Lab & Underground mines	(Cook, et al., 1968a), (Cook, 1969), (Gibs, 1969)
Reef Boring	Vaal Reefs	(Lundstrom, 1985)
TBM (Jarva MK6 -1976 model)	Bafokeng Rasimone Platinum Mine (BRPM)	(Stander, et al., 2001)
ARM1100	Lonmin Platinum Rowland Shaft	(Moxham, 2004)
Narrow reef miner, oscillating disc cutter, activated drum system.	Anglo Platinum Mines	(Croll, 2004)
Continuous mining hard rock-cutting machine, Mechanised XLP fleet.	Lonmin Platinum	(Pickering & Ebner, 2002), (Pickering & Moxham, 2006) (Pickering, et al., 2006)
Mechanised XLP Fleet	Anglo Platinum	(Fourie, Smith, Valicek, & Krafft, 2017)
Epiroc Mechanical Miner	Anglo American, Twickenham mine	(Hiyate, 2018)

The study also found that key projects in the reef-cutting domain is underway at three major South African platinum mines. These projects are listed in the table below:

Machine	Location	Reference
Herrenknecht D1000 Reef Borer	ARM Modikwa Platinum Mine, South Africa	(Van der Bijl, 2024)
Master Drilling Reef Miner	ARM Bokoni Platinum Mine	(Van der Bijl, 2024)
SANDVIC MN220 Reef Miner	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)
Atlas Copco Slot Borer	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)

Mechanical rock-cutting application guidelines

Although mechanical rock-cutting as a mining method has not been widely adopted in the mining industry as of yet, the number of tunnelling machines utilised over the past decade has escalated, testimony to their continuing success and flexibility for application on projects of different diameters, lengths, and ground conditions. There are various guidelines available for machine selection and for developing a suitable specification for a machine for a given project. Proper application of these guidelines is an essential part of machine selection to ensure optimal performance of these machines in a given project.



The success of tunnel boring machines (TBMs) in projects has proven the use of TBMs to be a promising approach to meet these challenges. In order to better understand the possible gains when using mechanised rock-cutting, some of the important factors governing and influencing the machine's performance are set out and explored in this report. The current trends and main challenges in the tunnelling industry are to go ‘faster, larger, deeper and longer’.

The performance of the TBM is represented by the advance rate, which is a function of the penetration rate (PR) and utilization factor (U), and operational parameters. The ground conditions and operational parameters impact both PR and U parameters, while U is also impacted by site set-up, maintenance, ground control, and experience of the crew.

The typical value of U ranges from 5% to 55%, with the most common range being 20-30% (Rostami 2016). This indicates that typically, TBMs work only for a few hours per shift, with the rest of the time being recorded as downtime involving other tunnelling activities. Paltrinieri (2015) noted that utilization factor estimation requires a combination of both ground conditions and/or machine factors. The estimation of U requires careful consideration of the various tunnelling activities occurring at the project site, including machine maintenance, ground support, surveying, muck transportation systems, cutter change, unexpected breakdown, and so on. Interdependence among these various activities makes the estimation of U a complex process.

The value of applying guidelines

Based on the findings and costs presented in this study, indications are that TBMs are significantly faster than typical excavation processes in a straight single tunnel, but this comes at the cost of TBM-like machines with high capital costs and larger machines also have much more challenges compared to smaller more mobile rock cutters. Albeit studies conducted at Stillwater Mine indicated successful use of TBMs for reef mining. Willis et al. (2014) detail the two main projects of a 5.5 m diameter and 7.1 m diameter heading where a compelling case of high advance rates is stated. The authors note in comparison to conventional drill and blast operation, a 5.75 times faster rate of lateral advance. Although the capital outlay is estimated at 3.6 times the conventional cost of a heading, the high productivity and lower direct operational costs render these projects successful.

Initial mechanical rock-cutting systems developed between the 1960s and 1980s seemed to have production costs on par or slightly higher than conventional stoping costs, with the difference being the high initial capital costs. The cutting performance needed to be at least three times conventional advance rates to make up for the capital cost. At that time, the biggest hurdle to success was the cutter technology, machine power capacity, mobility, and the discontinuity of cutting operations due to additional mining activities that took up too much available time.

The study found that the root causes of failure for reef-cutting technology in the past included:

- geological constraints
- technological constraints
- economic climate
- mining layout and support challenges
- poor pre-implementation research, testing and/or planning
- low production levels and uneconomical unit costs due to low advance rates, high running costs and poor utilisation of machines
- lack of mobility and flexibility due to the size and weight of machines as well as steering limitations

Mechanical rock-cutting was shown to be significantly faster at competitive costs but does need a significant portion of upfront planning and investigation work.

2 AIM OF RESEARCH PROGRAMME

The Mandela Mining Precinct is mandated to facilitate the development of skills, capacity and capability in mining research, development and innovation. To this end, for South African Mining Extraction RDI (SAMERDI). The SAMERDI strategy is missioned to improve the contribution of Research and Development (R&D) and innovation in the mining sector.

The focus of the research programme is to provide sustainable mechanised drill, blast, and mechanical rock-breaking solutions in advancement to facilitate achieving zero harm, whilst maintaining and defending desired production rates at minimised costs, within the Gold, and PGM mining industries.

The research further has the strategic intent to develop automated mining solutions for NRHR mines. This is achieved by optimising operational mine design and extraction practices and developing new technological business improvement solutions with a strong drive to convert current mining to semi-autonomous mining.

The focus of the Mechanised Mining Systems (MMS) Programme is to develop or demonstrate solutions that will lead to the increase of economically feasible gold, PGM and Chrome orebodies in SA through new mining approaches.

2.1 Aim of this particular milestone

This milestone aims to close out the 2024 study conducted on the Mechanical Rock-cutting Technical Design.

2.2 Methodology used

This report was compiled by considering the work conducted up-to this point in time.

3 MECHANICAL ROCK-CUTTING PROCESS

Tunnel boring using mechanical rock-cutting is a method employed to construct tunnels through solid rock. Typically, this technique uses specialised machinery called tunnel boring machines (TBMs) equipped with rotary cutters or disc cutters that break and excavate rock by chipping away the rock face.

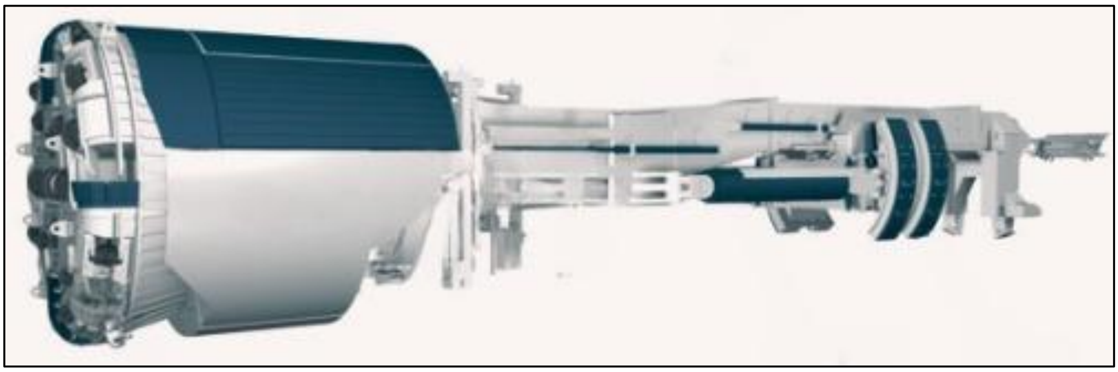


Figure 1: Example of a mechanised rock-cutting machine.

These machines are designed to handle a very specific set of conditions, meaning that multiple machines with different designs are sometimes utilised for a single tunnelling project. The cutting process involves rotating cutters or moving impact positions, which gradually wear away the rock while the rotation allows for simultaneously removing debris. This method is particularly advantageous due to its precision, efficiency and absence of cyclical excavation processes. The excavation also typically has a smoother tunnel surface and potentially faster excavation rates compared to traditional drilling and blasting techniques.

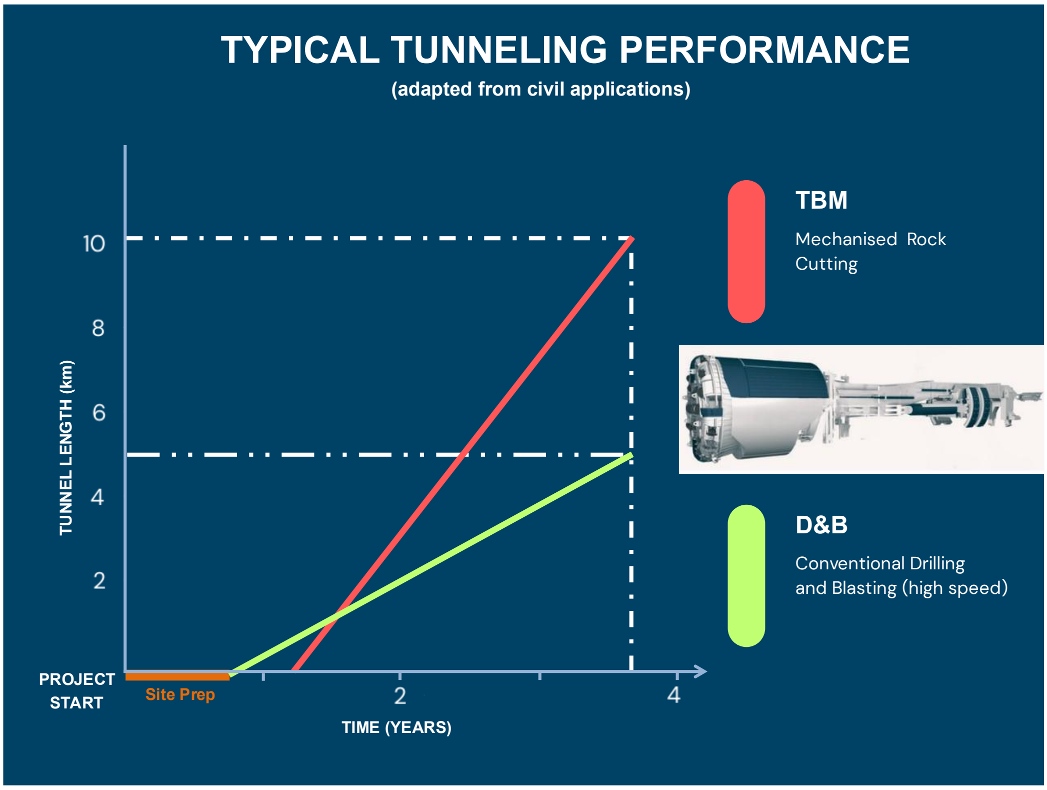


Figure 2: Image showing the typical tunnelling performance.

Mechanical rock-cutting does, however, need a significant portion of upfront planning and investigation work. The generalised timeline (Figure 3) indicates the typical steps and durations in a broad outline for a mechanised tunnelling project.

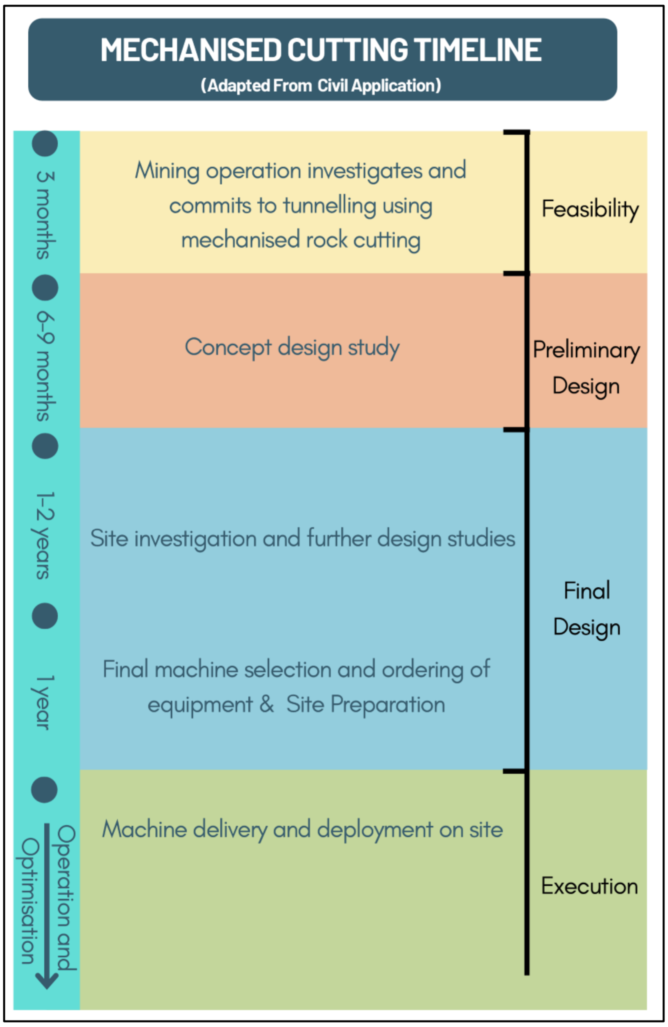


Figure 3: Typical mechanised rock-cutting project timeline

The design and applicability of a mechanised rock-cutting machine are strongly dependent on the input data, as can be seen from Figure 3. Considering the information gathered and the process as presented in this chapter, the following image summarises the gathering and application process.

As shown in Figure 3, the timelines are provided, which influence machine selection up to the final stage of ordering the machine. The OEMs typically need about 1 year to produce and "bench test" the machine before delivery. This thus represents the final stages of the up-front work before implementation.

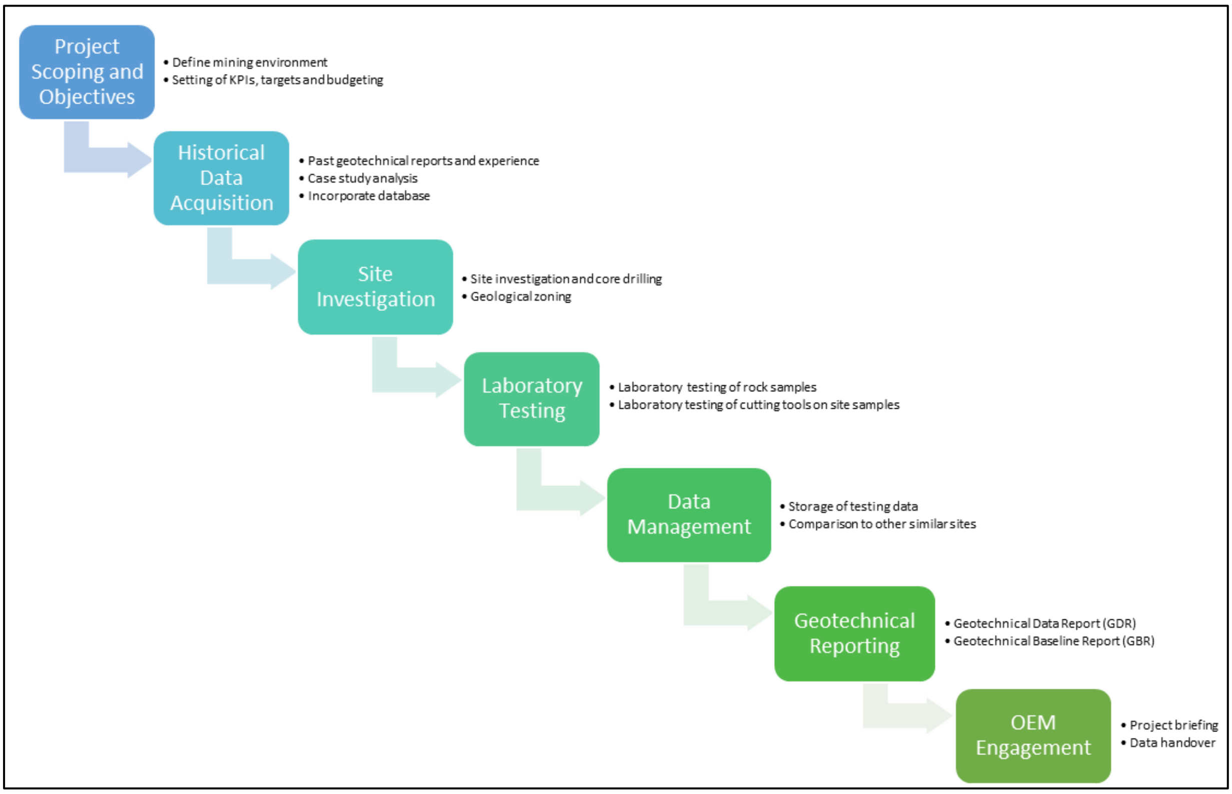


Figure 4: Typical data gathering process of a mechanised rock-cutting project

Figures 3 and 4 clearly indicate the dependence on having the correct data available. A typical mechanised rock-cutting project entails a number of different steps, while the up-front investigations and planning are critical components as to the success of such a project. Figure 5 is a typical outline of the up-front investigations required for such a project.

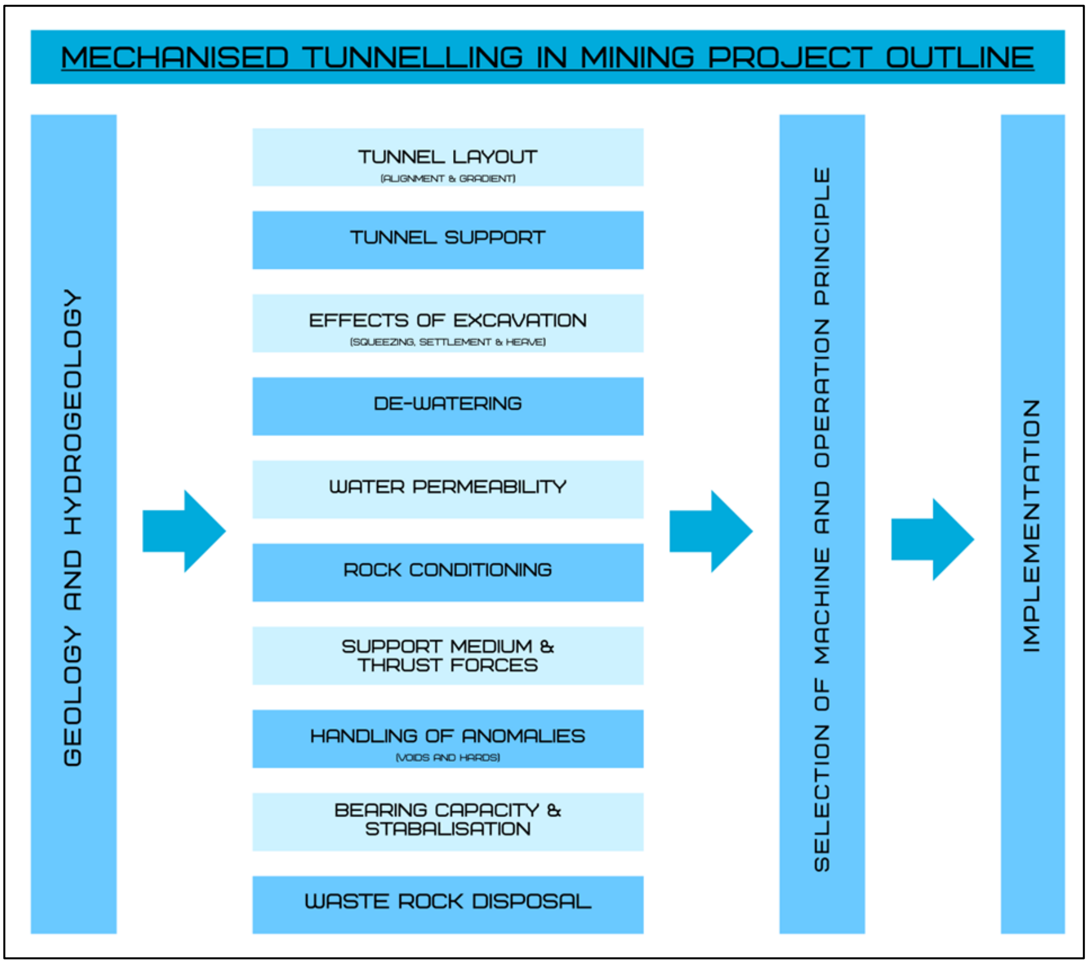


Figure 5: Typical project outline of a mechanised rock-cutting project

As part of the process to clarify the process and help the reader understand the requirements, a series of checklists were also created to guide the process and ensure relevant information is recorded for the use of designing appropriate machinery. Figures 6 and 7 are images of the checklist front pages of the Geotechnical Data Report (GDR) and Geotechnical Baseline Report (GBR) checklist. The geotechnical checklist is indicative of all the relevant information that is required when collecting geotechnical data for a mechanical rock-cutting project. The geotechnical baseline report is aimed at setting out the project details as well as the geotechnical input parameters needed to effectively select and design a mechanical rock-cutting machine and determine the project risks.

Geotechnical Information Checklist
for Mechanised Tunnelling in hard rock

- [ ] **Longitudinal section of the tunnel showing**
  - [ ] Tunnel design
  - [ ] Regional geological profile/information
  - [ ] Exploration borehole locations
- [ ] **Horizontal sections of the tunnel with borehole locations**
- [ ] **Geotechnical Baseline Report (GBR)**
- [ ] **Minimum rock property properties/tests for each zone/rock type**
  - [ ] Bulk Density
  - [ ] Quartz content

Figure 6: Extract from the geotechnical information checklist for mining applications.

Geotechnical Baseline Report Checklist
for Mechanised Tunnelling in hard rock

- [ ] **Project Introduction:**
  - [ ] Project Name
  - [ ] Project Site / Location
  - [ ] Design Team
  - [ ] Purpose of Report / Study
  - [ ] Project Constraints
- [ ] **Project Description:**
  - [ ] Project Location
  - [ ] Project Type & Purpose
  - [ ] Summary of key project features and outcomes
  - [ ] Project sections and specifications
- [ ] **Sources of Geologic & Geotechnical Information:**
  - [ ] GDR description
  - [ ] Other available Geologic & Geotechnical reports

Figure 7: Extract from the geotechnical Baseline report checklist for mining applications.

The design of a mechanised rock-cutting project can be set out and summarised as indicated in Figure 8.

SELECTION OF A TUNNELLING SYSTEM FOR MINING APPLICATIONS

RECOMMENDED STEPS IN THE DECISION-MAKING PROCESS
FOLLOWING THE UP-FRONT STUDIES AND INVESTIGATIONS

STEP 1	**ANALYSING AND SUMMARISING GEOTECHNICAL REPORTS** **Output**: Tunnel Classes and possible machine types
STEP 2	**ANALYSING THE INTERACTION BETWEEN THE MACHINE AND THE ROCK** **Output**: Basic requirements for support, stability, excavation and machine type
STEP 3	**PRELIMINARY MACHINE TYPE SELECTION** **Output**: Guidance of applicable machine types derived from a process of elimination
STEP 4	**MUCK BEHAVIOR ANALYSIS** **Output**: Refinement of machine selection by considering muck transportation
STEP 5	**MACHINE SELECTION** **Output:** Selection of tunnelling machine / system
STEP 6	**TUNNEL CATAGORISATION** **Output:** Identification and grouping of excavation classes, used to determine machine type and operation mode

Figure 8: Mechanised tunnelling project outline

As seen in Figure 8, the machine selection is a prominent step and would thus be a significant undertaking during the design process. Figure 9 gives an overview of the available machines and options for mechanised rock-cutting for tunnelling.

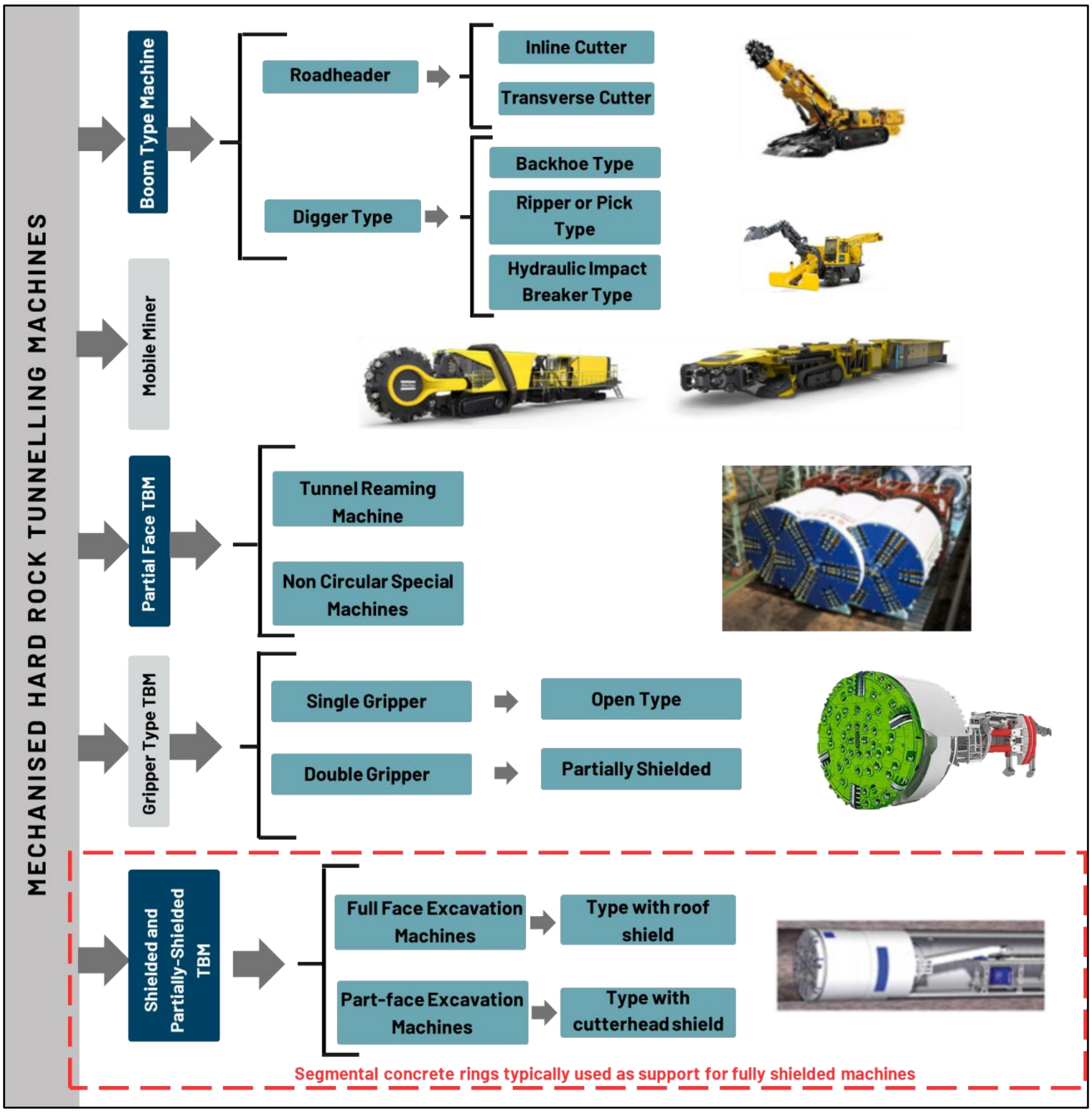


Figure 9: Mechanised tunnelling machine options

Considering the operational environment of the SAMI, Figure 9 can also be represented as shown in Figure 10. Typically, the Gold and Platinum operations would not consider a machine that makes use of segmental concrete rings, as this is a very expensive support medium and far exceeds the typical support requirements of a mining operation. The machine selection forms part of the final design before ordering.

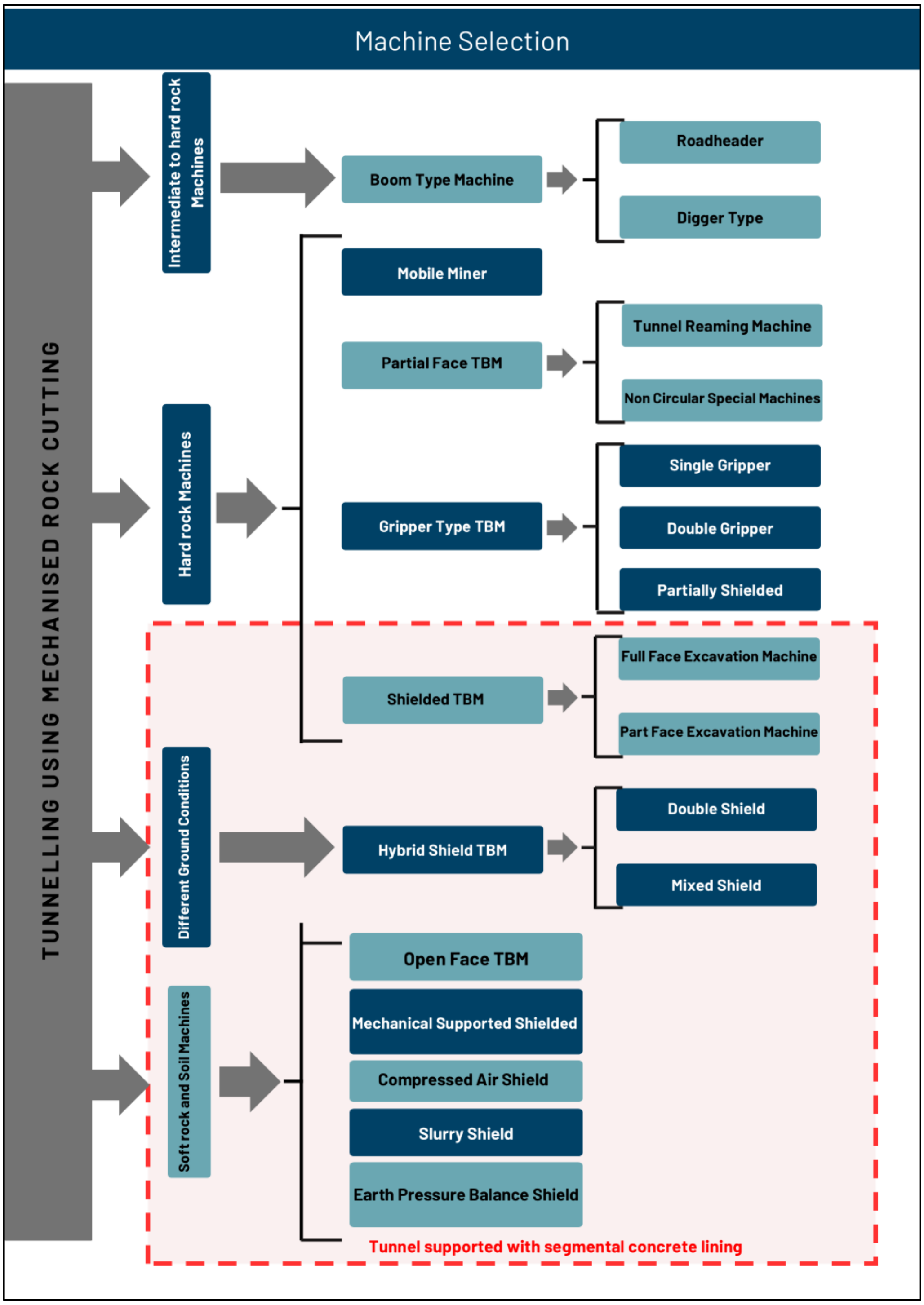


Figure 10: Hard rock mechanised tunnelling machine selection

Geotechnical investigations are a crucial part of using mechanised rock-cutting machines for tunnel construction, as they provide essential information about the subsurface conditions that will directly impact the machines performance and safety. These investigations involve studying rock properties, groundwater conditions, and potential geological hazards, which help engineers design the most suitable TBM and determine the optimal tunnel alignment.

In order to assist in the understanding of the overall process as well as the visualisation of the involved processes this study produced a framework, based on learnings from historical literature and case studies to formalise the basic principles, supporting the requirements from the initial study phase up to the feasibility level. The framework also covers the stages from preliminary design up to the final design processes, leading to the final equipment selection, including an indication of the timelines of the various processes.

4 REVIEW OF MECHANICAL CUTTING APPLICATION

The scope of this literature review was limited to the testing and application of mechanised rock-cutting systems to mine reefs in South African hard rock mines, however, where applicable and necessary, references and correlations to international studies will also be used. The study reviewed past and current ongoing projects (where information is available to the public). Papers that were associated but not directly applicable to the scope were also added if they formed a key basis for understanding the historic development of mechanised cutting systems that were used for on-reef applications, such as the initial raise boring trials in the Vaal Reef South that formed the basis of research into understanding the requirements for successful and efficient rock-cutting in South African hard rock conditions.

4.1 Historic Mechanical Reef Mining Projects in South Africa

Vogt (2016) reviewed rock-cutting for underground mining looking at past, present, and future technologies. He discussed the need for rock-cutting solutions, applicable rock properties and the future of rock-cutting systems. Also discussed is the history of rock-cutting specific to South Africa, making this paper key to this study. Albeit many differences in cutting system setups and machine designs were noted, the final selection ends up becoming a type of longwall continuous system. If the geometry is limiting and more flexibility is required, a mobile continuous miner becomes the main selection.

The main rock properties revealed were strength, brittleness, abrasiveness and specific energy of excavation. These properties affect how cutters and machines are designed to effectively break the rock from percussive hammers, applied force with inventors and rotation, to angled picks and drag bits. This has been successfully applied in soil and soft-rock excavations but slow adoption in hard rock environments was noted due to the high demand of forces required to break the rock and the increased abrasive nature of hard rock inducing a high rate of tool wear. Out of all the various cutting set-ups reviewed, it seemed that disc cutters emerged as the cutter best suited to the challenges of hard rock-cutting, but still faced the challenge of economic viability (Vogt, 2016).

Vogt (2016) was able to deduct that the majority of machines reviewed were able to cut rock successfully but overall cutting systems failed due to constraints from underdeveloped rock collection and transportation systems that fail to effectively move cut rock from the cutting interface. Other major findings revealed that there was a lack of interest and partnership from miners. An example was in 1998 when Atlas Copco shelved the first functional and proven mobile miner (originally developed by Robbins) due to a lack of interest from miners. Vogt (2016) believes that the miner is the final winner of mechanised continuous cutting systems and not manufacturers and should therefore come to the table to assist manufacturers not only in development but sharing the risk and reward of continuous implementation, optimisation and application of the technology. Vogt (2016) believes that the only way for the technology to mature is through learning, which in turn is achieved through continuous testing and application.

In his review of hard rock-cutting in South Africa, Vogt (2016) found that two main methods of excavation were studied, namely bulk rock-cutting and selective slot cutting. The major research projects reviewed included:

- Wire cutting in the Anglo Gold mines (1960’s) – (Barnes, 1969)
- Slot cutting in narrow reef gold mines for selective mining and in-stope waste sorting conducted by COMRO (1960’s-1970’s) – (Cook, 1970), (Hojem et al.,1971)
- Reef boring using raisebore technology (1970’s-1980’s) - (Joughin, 1976)
- The hollow stope cutting tool (the Stope Corer) developed by De Beers in the 1980’s – (Mulgrew, 2015).
- Swing hammer and impact ripper (1970’s-1980’s) – (Nicoll, 1976), (Joughin, 1978), (Jager and Turner, 1986), (Haase and Pickering, 1987), (van der Merwe *et al.*, 2001)
- Diamond wire and water jet cutting (1980’s-1990’s)- (Dunn, 1989), (Fenn and Marlowe, 1990), (Scott and Russell,1993), (Carter, 1997)
- TBM trials in South African mines (1970’s-2000’s) - (Taylor et al., 1978), (Marlowe et al., 1983), (Pickering et al., 1999), (Stander et al., 2001).
- Oscillating disc cutting, Activated drum cutting and Narrow-reef miner tests on Platinum mines (2000’s) – (Croll, 2004), (Pickering et al., 2006)
- Hybrid technologies (i.e. mobile miners combining TBM and road header technologies) in 2010’s - (Janicijevic and Valicek, 2015)
- Reef borers on gold and platinum mines in South Africa (2010’s) - (AGA, 2015), (Janicijevic and Valicek, 2015)

The projects listed above will be used as a guideline for the history of hard rock-cutting projects in South Africa (starting in the 1960's), along with any additional relevant information found during the literature review for this study.

According to Barnes (1969), trials on on-reef cutting in South Africa were done as early as 1955. The author himself formed part of trialling wire saw cutting where the immediate footwall of the East Rand Goldfield, Jeppestown shale, was cut at a rate of 6in. per hour (152.4mm/h). A summary of the details of the study is indicated in Table 1.

Table 1. Project details: East Rand Goldfields (Barnes, 1969)

Project Owner	Not specified
Strategic Partners	Not specified
Project location	East Rand Goldfields, South Africa
Project timeline	1955-1960's
Project Objectives	Improve stoping width control and to achieve improved blasting efficiency.
Machine Type	Wire Saw (Consisting of low horsepower (hp) motor, endless special rope, water and sand)
Reference	(Barnes, 1969)

The tests in the East Rand Goldfields were similar to those conducted on quarries in the Northern Transvaal. A low hp motor was used to drive a specialised endless rope with water and sand to cut into the footwall. The hypothetic application of this method was submitted to the government mining engineer in the same year of testing (1955). Although fewer promising results were obtained in the Orange Free State Goldfields, the relatively uniform conditions and rock properties of the Merensky reef, in particular with overlying Merensky pyroxenite, were just as attractive as the East Rand for large-scale testing. The main objective of the cutting of the footwall using wire saw cutting was to achieve early gains in rock-breaking efficiency as well as improved stoping width control. The author believed that given the applicable rock type and ground conditions, up to 200ft (60.96m) of undisturbed 'faces' could be cut in advance where breakage followed rock-breaking by light blasting into the second free face and would yield significant rock-breaking efficiency. The author also mentioned the possible use in areas where rock-cutting of waste was trialled (Barnes, 1969).

In 1964, the Transvaal and Orange Free State Chamber of Mines formed the Chamber of Mines Research Organisation (COMRO). Since its inception in the 1960s up to the late 1980's COMRO has produced world-leading research in mining and related fields (SAIMM, 2014). Mechanical rock-cutting research was one of the major topics being studied with the first publications coming from N.G.W. Cook, the then director of mining research at COMRO. From his references it is noted that Cook found inspiration from the studies being done in the United States, which is not surprising as all of the continuous miners developed for South African coal mines at the time were all of American origin (Inch, et al., 1980).

In the first publication regarding rock-cutting, Cook et al. (1968) describes the challenges regarding stoping width and mining at increased depths. The objective of this research was focused on solving mining problems whilst also addressing mining costs. A summary table of the study is indicated in Table 2.

Table 2. Project details: COMRO rock-cutting trials (Cook, et al., 1968a)

Project Owner	COMRO
Strategic Partners	Not specified
Project location	New Goldfields, South Africa
Project timeline	1968
Project Objectives	Laboratory tests on cutting Witwatersrand quartzite. Developing a prototype cutting machine to reduce stoping width, more selective mining, and improved mining unit cost.
Machine Type	Prototype Continuous Rock Cutter (similar to early crawler tractors)
Reference	(Cook, et al., 1968a)

To achieve improved cost and grades, mining closer to the actual thickness of the thin reef is needed and this initiated the investigation of mechanical cutting of the reef (Cook, et al., 1968a). A table of the reef thickness in major gold bearing zones are indicated in Table 3.

Table 3. New Goldfields reef thickness (Cook et al., 1968a)

Goldfield	Reef	Average Thickness
Evander	Kimberly	25 in. (63.5cm)
Far West Rand	Ventersdorp Contact	30 in. (76.2cm)
Far West Rand	Carbon Leader	10 in. (25.4cm)
Klerksdorp	Vaal	20 in. (50.8cm)
Orange Free State	Basal	15 in. (38.1cm)

To investigate alternative rock-breaking processes to find a more selective and cost-effective method to mine narrow reefs, Cook et al. (1968) used the effective energy and fragment size to compare the various methods. The aim was to find a method that represented the relationship close to point A on the graph in the figure below (Figure 11). From this rock-cutting, the authors concluded that rock-cutting seemed to be the most probable solution for a more selective mining approach. The authors then turned their focus to a series of rock-cutting experiments in an effort to develop a prototype rock-cutting machine. During these experiments, the factors influencing rock-cutting were evaluated, such as the mean peak cutting force, the depth of cut, the mean peak penetrating force and tool wear (Figure 12).

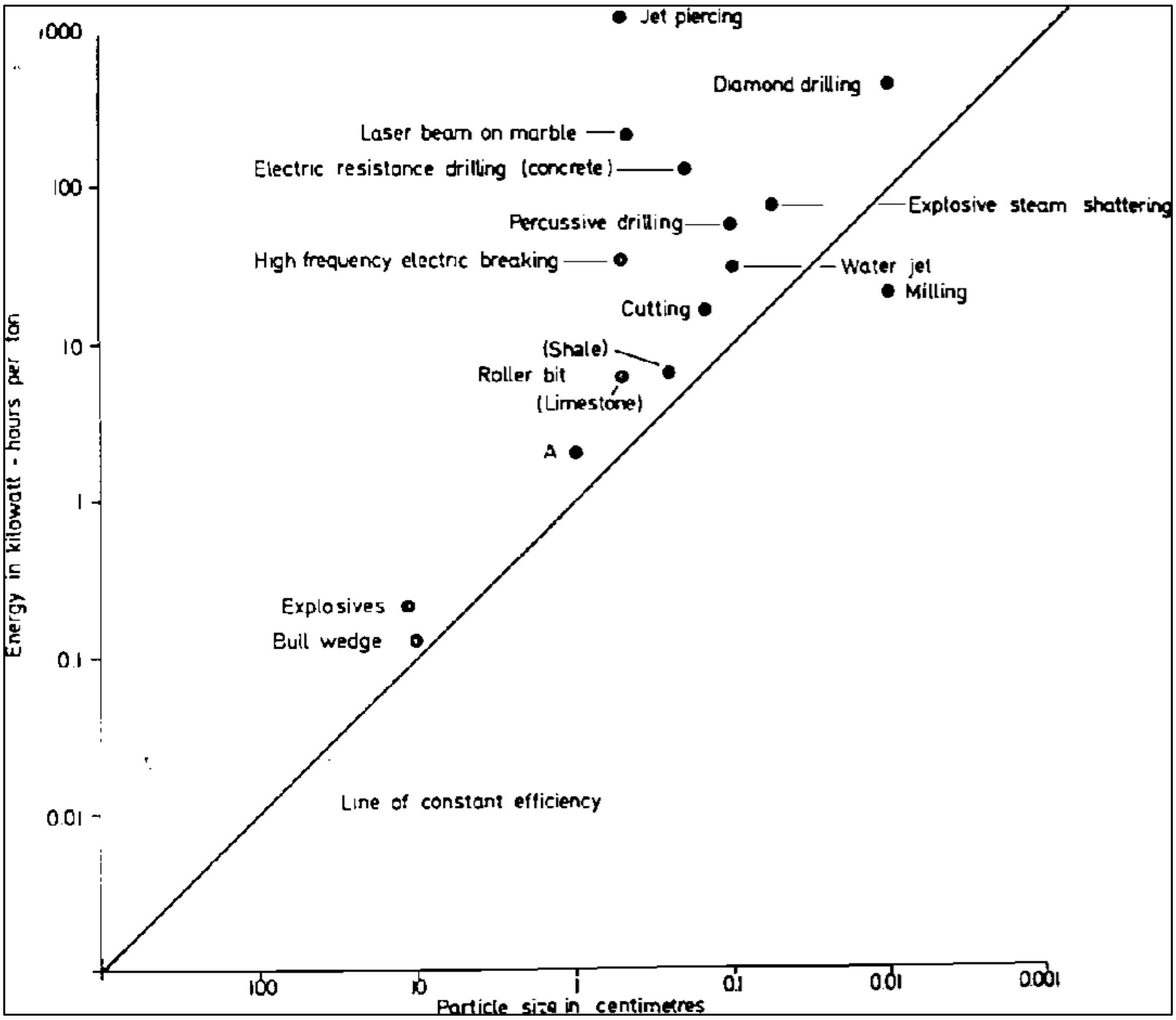


Figure 11. Energy hours per ton vs. particle size of alternative rock-cutting methods (Cook et al., 1968a)

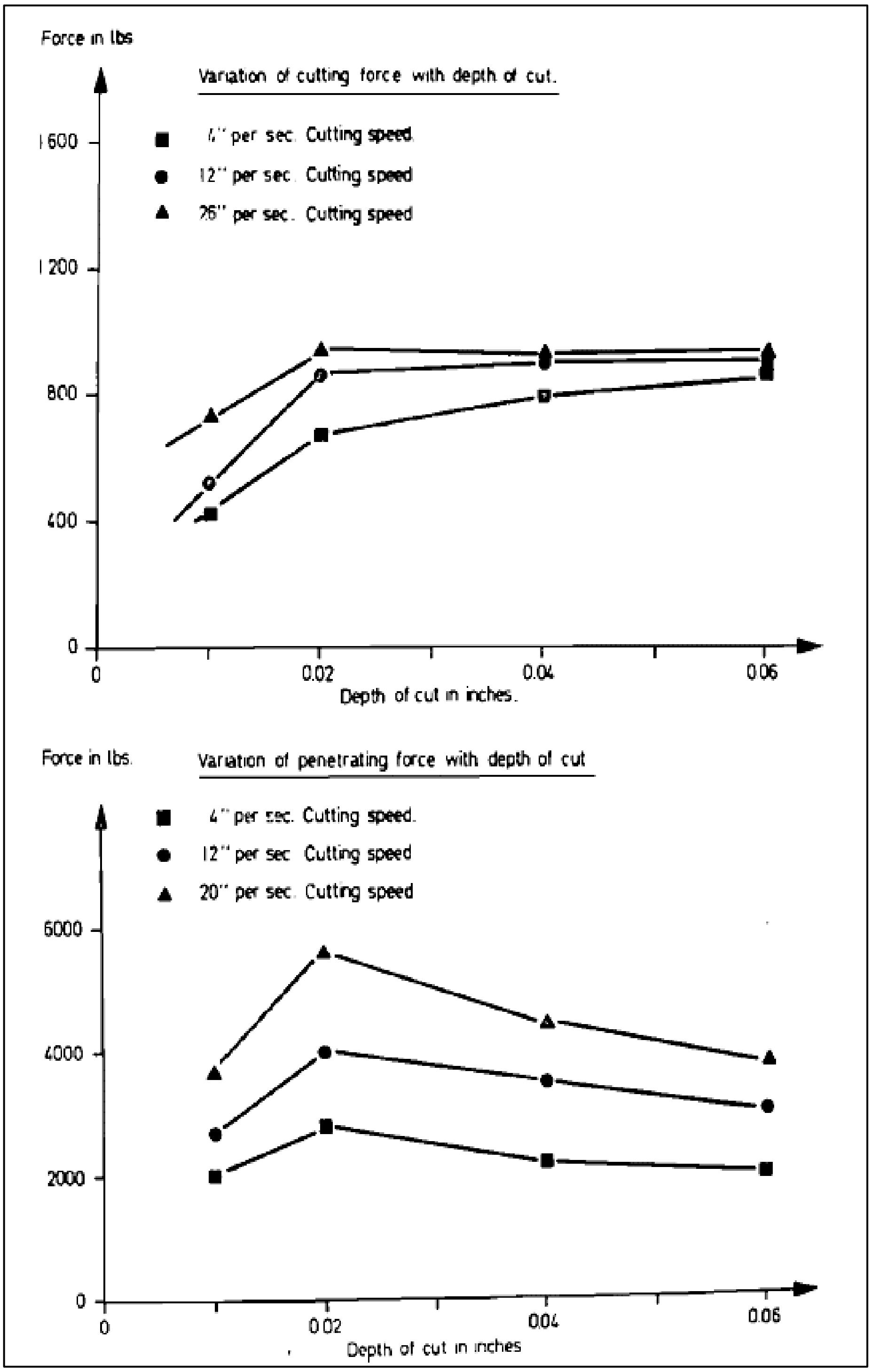


Figure 12. Graphs detailing the cutting force versus cut depth and penetration force vs. depth of cut (Cook et al., 1968a)

Cook et al. (1968) stated that the average face advance in deep-level gold mines using explosives rock-breaking was between 15 and 18 ft per month (4.6-5.5 m/month) with only seven mines managing production rates greater than 20 ft per month (6 m/month). The authors designed the rock-cutting machine to achieve 1ft (0.3 m) of cutting advance per shift, ultimately yielding an average monthly advance rate of 26ft per month (7.9 m/month).

Two key criteria used to establish the configuration of the rock-cutting machine were the size of the cutting machine and to ensure cuts are made where the cutting tools do not work against the greatest stresses in the face normal to the plane of the reef. The machine was therefore designed to cut two slots parallel to the reef above and below the portion of gold-bearing reef (Cook et al., 1968a). An image of the prototype rock-cutting machine is indicated in Figure 13 where the machine is in the extended position ready to commence a cutting stroke where the sled that carries the machine is shown on the side of the image.

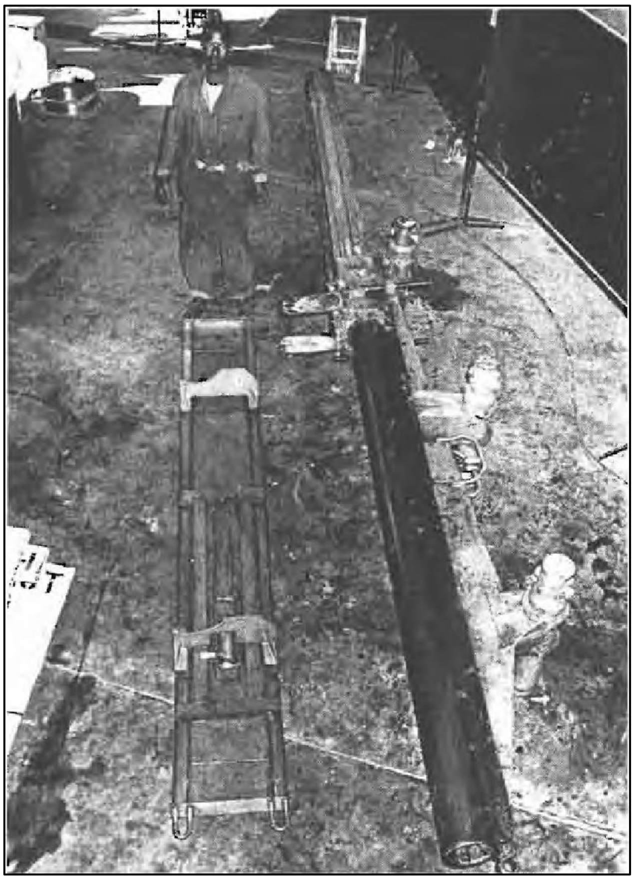


Figure 13. Prototype rock-cutting machine developed by COMRO (Cook, et al., 1968a)

Cook et al. (1968) give a detailed description of the workings of the proposed prototype rock-cutting machine: “The basic frame of the machine is a 6-inch diameter pipe to which a stiffening web has been welded; this frame clamps directly onto hydraulic mine props. The saddle, which holds the cutting tools, slides on the pipe frame. The hydraulic cylinder is mounted inside the pipe and during the cutting stroke, the piston rod is in tension. The cutting force is transmitted from the piston rod to the saddle by means of a tabular member, which slides over the pipe frame. The cutting machine is mounted on a sled that incorporates a hydraulic jack that permits the machine to be raised, lowered, or tilted. The machine is moved in a stope by towing the sled with a small winch. The total weight of the machine, including the sled and the props, is less than one ton.”

The mining method suggested follows the sequence of cutting a kerf in the gold-bearing rock with the conventional blasting of the waste being done afterward to fill the stope. In a follow-up publication, Cook (1969) gives remarks on the potentialities of rock-cutting and gives schematics of a hypothetical rock-cutting machine and its use. The author reiterated the potential impact of this technology as previously un-mineable narrow reefs become probable for mining with rock-cutting. The response also included two schematics detailing the proposed mining method and machine configuration in Figure 13 and 14 respectively. He also mentioned that at the time trials were being done to indicate proof-of-concept and were not production-ready. He stated that the progress, even though slow, was still positive and that a lot more can come from rock-cutting in the future (Cook, 1969).

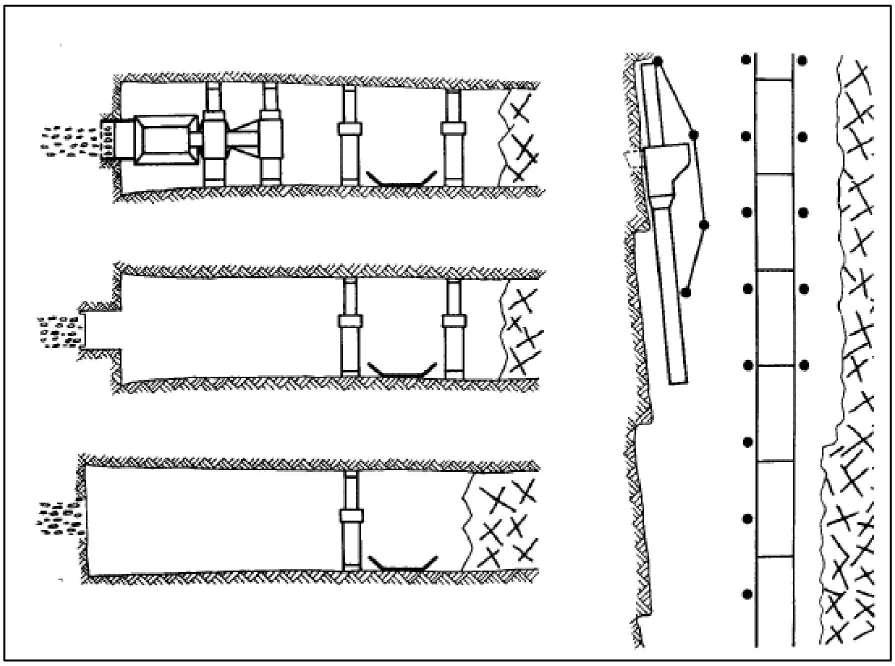


Figure 14. Proposed mining method for the prototype rock-cutting machine (Cook, 1969)

In the closing arguments, Cook et al. (1968) stated that it should be remembered that the proposed rock-cutting machine is indeed still a prototype and that a lot of additional research and development will be required. The authors produced a table to compare a hypothetical cost of mining between conventional explosives rock-breaking and the newly proposed rock-cutting method (Table 4). In this theoretical comparison, the author indicates the potentiality of lowered total mining unit cost and highly improved mined reef grades.

Table 4. Cost comparison between explosives and rock-cutting stoping on a typical deep level gold mine (Cook, et al., 1968a)

	Explosives	Rock cutting
Depth below surface ft	7,000	7,000
Stoping width (effective) in.	42	10
Grade of ore dwt/ton	10	42
Shifts/day	1	3
Face advance—ft/month/shift	20	25
Fathoms²/month	19,000	20,000
Tonnage milled/month	200,000	60,000
Number of stopes 120ft in length	286	80
Productivity fathoms/Bantu/month	4·4	5·2
Ventilation c.f.m.	1,700,000	600,000
Refrigeration (ice tons)	1,000	300
Cost of timber/month	R44,000	R7,000
Total cost of stoping machinery	R1,000,000	R720,000

In the discussion segment of a follow-up publication on the paper "Rock-Cutting and its Potentialities as a New Mining Method" Mr. R.E. Barnes sets the scene by discussing the lack of research investment compared to the scale of revenue generated in the respective commodities in the mining industry. At the time of publication, he mentions that less than 1% of sales from gold and coal were spent by industry on research. He mentioned this to explain how critical research is and that the potential rate of return on research expenditure into rock-breaking is high. Barnes further mentioned that at the current stage, the economic and practical capability of tunnelling machines cannot be envisaged. He also believed that the research has the potential to lead to successful rock-cutting machines with applications largely independent from rock types (Barnes, 1969).

At the Tunnel and Shaft Conference held in Minneapolis from 15-17 May 1968, mining experts discussed the problems and progress related to rapid excavations. The then director of mining research at the South African Chamber of Mines, N.G.W. Cook was also present at the conference and presented an analysis of hard rock cuttability for machines. In his opening statement Cook (1968b) mentioned that there are two main rock-breaking methods used in tunnelling namely, drill and blast and mechanical loading. The author discusses how rock-breaking through the use of explosives has become a well-established practice that is flexible, mobile and has a low capital cost. However the sequence of operations and relative uncontrollable nature of blasting often results in over-breaking beyond the planned perimeter. The paper further details the analysis of bit penetration, coefficient of cutting friction, cutting stability, tool wear, and cuttability. The findings of the analysis indicated that hard rock embrittled and weakened by flaws in their structure are quite easy to cut. When subject to mechanical loading, these flaws cause the rock to break by chip formation. Hard rock that does not have weakening flaws requires much more applied stress to induce failure in the rock and is the main cause of bit wear. It was also found that the cutting machines of that time was extremely heavy, lacked mobility and had constraints regarding actual operational continuity. The author suggested that for rock-cutting to be economical the cutting of rock is to be continuous as a means to offset the extreme capital cost with lower operational cost (Cook, 1968b).

Joughin (1976) examined the potential for mechanizing stoping in gold mines, particularly in the Witwatersrand region, by identifying key requirements for stoping machines and evaluating existing and developing technologies. The study aimed to improve mining efficiency, increase productivity, and reduce operational costs.

Table 5. Project Details: Review of potential Mechanized stoping in gold mines in South Africa

Project Owner	Mining Research Laboratory of the Chamber of Mines
Strategic Partners	A conglomerate of gold mining companies and manufacturers
Project location	Gold mines in the Witwatersrand Basin of South Africa
Project timeline	1968-1976
Project Objectives	Review of the potential of mechanized stoping in gold mines
Machine Type	• Continuous rock cutter • Reef borer • Swing-hammer miner • Impact ripper
Reference	(Joughin, 1976)

In conventional stoping methods, drilling and blast is the primary method used to fragment the rock mass for mineral extraction, using handheld rock drills (hole diameters of 28–42 mm, depths of 0.9–1.2 m) and explosives. Scrapers and manual shovelling are used for rock clearance, taking an entire shift to clear blasted material. The average productivity is 15 centares (ca) per worker per month with a face advance rate averaging 5.62 m per month (highly variable). Stoping costs in 1975 ranged from

R 10 to R 20 per centare, contributing 30–40% of total mining labour costs. Capital investment in stoping equipment was typically R500 per stope worker, less than 1% of total mine investment.

Joughin (1976) listed a host of potential benefits of mechanization, such as:

- reducing unnecessary barren rock mining
- enhancing gold recovery by limiting gold loss in fragmented footwall material
- eliminating the 4-hour re-entry delay after blasting
- mechanized machines could increase face advance rates to 0.25 m per shift (targets 30 ca per worker per month, double the industry average)
- reducing rockfalls and rock bursts through better support systems
- minimizing heat and dust exposure by using fill methods and limiting rock fragmentation

Figure 15 depicts a series of curves that represent the relationship between the width and length of a cutting machine or panel and the proportion of reef that is fully enveloped. Joughin (1976) used this to illustrate the importance of the straightness and shape of the reef when it comes to cutting machines that operate linearly. Due to curvature and faulting within the reef, the longer the panel becomes, the higher the risk of losing sections of reef that do not conform to the straightness of the cutting line. Is shorter cutting lengths are used, the machine can follow the reef with higher accuracy and a lower risk of losses due to reef curvature and faulting. This relationship is therefore critical not only for the machine size but also for the design, selective mining ability and overall cutting cost relative to the potential earnings, while putting a number to faster mining rates and earlier accessibility remains a very difficult and complex undertaking.

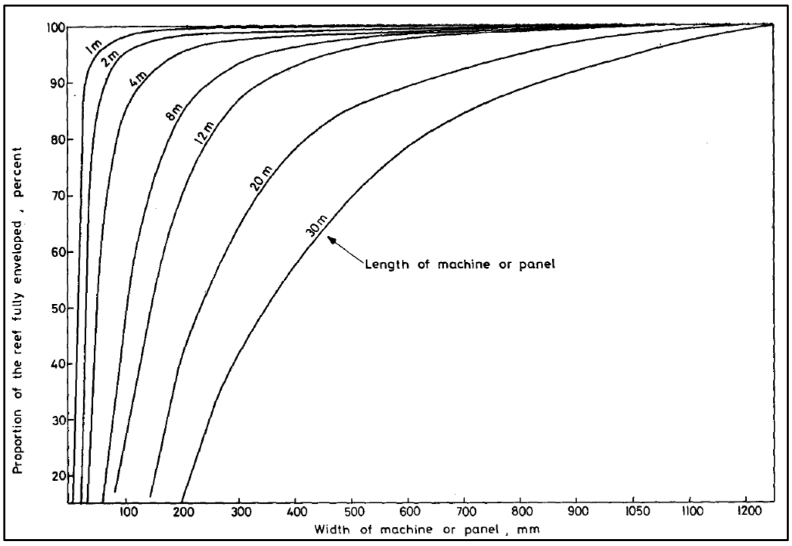


Figure 15. Proportion of reef fully included in a straight panel of specific length and width (Joughin, 1976)

Joughin (1976) not only looked at how the straightness of the reef and machine geometry is affected, but also looked at the difficulty associated with the mechanical workability of the rocks being cut in the Witwatersrand basin. The graph (Figure 16) depicts how an increase in the percentage of hard minerals (i.e., quartz content) can exponentially impact the indentation strength. Rocks with a high quartz content are also more abrasive which further complicates the cutting process as slower rates are experienced due to a high rate of cutter wear, which ultimately affects productivity and costs.

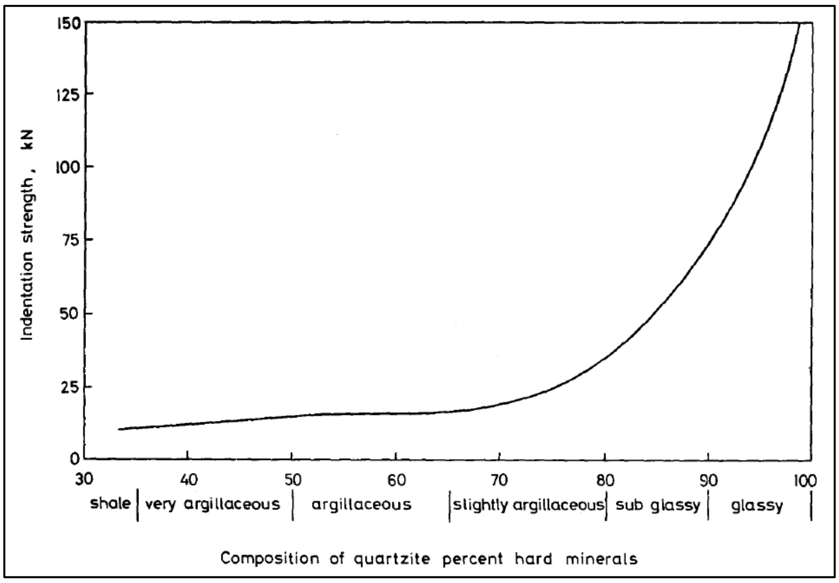


Figure 16. Indentation strength of Witwatersrand sedimentary rocks for a spherical 10mm indenter (Joughin, 1976)

Joughin (1976) discussed the performance requirements used as part of the design of appropriate cutting machines, stating that, at the very least, these machines should have a mining rate greater than that of existing methods. At the time, an acceptable advance rate of 0.25 m per shift was deemed an appropriate criterion, being roughly double the average achieved conventionally at the time.

Assuming an availability of 5 hours per shift, Joughin (1976) calculated the typical average mining rates of a cutting machine when working in panels of various lengths as noted in Table 6.

Table 6. Average mining rate for continuous mining machines in different panel lengths (Joughin, 1976)

Panel length (m)	Mining rate (ca/shift)	Mining rate (ca/h)
10	2.5	0.5
20	5.0	1.0
40	10.0	2.0

Joughin (1976) discussed the various machine types under development and testing in South African gold mines:

- **Continuous rock-cutting machines**: Uses drag-bit cutters to cut a 25 mm slot along the reef, achieved an average rate of 3 ca per shift in trials; new designs aim for 5 ca per shift. Expected bit costs of R 1.00 per centare. A front view image of the continuous rock-cutting machine is shown in Figure 17, with a typical layout of the cutting machine in a panel indicated in Figure 8.

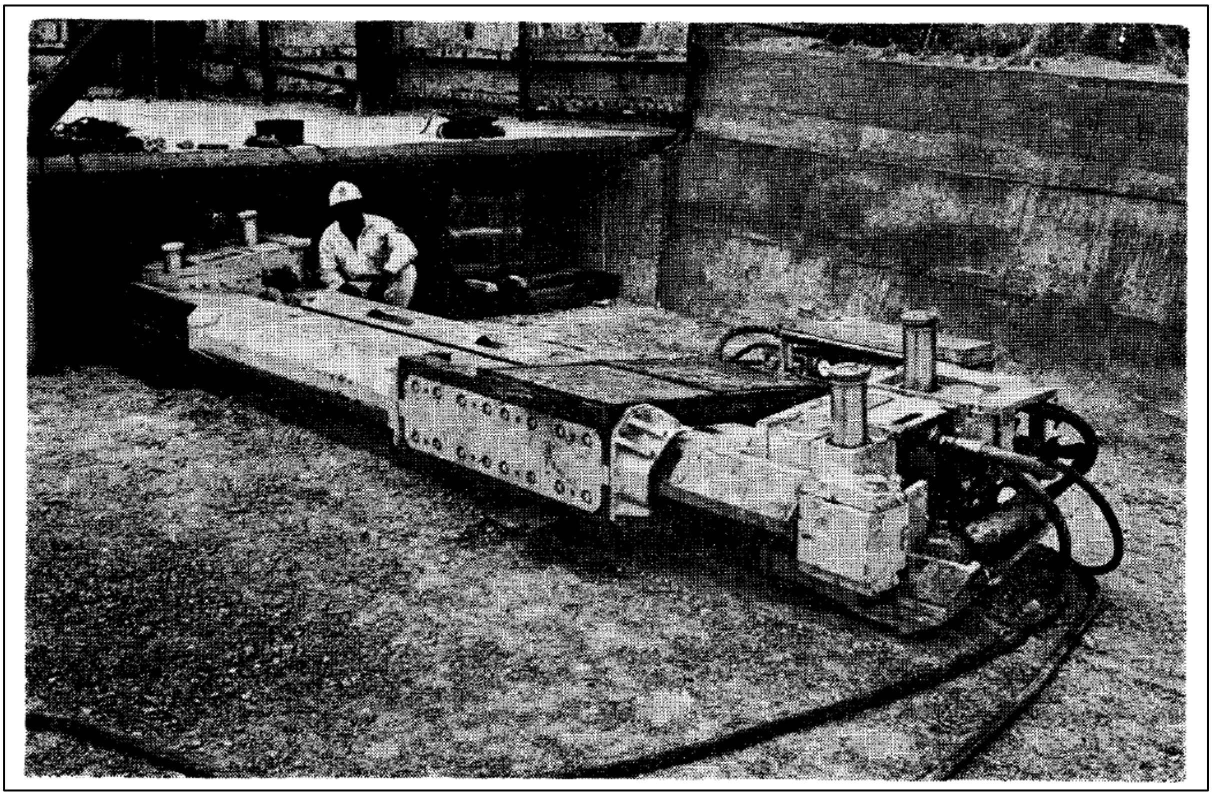


Figure 17. Continuous rock-cutting machine (Joughin, 1976)

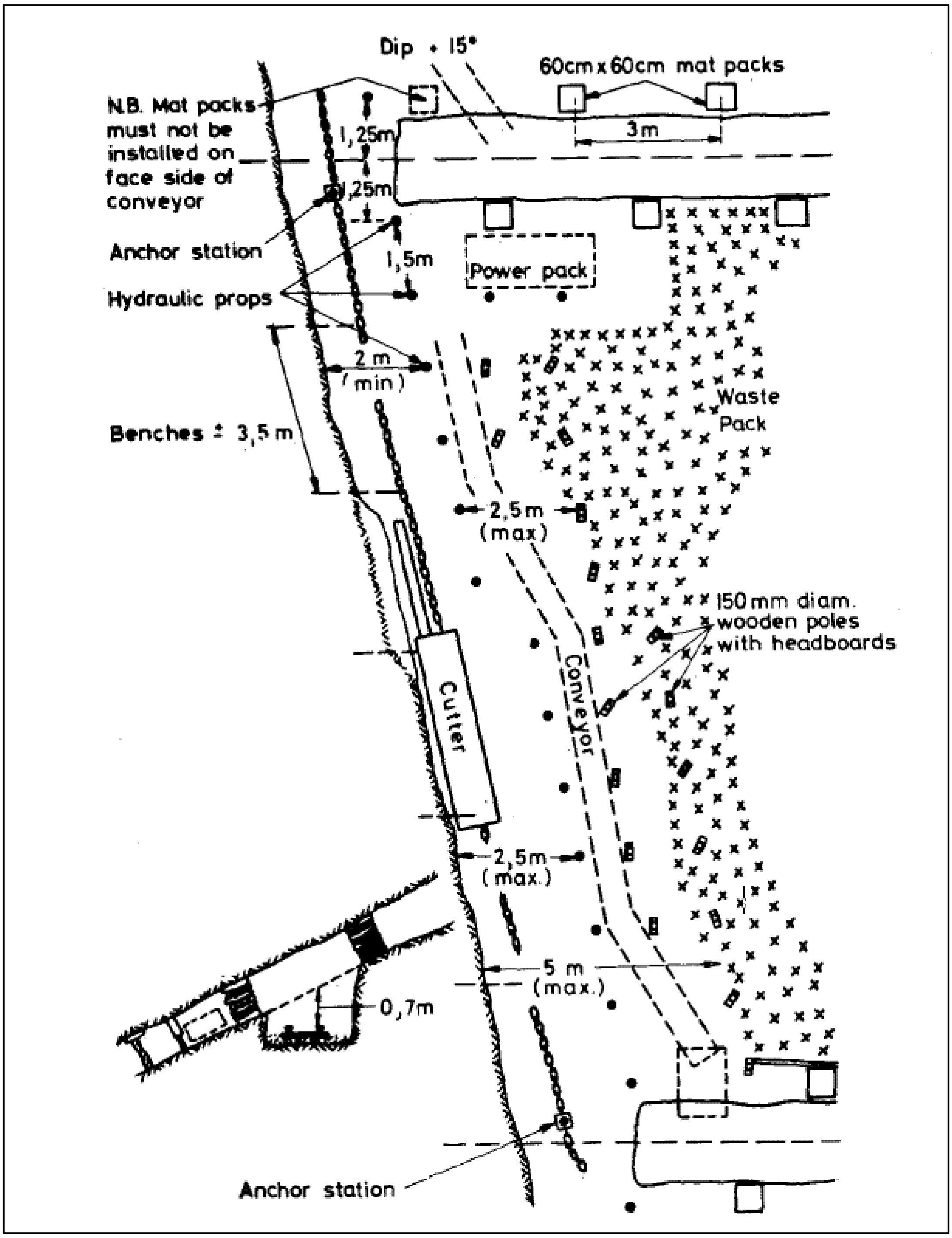


Figure 18. Schematic of the layout of a rock-cutting panel (Joughin, 1976)

- **Reef Boring Machines**: Utilizes raise-boring technology to extract reef material. The estimated reaming rate is 2 m/h; mining could be 0.5 ca/h. Cutter costs were estimated at R 40 per centare, making it less economically viable.

- **Swing-Hammer Miner**: Mounted on a conveyor, continuously moves along the face. Uses rotating hammers delivering 500 J blows at 180 strikes per minute. Estimated mining rate: 5 –10 ca per shift. Expected stope-labour productivity: 25 ca per worker per month. Figure 19 shows an image of the swing-hammer miner tested, which seemed to have been a rail-bound linear mining machine like the continuous rock cutter.

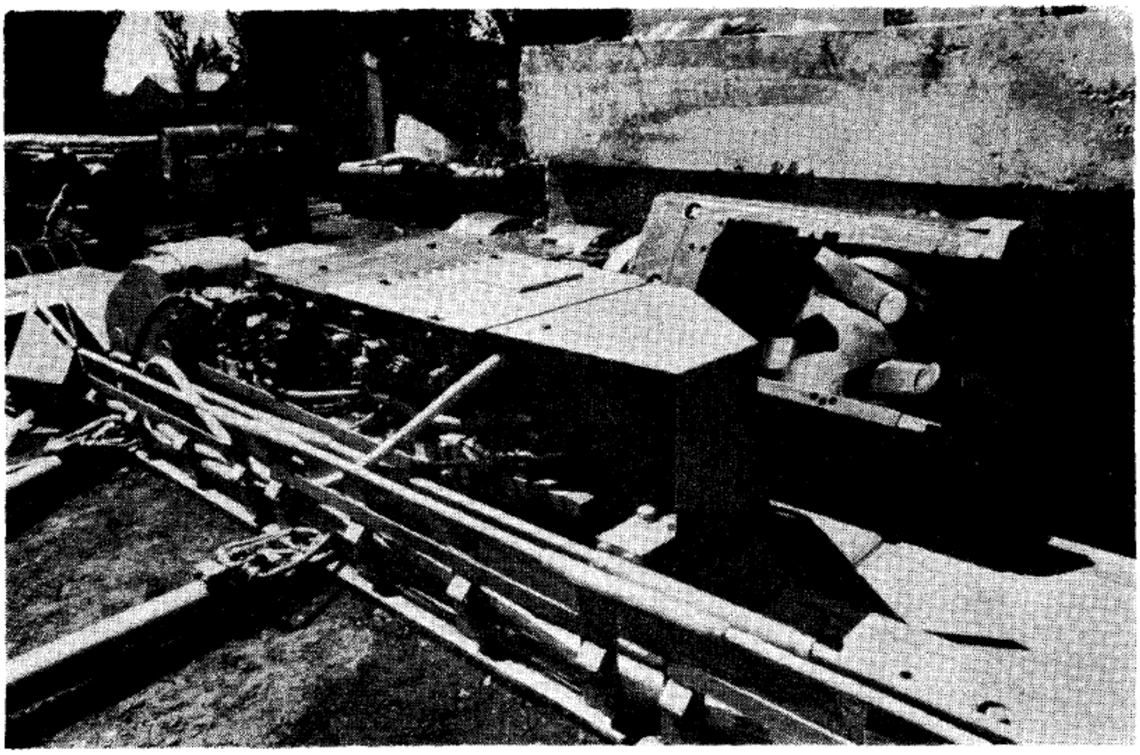


Figure 19. Image of a swing-hammer miner (Joughin, 1976)

- **Impact Rippers**: Uses a hydraulic impactor (2000 Joule per blow at 300 blows per minute). Estimated instantaneous cutting rate of 4 ca/h.

- **Armoured Face Conveyors**: Positioned close to the face before blasting, allowing rapid clearance. Reduces rock removal time to less than an hour. Could enable 0.6–0.9 m face advance per shift (far above the industry average). Estimated stope-labour productivity: 30+ ca per worker per month.

Mechanization can significantly improve stoping efficiency, but costs and feasibility depend on reef characteristics. Selective mining technologies (rock cutters, reef borers) show potential but need improvements in speed and cost-effectiveness. Machines relying on face stress-fracturing (swing-hammer miner, impact rippers) are promising, with expected productivity of 5–10 ca per shift. Face conveyors are highly effective and could transform mining operations by enabling faster face advances and better rock clearance. The potential demand for mechanized stoping machines is high, given the industry's need to increase productivity and reduce labour costs.

In the paper: "The role of the State in the South African Mining Industry and some modern practices in gold mining", Gibs (1969) discusses the experimentation of modern methods to improve the cost and efficiency of mining. Due to the challenges of mining at increased depths and the narrow reef thickness, mechanical rock-cutting has been investigated thoroughly through experimentation by the Mining Research Laboratory of the Chamber of Mines with multiple tests and underground trials being done. The feasibility of rock-cutting seems possible and if successful this technology could make deep-level mining possible where conventional explosives rock-breaking is not possible (Gibs, 1969).

In the paper "Blindhole boring at Vaal Reefs South", Lundstrom (1985) discussed the success of blindhole borers used for mechanised boxholing since the mid-1970s and also describes the methodology and machine configurations. Although the paper does not speak directly to reef boring, the learnings from mechanised boring in itself were valuable to this study. A summary of the details of the study is indicated in the table below.

Table 7. Project details: Vaal Reefs South Blind Boring (Lundstrom, 1985)

Project Owner	Anglo American corporation (Research and Development Services)
Strategic Partners	Robbins, Transbor (Pty) Ltd., Wirth
Project location	No. 9 Shaft, Vaal Reefs South, South Africa
Project timeline	1974-1985
Project Objectives	To review the justification for mechanised boring as well as new design concepts that would offer greater flexibility, more economical operation, or a significantly higher boring rate.
Machine Type	Blindhole borers (Robbins 52RE, Robbins 52RH, Robbins 53RH, Wirth BHB 152
Reference	(Lundstrom, 1985)

The different machines used and Vaal Reefs and their configuration are summarised in Table 8.

Table 8. Machine configuration for Vaal Reefs South raise borers (Lundstrom, 1985)

Machine Name	Machine Configuration
Robbins 52RE	• Hydraulically driven with an electric motor and pump powering thrust cylinders. • 1.52 m diameter cutter head • One-piece casting cutter with welded cutter saddles, a stabilizing stinger in the centre with a tricone bit. Four stabilizing rollers on the skirt. The cutter has nozzles and flushing water for dust, cutter cooling, and removal of cuttings. • A base plate, main frame, crosshead, guide columns, thrust cylinders and headframe form the Derrick Assembly. This assembly is mounted on a rotating base (mounted to a sub-base) allowing the borer to be rotated in any direction. • Scraper plates direct cuttings from the cutter head periphery and into the cylindrical box and finally through the cute onto a conveyor.
Robbins 52RH	Similar to 52RE, however: • Electrically driven • 1.83 m diameter cutter head • Like the 52RE, the 52RH required 6.2 m high x 6m wide excavation for machine assembly
Robbins 53RH	• Lightweight and can be transported and erected in standard-size haulages • No prior site preparation required, except for concrete sub-base • Rotational power is transmitted through the cutter head via the rotating drill string powered by two heavy-duty gear-type hydraulic motors.
Wirth BHB152	• Similar concept of rotating drill string • Thrusting mechanism is located directly behind the cutter head

	• 8x trust cylinders of 125 mm diameter apply up to 1732 kN of thrust to the cutter head. • The four-gripper cylinder each apply 1420 kN of force. • Water is used as a hydraulic medium for the up-hole thrusting mechanism at up to 180 bar • The configuration allows the drill string to be in tension and not compression, requiring less stabilization in holes dipping more than 60°. • Rotational force applied by two 92 kW hydraulic motors through a planetary gear system giving a maximum torque of 85 000 Nm at a rotation speed of 0-20 r/min. • Outer diameter of drill rods of 260mm and a length of 600 mm each.

A series of schematics depicting the various boring methods using the Robbins 53RH is shown in Figure 20 with a schematic of the same borer erected in a tunnel shown in Figure 21. As found in the literature, most of these original borers were large and required preparation excavations and assembly before use, whereas the third and fourth-generation borers were much smaller and versatile. This has set the foundation for improved mobility and, later on, the platform for mobile reef borers.

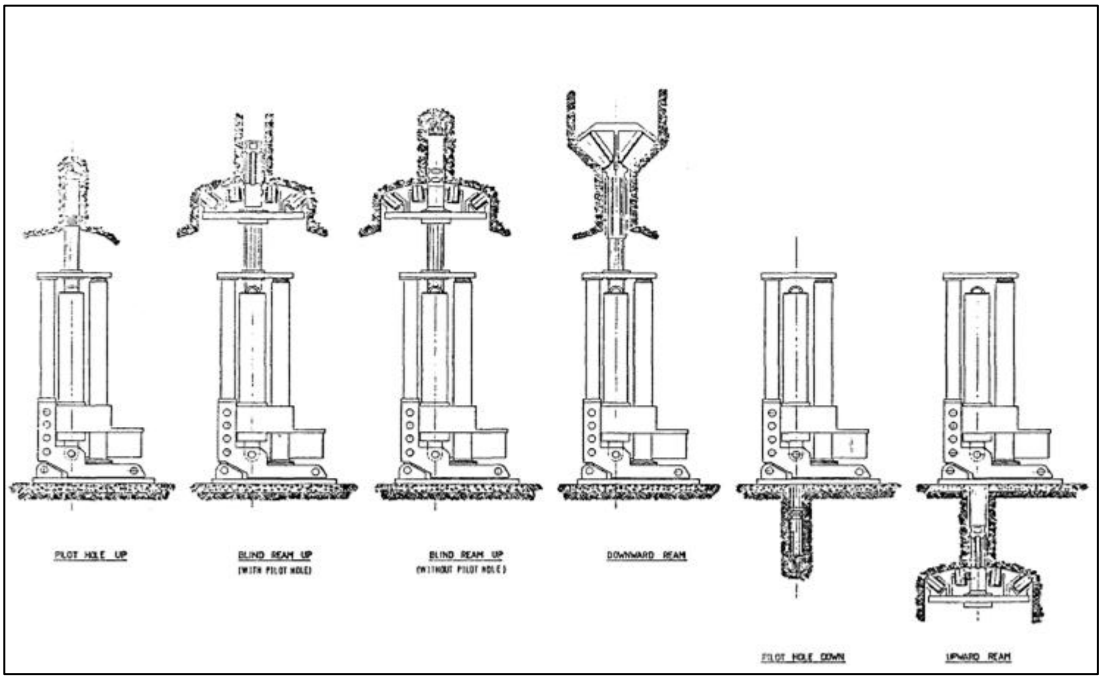


Figure 20. Operating modes of the Robbins 53R (Lundstrom, 1985)

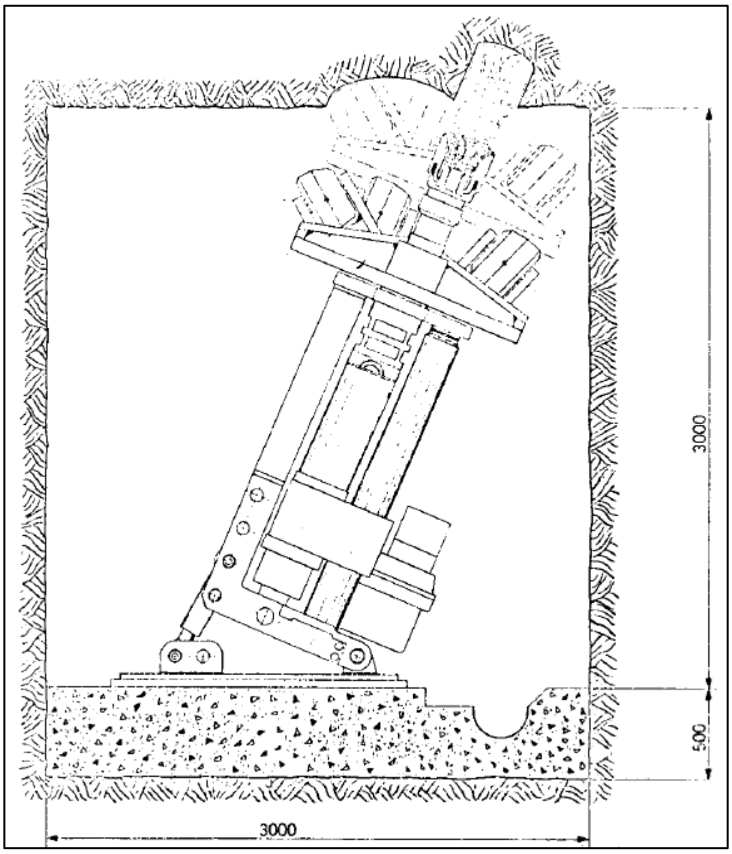


Figure 21. Robbins 53RH in a 3 m tunnel (Lundstrom, 1985)

The blind boring trials at Vaal Reefs South had achieved more than 13 000 m (1985) since the first induction of the Robbins 52RE borer in 1975. Even though some success has been achieved, the capability of the machines has reached a peak and therefore requires a radical design change if greater flexibility, economical operation and increased boring rates are to be obtained. At the time, the Wirth BHB150 had only completed 672 m with the main challenge being the clearing of cuttings. The study also found that the pre-piloted holes did not provide significant improvements in average penetration rates. The reaming of the pre-piloted hole was done at an average penetration rate of 1.97 m/h whilst the non-piloted hole achieved an average penetration rate of 1.83 m/h. The overall average across all holes drilled using the piloted approach was 0.95 m/h which reaffirms that there were no significant gains by using pilot holes apart from the fact of knowing exactly the final position of the holing (Lundstrom, 1985).

Lundstrom (1985) believes that the teething problems in mechanised boring applications are due to a lack of pre-use field testing. The manufacturers are discouraged by the high capital outlay required for extensive field testing, before being used by customers. Albeit the designs of these machines are based on sound engineering principles, it is only in the production environment that the true reliability and performance of these innovations become apparent. At the time of publication, Lundstrom (1985) stated that research and development into high-pressure water jets for improved cutting rates and a steering facility for borers were already underway. The author further foresaw the use of microprocessors to achieve automated steering.

In the first volume of the proceedings from the Rapid Excavation and Tunnelling Conference (RETC) held in New York, Marlowe and Page (1985) reviewed blindhole boring in South Africa and discussed laboratory experiments in rock-cutting assisted by high-pressure water jets. The authors also presented results from underground boring experiments and supplied a test program for the future. According to the authors, blindhole borers have been on the market since 1967. The first mechanised borer (VTB-Vertical Thrust Borer) developed by Calwled, initially intended for the New Mexico uranium fields, arrived in South Africa in 1973 as part of a mechanisation drive in gold mining.

Wilson and Graham (1974) believe that the main reasons for pursuing raise boring in South African gold mines were to reduce the time necessary to open new mines, to improve the safety of personnel and equipment, to battle the rapidly rising cost of labour on mines, to obtain the improved stability of circular machined excavations as opposed to conventionally blasted square excavations, to possibly reduce the amount of waste development required and finally the possibility of enhancing the degree of mechanisation within labour-intensive conventional gold mines. In their paper on boring thrust and its potential in the hard-rock mining industry in South Africa, the authors also discussed the results from penetration tests taken during actual drilling in Witwatersrand quartzite to investigate the relationship between thrust applied and the penetration rate achieved. As seen in Figure 22 there seems to be a linear relationship between the amount of thrust applied and the penetration rates achieved. This was populated using data from various drill rods used at different thrust rates. Figure 23 depicts the specific energy relationship with the reamer thrust when boring in quartzite, and from the graph, it is noticed that as thrust increases the specific energy also decreases in a non-linear manner. This relationship reaches an asymptotic-like flattening at extremely high trust which means that for thrusts higher than the flattening point there will be no difference in the specific energy.

A summary of the cutting cost at the time of the trial (1974) is indicated in Table 9, and at the time, the exchange rate was one rand for every $ 1.48.

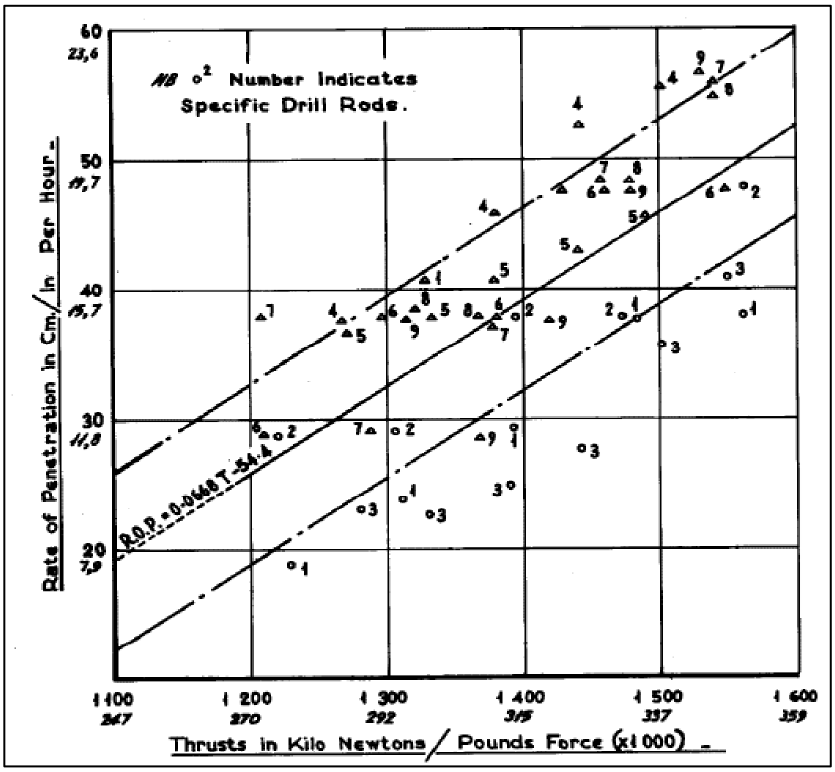


Figure 22. Penetration rate vs reamer thrust in Witwatersrand quartzite (Wilson & Graham, 1974)

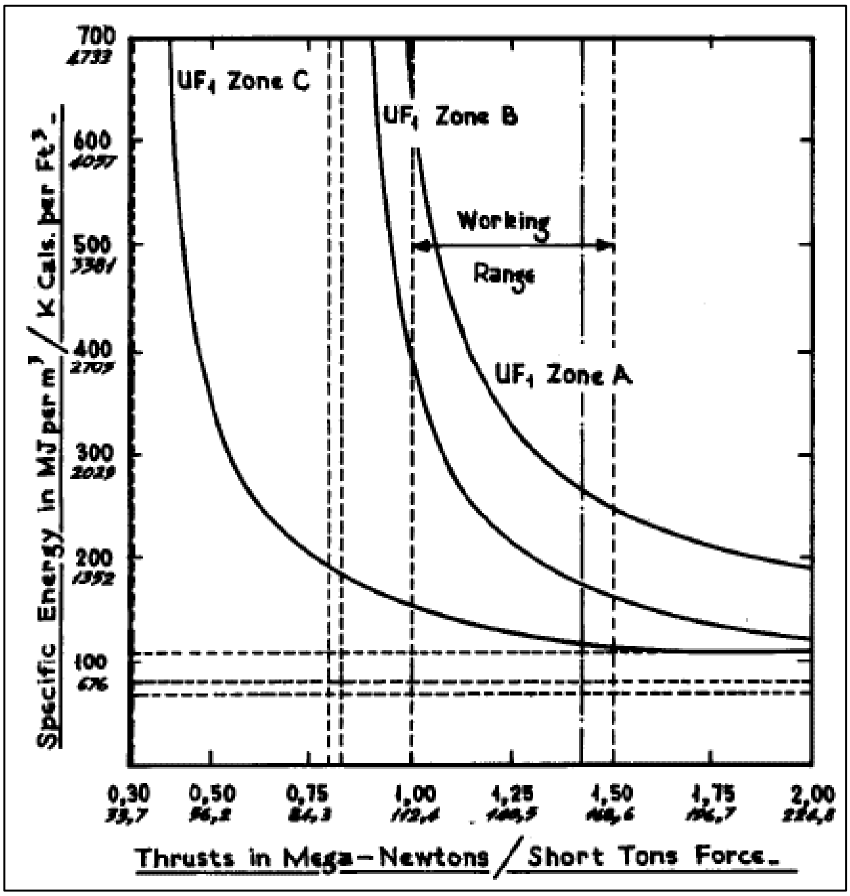


Figure 23. Specific energy vs. reamer thrust for 2.1 m diameter hole in quartzite (Wilson & Graham, 1974)

Table 9. Summary of mechanised cutting using raise borers in South African gold mines (Wilson & Graham, 1974)

Raise No.	Reamer Cutter Cost (Rand/ft)	Pilot Bit Cost (Rand/ft)	Labour Cost (Rand/ft)	Maintenance Cost (Rand/ft)	Total Direct Cost (Rand/ft)
1	49.46	5.30	21.44	2.60	78.80
2	52.10	5.30	12.61	2.60	72.61
3	47.29	5.30	16.72	2.60	71.91
4	39.15	5.30	20.69	2.60	67.74
5	12.03	5.30	35.02	2.60	54.95
6	19.00	5.30	22.05	2.60	48.95

Since 1974 the Research and Development Services (RDS) of the Anglo American Corporation played a leading role in the development of blind hole borers. At the time of publication, there were 37 machines in use in South Africa consisting of first, second and third-generation machines with the fourth-generation machines expected to hit the market soon. The paper concluded that the potential of water jet assistance in improving cutting and reducing the overall cost of boring could still be achieved in the near future even though initial field trials yielded disappointing results (Marlowe and Page, 1985). Initial laboratory experiments found that the benefits of using water jets to assist cutting included cooling of cutters and bits, reduced tool wear, and a reduction in required torque due to the removal of cuttings from the tool interface and the promotion of additional cracks at the cutting interface due to cooling (Fenn and Protheroe, 1982). Additional tests on water jet cutting were done at the Colorado School of Mines in conjunction with disc and kerf cutters and found a 25 % and 27 % reduction in rolling force required, and 10 % and 36 % reduced thrust required for disc and kerf cutters, respectively (Ozdemir, 1984).

As the drive towards general mechanization of mines in South Africa progressed throughout the 1980s and 1990s, non-explosive rock-breaking became a key research topic as part of the integration of technology as a survival strategy, especially for labour-intensive South African gold mines. The maximum face advance achievable using conventional methods was around 25 m/month and it was hoped that non-explosive rock-breaking methods could yield rates of up to 100 m/month. Many concepts were trialled, but not all technologies studied at the time were adopted universally, and initial mechanisation efforts were focused on improving the direct drill and blast operation through improved machinery and cleaning systems. Variations in geotechnical areas have a significant effect on the success achieved by alternative non-explosive rock-breaking methods. Attempts to quantify these effects were, however, only started at a later stage. Research into the development of more powerful hammers and wider stoping widths still continued as the machines were unproductive, especially in areas with no stress fracturing at depths less than one kilometre. Researchers looked into the principle of using a plasma hole maker to break rock and developed a test rig that utilizes a high-pressure downhole slug of water to break the rock. Underground trials were completed successfully with the water pulse gun managing to break up to 0.5 m of burden in both fractured and unfractured conditions. The key next steps were to develop a practical mining machine that could be used ideally in areas where drilling is still required but explosives can't be used. An example of the principle of the plasma hole maker is indicated in Figure 24. Researchers also believed that although minor adjustments to the current mechanised rock-breaking technologies could render them viable, the adoption of selective mining should be considered to improve overall yields and the concerns relating to the cost of providing acceptable environmental conditions should also be addressed (Willis, 2000).

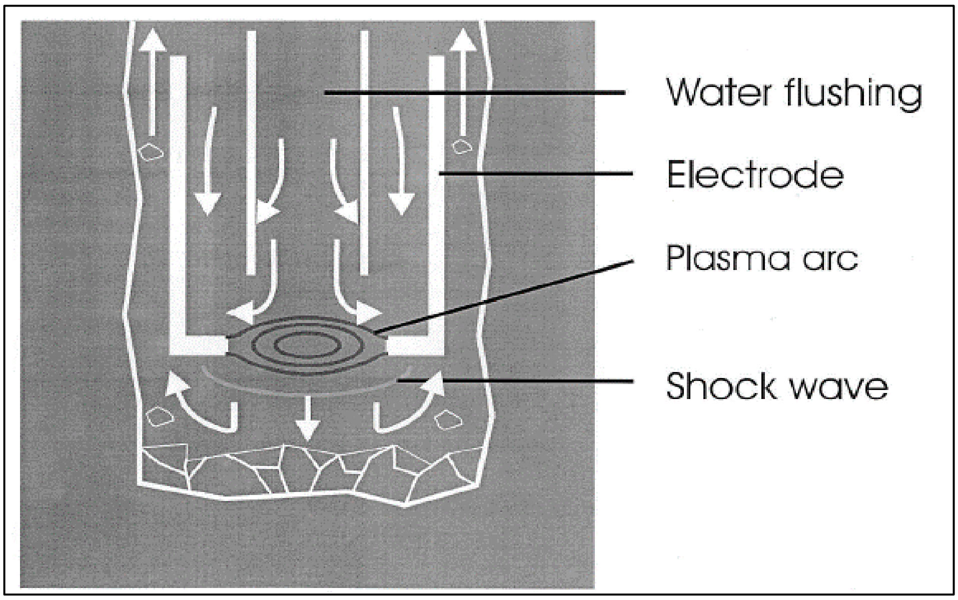


Figure 24. Principle of plasma hole maker (Willis, 2000)

In the paper: "A practical approach to hard rock selective mining" Willis et al. (2001) discusses the development of mini-disk cutters and the application thereof in South Africa. Also highlighted is the collaboration between CSIR: Miningtek and EEA in developing mini-disc cutting solutions after realizing the potential benefits of selective continuous mining in hard rock mines for short and longwall applications. A summary of the study is shown in Table 10.

Table 10. Project Details: Development and use of mini-disc cutters in South Africa (Willis, et al., 2001)

Project Owner	CSIR: Miningtek
Strategic Partners	EEA
Project location	CSIR Lab, intended for UG2 reef in Platinum mines in South Africa.
Project timeline	Approximately 1999-2001
Project Objectives	To build and test a 780 mm diameter by 800 mm deep drum cutter head to investigate the potential of mini-disc cutters in long or short wall applications for selective hard rock mining.
Machine Type	Mini-disc Drum Cutter
Reference	(Willis, et al., 2001)

Willis et al. (2001) state that the key driver towards rock-cutting is to obtain continuous mining as the conventional drill and blast process is cyclical, time-consuming and labour intensive. Non-explosive rock-breaking provides improved rock conditions, greater safety and higher productivity than conventional methods.

Reviewing the history behind mini-disc cutting, the authors found that it was from excavations using TBM's that the superior performance of disc cutters was realised and it was also noted that the cutter spacing determined the cutter heads efficiency (Willis, et al., 2001).

According to Willis et al (2001) mini-disc cutters have the following advantages:

- Flexible spacing
- True rolling
- Higher performance
- Single tracking
- Longer wear
- Low-cost replacement

The program of work for the study conducted by the CSIR: Miningtek was to develop a continuous cutting machine capable of selectively mining UG2 reef in South African platinum mines. The CSIR: Miningtek has invested in two large stiff test rigs to assist in laboratory experiments into mini-disc cutting. The initial work carried out was extensive rock property measurements including:

- Compressive strength
- Tensile strength
- Toughness
- Grain size
- Cerchar data

Using the stiff testing rigs, a series of linear cutting tests were run using a full-sized mini-disc cutter. The initial tests yielded only half of the expected advance rates and it was later identified that the root cause of this was the lack of force transference to the cutting disc and the failure of components in the hydraulic system. Even with these challenges, a 40 to 50 m/month advance rate is still possible for a 30 m panel based on the results obtained. Sufficient evidence indicated that mini-disc cutting could offer low-risk, continuous cutting for both mining and micro-tunnelling for cutters of 2 m diameter and less. The authors added a disclaimer that further underground test work and development is required for the continuous cutting system to reach its full potential and be practically viable (Willis, et al., 2001). The proposed mining system using mini-disc drum cutters (Figure 25) is indicated in the schematic Figure 26.

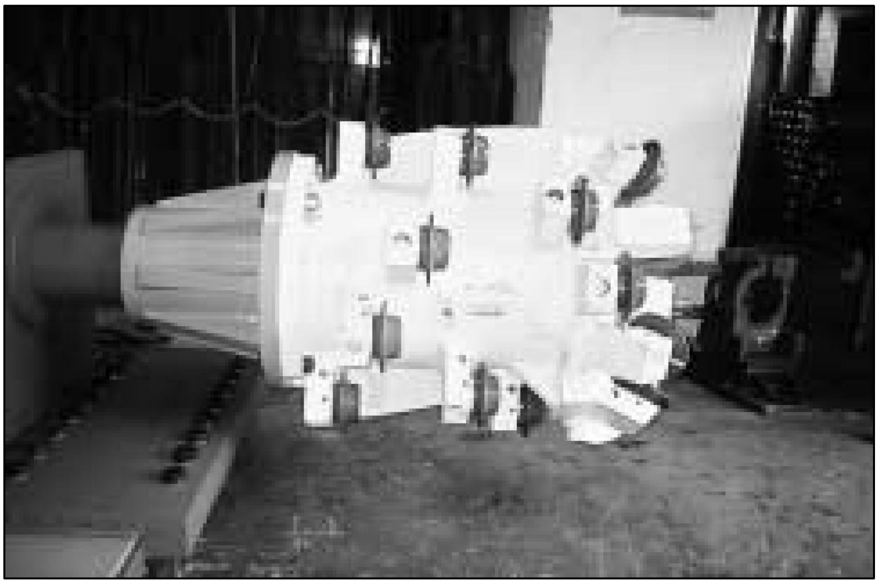


Figure 25. Photo of a 780 mm test drum based on mini-discs (Willis, et al., 2001)

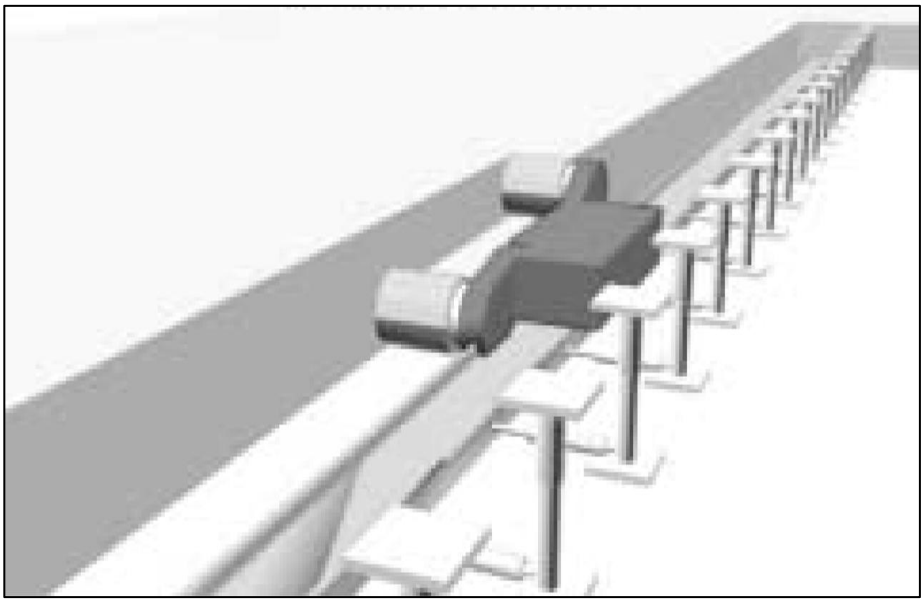


Figure 26. Proposed mini-disc drum cutter mining system (Willis, et al., 2001)

Anglo Platinum anticipated the future need for improved mechanisation and increased reef development rates and has therefore invested in research and development of continuous mechanical rock-cutting solutions. Based on the proposal from Bomar, a South African mining contractor, in collaboration with the Robbins Company (USA), the development division of Anglo Platinum proceeded with an underground trial where a TBM was used for the establishment of a reef raise at Bafokeng Rasimone Platinum Mine (Stander, et al., 2001). The project summary is indicated in the table below.

Table 11. Project Details: TBM used for reef development on a South African platinum mine (Stander, et al., 2001)

Project Owner	Anglo Platinum
Strategic Partners	Development Division of Anglo Platinum, Bomar, Robbins Company
Project location	Bafokeng Rasimone Platinum Mine (BRPM), South Africa
Project timeline	13 December 2000 through to holing on 15 June 2001
Project Objectives	To increase the rate of reef development both for new mechanised stoping technology and on conventional new developing mines. The establishment of a reef raise between 3 Level and 2 Level at BRPM (North) Mine.
Machine Type	Jarva MK6 (TBM) – Built in 1972
Reference	(Stander, et al., 2001)

The TBM used for the project was manufactured in 1972 and had the following specifications, as noted by Stander et al. (2001):

- Atlas Copco Robbins Java MK6.
- Year of manufacture 1972.
- Open type 4 gripper machine.
- Diameter 2100 mm.
- Motor 175 kW water-cooled
- Thrust 230 tons at 200 bar.
- Number of cutting discs: 18
- Cutter size: 330 mm
- RPM: 9,5
- Stroke length: 600 mm
- Conveyors: 450 mm wide
- Power requirements: 500 kVA
- Motor circuit: 380 V 50Hz
- Mass TBM: 25 ton

- Mass back-up: 6 ton
- Water requirements: 12 litres/second @ 7 bar
- Dust suppression: 5 spray nozzles on cutter head
- Cutter head: open type front loading cutters

The rock engineering criteria for the test site were as follows (Stander, et al., 2001):

- Pyroxenite 130 MPa
- Merensky Reef 123 to 133 MPa
- Anorthosite 180 to 290 MPa
- Leuconorite 189 to 235 MP

The details regarding the various activities of a TBM system are indicated in the table below:

Table 12. Activities of the TBM used to develop on-reef on a platinum mine in South Africa (Stander, et al., 2001)

Activity	Description
Cleaning	Chippings are removed via an internal conveyor onto a second main conveyor. Cleaning of the raise done using scraper winches.
Ventilation	Initial flexible ducting was damaged by the scraper winch, leading to the option of using galvanised steel pipes with dust filters extending from the cutter head driven by a 7.5 kW high-pressure fan.
Flammable gas detection	A flammable gas sensor was mounted as close as possible to the cutter head with the limit set at 1.2 %. The exhaust ventilation was on a separate circuit and would continue to operate if the sensor cut out the power to the TBM when the 1.2 % limit was breached.
Underground transport	TBM was transported in disassembled components. This was limited to a payload of 10 tonnes and a maximum length of 5 m.
Launching	A specialised ramp had to be constructed to provide a platform from which the TBM could sump into the reef horizon above the cross-cut elevation.
Boring	After collaring the grippers were installed, adjustments made and the machine was surveyed in and laser targets set whereafter boring commenced.

During the boring process, there were several delays and problems experienced, including steering challenges, damage to services due to cleaning with scrapers, mechanical failures, maintenance challenges and the intersection of flammable gasses on three occasions (Stander et al., 2001). Table 13 depicts the performance measured during the TBM trial.

Table 13. Performance measurements of TBM cutting on a platinum mine in South Africa (Stander, et al., 2001)

Item	Performance
Penetration	Average penetration rate of 0.47 m/h achieved: ● Anorthosite (0.36 – 0.40) ● Norites (0.60) ● Merensky Reef (0.90 – 1.10)
Cutter life	Better than anticipated, achieving a life of 12.21m^3 rock/ring. Initial centre cutters had a low life but were mitigated by the use of carbide cutters.
Statistics	● Best advance/day = 13.8 m ● Best advance in a week = 47.6 m ● Best advance in a month = 104.7 m ● Best ROP = 1.33 m/h
Availabilities and Delays	Total available hours = 3208 Total delay hours = 2492 ● TBM availability = 82.5 % ● TBM utilisation = 22.3 % ● Delay = 77.3 %

The lessons learned from the trial (Stander et al., 2001):

- The best results were achieved in the least disrupted reef
- The scraper cleaning system did not work successfully, alternative solutions like conveyors needed
- The method of service installation and operator selection is key in avoiding delays and poor performance
- Relook into ventilation in confined spaces required
- Extensive pre-planning required before the implementation of a TBM project

Croll (2004) gives insight into the attempts made by Anglo Platinum to achieve improved mechanization of current and new mining operations. Albeit mechanization attempts have been conducted since the early 1900s, Anglo Platinum's attempts only really started to gain traction in 1998 with both success and failure. A summary of the study is indicated in Table 14.

Table 14. Study Details: Anglo Platinum Mines (Croll, 2004)

Project Owner	Anglo Platinum
Strategic Partners	DBT (German-based company) RCTS (The old Robbins Raise Boring Company)
Project location	Anglo Platinum, South Africa
Project timeline	Approximately 1998 to 2004 ODC initiative has stopped the progress due to the commercialization and outdated technology.
Project Objectives	Reducing pick wear costs and testing reliability of the activated drum system
Machine Type	Activated drum system
Reference	(Croll, 2004)

Even though Croll (2004) discusses the methodology behind the implementation of mechanised systems and the various programmes run, of key interest is the rock-cutting systems. According to the author the different types of rock-cutting systems trialled included an oscillating disc cutter (Figure 27), an activated drum system (Figure 28) and a narrow reef miner (Figure 29) with each employing different methodologies to cut the rock. The objective of each of these programmes was to provide a continuous mining system.

According to Croll (2004), the research published on methodologies regarding mechanization in the 1980s was thorough and complete. He also concluded that it is clear that 'one size doesn't fit all' and that technology needs to adapt to what Mother Nature provides us.

Figure 27. Oscillating disc cutter (Croll, 2004)

Figure 28. Activated drum system (Croll, 2004)

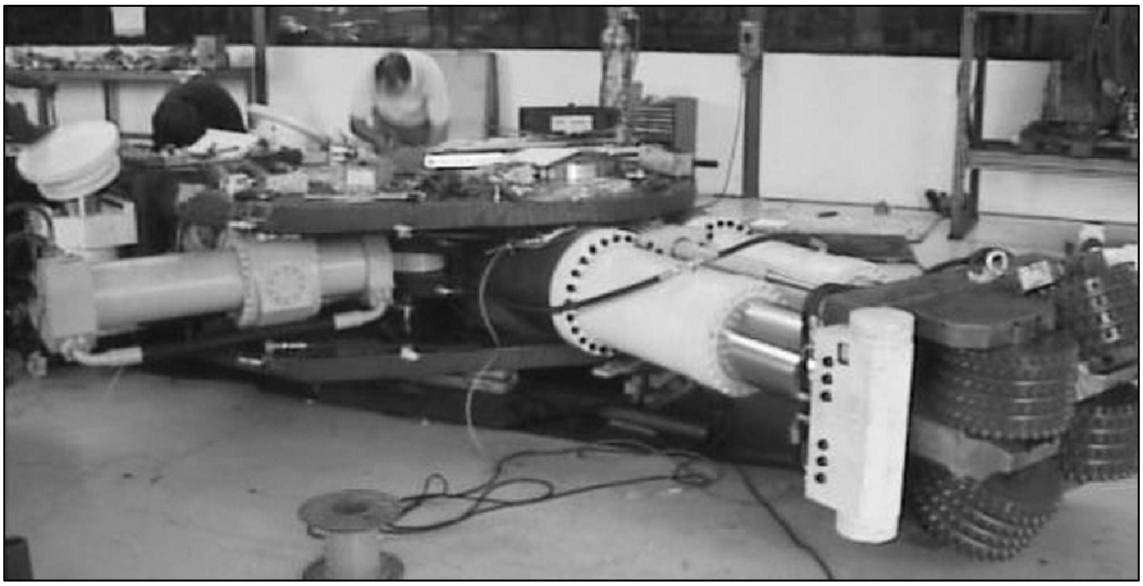


Figure 29. Narrow reef miner (Croll, 2004)

According to Lanham (2005), ore passes are essential for the transportation of broken rock in underground narrow tabular mines and remain an arduous and hazardous task as evident from the many injuries and fatalities recorded, especially in the gold and platinum mines. Due to the routine nature of ore pass development and the need to improve safety, Lonmin set out to test a boxhole borer in collaboration with Sandvik Mining and construction's (SMC's), Voest Alpine Bergtechnik (VAB) division to develop orepasses through mechanical cutting at improved speed, safety and cost. The detail of the project is summarised in Table 15.

Table 15. Project Details: Lonmin joint venture with Sandvik to test a borer that can develop ore passes safer, quicker and cheaper (Lanham, 2005)

Project Owner	Joint venture with Lonmin and Sandvik Mining and Construction (SMC's), Voest Alpine Bergtechnik (VAB) division
Strategic Partners	Sandvik Mining and Construction (SMC's), Voest Alpine Bergtechnik (VAB) division
Project location	Lonmin's Eastern Platinum mine, Newman incline shaft on the mine's No 8 level
Project timeline	2005

Project Objectives	A borer that can develop ore passes without putting lives in danger. Compact to operate from a normal haulage without the need for mining out of excavation or having to through concrete civils. Setup of the machine within 8-hour shift.
Machine Type	Borer / raise-boring machine / ABH 1600 (prototype) • Hydraulically powered by a 280 kW powerpack • 6x off-the-shelf cutter heads, with a tricone bit (centre hole boring) • Remote operation with cameras for operator visuals • Spoil removal through a vacuum and hopper system
Reference	(Lanham, 2005)

The prototype SMC blind-hole boxhole borer was tested at Lonmin's Eastern Platinum mine. The ABH 1600 machine had been set up at the Newman incline shaft on the mine's No 8 level. This new SMC borer was the first in the world to successfully execute mechanical mining of an ore pass. The project was scoped on conducting a trial of the compact boxhole borer by developing 3 ore passes and measuring the speed, cost and safety of excavation. From the interview with Kevin Mocham, Lonmin Platinum's group manager for mechanisation and automation, the urgent need for mechanisation was highlighted and the machine requirements were highlighted. The requirements were that the machine had to be compact to operate from haulages and without a top access to reduce the need for extensive civil works as well as a set-up time limited to within an 8-hour shift. Additional design criteria laid down was that the machine should be able to bore up to a 30 m borehole with a deviation of less than 50 cm (Lanham, 2005).

Initial testing of the prototype was conducted in Austria where VAB constructed a massive 8 m concrete cube with a mock-up of a haulage running through it. The borer was able to advance through the concrete at a rate of 3 m/hour.

To deploy the boxhole borer, the machine is positioned similar to aiming with a canon. Before boring can commence, the operator is required to have a surveyors note that confirms the borer has been positioned correctly. Thereafter, the operator relies on a laser beam directed at the target. The operator can steer the machine in alternative directions should geological features influence the planned boring trajectory However, this can only be done once the machine is firmly within the hole (Lanham, 2005).

The borer has grippers in the front and rear of the machine that engages the sidewall to propel the borer forward similar to the crawling motion of a caterpillar that engages one leg followed by the next to advance forward. The rear grippers are engaged and through hydraulic pressure, the head advances into the cutting face. Once the maximum reach is achieved, the rear grippers are disengaged and the front grippers are engaged interchangeably to pull the borer forward to the next boring position. One of the factors limiting bore length was the length of the power supply and control cables, only allowing 1.5 m advance per push (Lanham, 2005).

The head of the machine relies on pressure to break the rock at the interface instead of percussion, which removes the need for water spraying at the face. Chippings are removed using a vacuum system and are collected in an overhead collector box and transferred to hoppers to transport the spoil to the surface (Lanham, 2005).

One of the main objectives of the project was to set up the machine within 8 hours. During the boring of the three trail holes, SMC technician proved that this is indeed possible. It was also stipulated that the machine be able to bore at least 30 m with a deviation of less than 50 cm and the machine had only three ore passes in which to demonstrate its ability. The machine made a seamless transfer from being a trail project to being a production machine as the first two ore passes were executed exactly as intended. The first two holes were in the order of 10 m, penetrating the UG2 reef to a depth of 20 cm.

In principle, the machine had the ability to bore longer holes than 20 m, however, it was recommended that the machine be used over short distances so that the cutter does not need to be replaced within one operation. During testing key issues with dust and chipping removal were encountered. These issues were resolved with the assistance of Colliery Dust Control, and VacAir did modifications to allow for the successful mining of the rock. It was found that the boxhole borer is more expensive than conventional ore pass development (Lanham, 2005).

Although the direct cost of mechanical boring is higher it is still on par with drop-raising and has a host of advantages that may tip the scale in favour of mechanical tunnelling (Lanham, 2005). Some benefits are:

- No top-access requirement
- Can do 1.5 to 2 m per hour whereas conventional drop-raising can only mine about 4 m at a similar cost
- No explosives required
- Smoother sidewalls less prone to scaling
- Limited haulage sliping and no heavy-duty concrete are required to set up the borer

The boxhole borer tested, ABH 1600, is a highly compact 3 m long machine and is based on raise borer technology. The borer is housed within a snug steel launch tube, which is horizontally mounted on a turntable. When the boxhole borer needs to be deployed, the launch tube is swung into position (similar to aiming a canon). The borer is hydraulically powered from a separate 280 kW power pack and uses applied pressure through the 6 (of the shelf) cutters to break the rock. A tricone bit assembly in the centre of the cutting interface is used to drill the centre hole. The box hole borer is equipped with front and rear grippers to stabilise the borer and to hydraulically propel the borer forward as drilling advances. The price tag of the Sandvik boxhole borer, at the time of publication, was estimated at R 8.5 million (Lanham, 2005).

Lonmin Platinum, Voest Alpine and Sandvik Tamrock entered into a partnership to co-develop and trail a narrow reef miner, the prototype ARM 1100. The machine was commissioned at Lonmin's Rowland Shaft and underground operations started in February 2002. Moxham (2004) describes the results of the trials conducted where more than 1100 m^2 UG2 was mined. A summary is indicated in Table 16.

Table 16. Project Details: ARM 1100 Hard Rock Narrow Reef Miner

Project Owner	Joint venture with Lonmin and Sandvik Tamrock, Voest Alpine
Strategic Partners	Sandvik Tamrock, Voest Alpine
Project location	Lonmin's Rowland Shaft
Project timeline	2002
Project Objectives	Finding a continuous non-explosive mining method to alleviate the challenges of dilution and mechanization in narrow reef gold and platinum mines.
Machine Type	ARM 1100
Reference	(Moxham, 2004)

The ARM 1100 tested at Lonmin's Roland shaft was evaluated under the following key performance aspects:

- Cutting efficiency (depth per pass, penetration rates)
- Cutter wear and lifespan
- Ore handling efficiency
- Safety and operational feasibility

The data collection during the trials included force, power consumption, and penetration rates achieved over 500 cutting operations. The conditions where cutting took place was in very hard and abrasive UG2 reef (UCS of around 120MPa) with a stoping height of 1.1 m and an orebody dip of 8°-13°.

Mechanical rock failure is a complex process influenced by the rock's physical and geological properties, as highlighted by Moxham (2004). The author describes the cutting process in detail, highlighting how tensile cracks are formed due to the hydrostatic pressure loading from the cutters. Tensile cracks radiate outward, forming rock-cuttings as they intersect, as depicted in Figure 30.

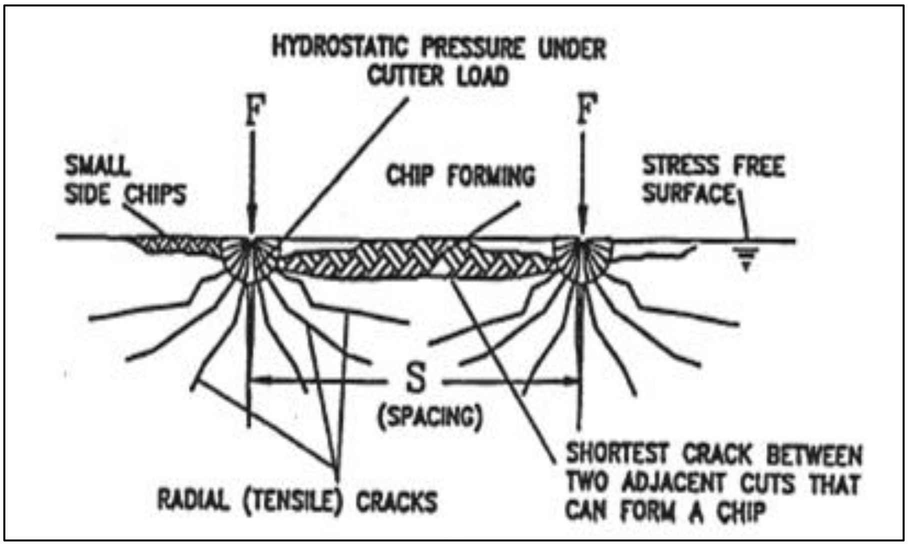


Figure 30. Schematic of the theoretical breaking process for rock under conventional disc cutter loading (Moxham, 2004)

Moxham (2004) details the specifications of the narrow reef miner (ARM1100) as follows:

- Disc cutting system using undercutting disc cutters to minimize power consumption whilst optimizing fragment size
- The estimated cut depth is 50-60mm per pass
- Machine stability is achieved through a stalking system, gaining improved control in confined spaces over the conventional crawler system
- The miner can develop its own entry into the stope and has an integrated rock removal system to ensure timeous removal of cuttings to avoid regrinding and excessive fines
- Additional features included the ability to accommodate a wide variety of mining layouts, easy automation, simple design and easily maintainable components

A front-view image of the ARM1100 is depicted in Figure 31, with rear and side-view images in Figure 32 was taken when the machine was cutting into the rase during the launching phase. From the images it can be noted that hydraulic cylinders drive the main components. The design process of the ARM1100 was simplified through the use of existing technology, especially from road headers (Figure 33)

Figure 31. Image of the ARM1100 Narrow Reef Miner (Moxham, 2004)

Figure 32. Images depicting the assembly of the ARM1100 and cutting into the rase (Moxham, 2004)

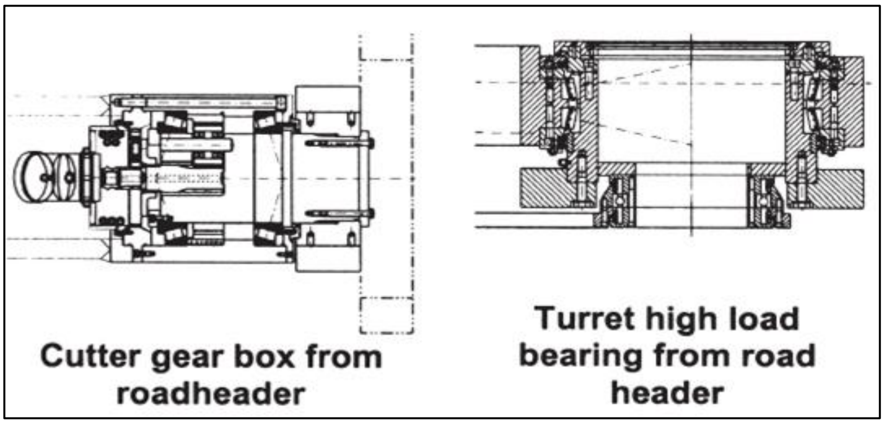


Figure 33. Existing Road header technology used for the ARM 1100 (Moxham, 2004)

The cutting trial was initiated on Roland Shaft Level 25, with the first cut made in February 2002. Different cutting set-ups were trialled within the first 6 months of cutting, with a total of 25 meters achieved in the period up to 17 July 2002. The initial two weeks were spent investigating the optimal slewing forces, cycle times, cutter penetration and depth of cutting. After operating parameters were set, 11 different cutter disc designs were considered and tested, as well as 2 different cutter heads. The cutters tested were manufactured with varying angles of attack, different bearing designs and cutting edges. A design was selected and manufactured using various tungsten carbide grades on the inserts (Moxham, 2004).

The cutters tested differed in three basic areas:

- Button orientation (15 and 20 degrees respectively)
- Shape of buttons/cutting edge (conical buttons, chisel type buttons, steel rings)
- Bearing configurations and angle of cutter axis

Images of the various carbide profiles tested is shown in Figure 24.

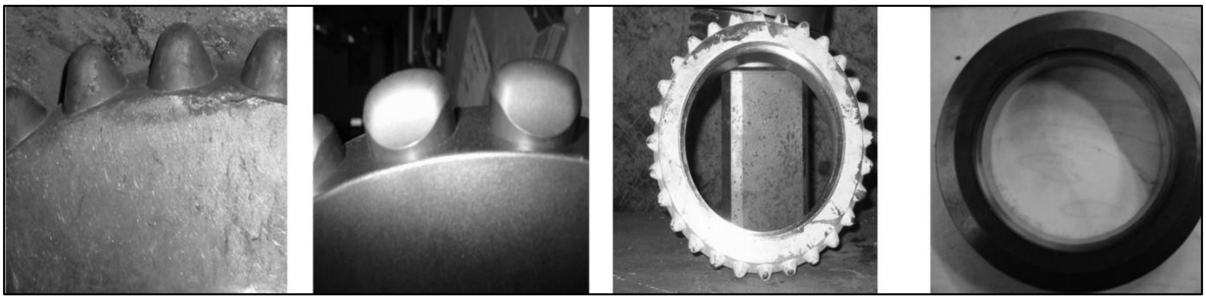


Figure 34. Various carbide profiles tested on the cutting machine (Moxham, 2004)

At the time of the study (2004), 15 conical button cutters performed the best in terms of wear, performance and material produced. According to Moxham, steel-ring cutters performed better and produced a bulkier-sized final product but wore out extremely quickly. Also noticed during the cutting tests were the noteworthy differences in chip size and, consequently, specific energy from the various cutter types. The author found that the biggest chips and lowest volume of fines were produced with the steel-ring cutter whilst conical buttons generated the smallest chips and highest volumes of fines and chisel bits producing fragment sizes in-between the other two mentioned. Figure 35 shows Images of undercutting with variations in cutting depth and the effect of undercutting as the depth of cut is increased. Variations in rock fragments produced associated with different cutter set-ups are shown in Figure 36.

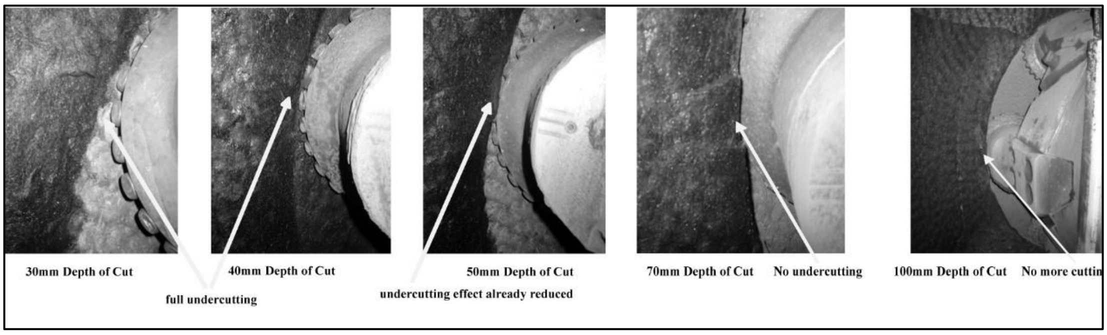


Figure 35. Effective undercutting at various cutting depths

Figure 36. Variations in rock fragments produced due to alternative cutter set-up

Originally the ARM1100 miner was designed with a total of six cutter discs mounted on the cutting head. However, observations during the trial indicated that more cutter heads would be required for a smoother and more effective cutting process. Moxham (2004) believed that future machines would need to have an increase in installed power to achieve improved cutting rates, less grinding, and ultimately lower fines generation.

Figure 37 depicts the typical data that was collected of the machine and cutting performance during each cycle of the machine. The productivity rates described by Moxham (2004) were advance rates of 850 mm/hr in hard rock, with a monthly production of 6000-8000 tonnes/machine, based on a monthly cycle of 22 days and 3 shifts/day. The prototype achieved a linear advance of 270 m.

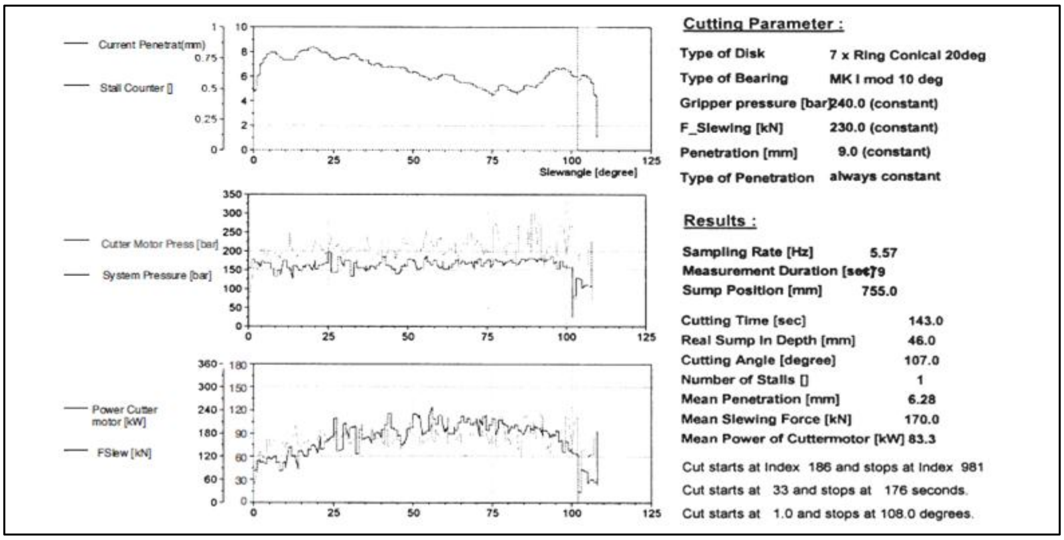


Figure 37. Typical data collected for each machine cycle (Moxham, 2004)

Various challenges were encountered during the trials, especially due to cutter wear or failure, rock fragmentation, roof support, ore handling and cleaning inefficiencies. The cost of the cutters accounted for more than 70% of the total production cost per ton. High wear and failure were induced on cutting set-ups due to the hardness of the UG2 and lack of fracture propagation. The original conveyor system required multiple improvements in design (see Figure 38) due to excess material remaining in the cutting path leading to regrinding and excessive fines. Observations made during testing included improved integration between support services and the machine, as initial installations were done manually (Moxham, 2004). Images of the scoop used to load the rock-cuttings onto the conveyor belt is shown in Figure 39.

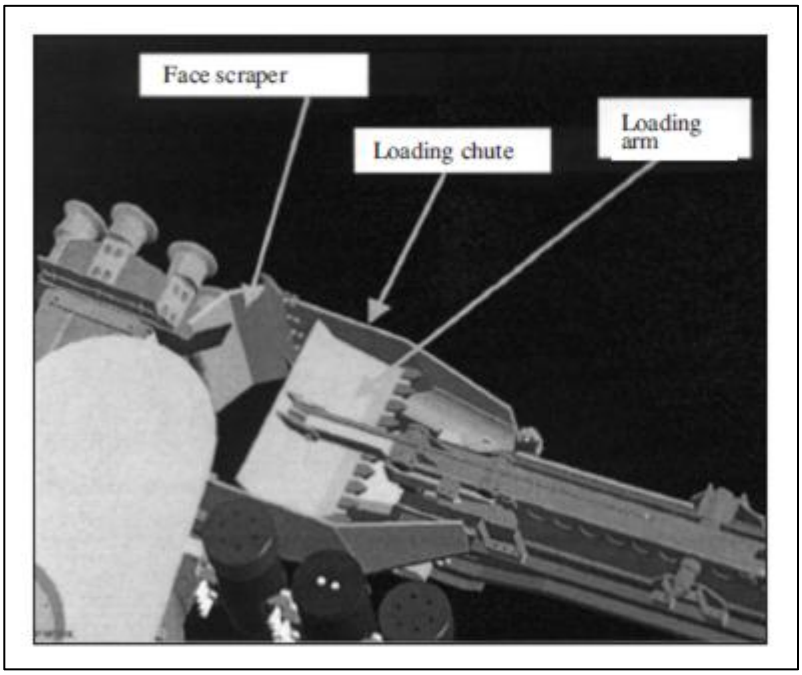


Figure 38. Modified conveyor loading set-up (Moxham, 2004)

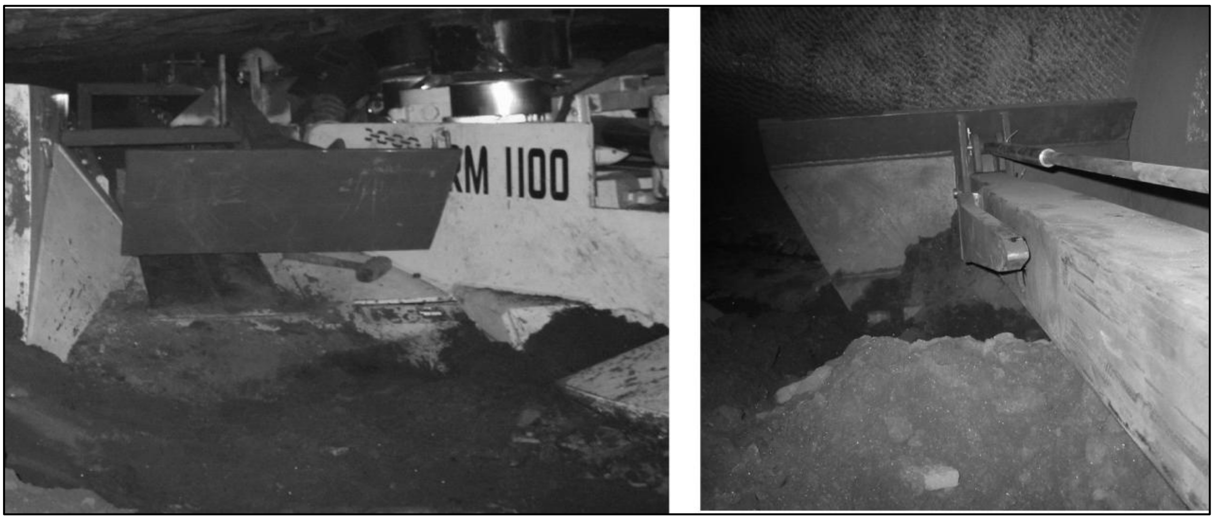


Figure 39. Images of the scoop used to load cuttings onto the conveyor (Moxham, 2004)

The following findings were made by Moxham (2004) as well as recommendations for future improvements:

- **Machine Feasibility**: The ARM 1100 successfully cut hard rock within a confined stope, proving the viability of mechanical rock-cutting in narrow reef mining.

- **Optimal Cutter Design**: The cutting set-up of 15° conical button cutters performed the best in terms of wear resistance and overall efficiency.

- **Rock Handling Solutions**: The initial material handling system was laden with inefficiencies that required multiple redesigning interventions. Alternative ore removal systems such as vacuum systems, mobile conveyors, and shuttle cars, are under evaluation for future machines.

- **Next Steps**: The MK II production machine was commissioned into operation at Rowland Shaft, incorporating improvements based on the trial findings. Potential for wider application in softer UG2 ores and Merensky reef mining was noted.

Pickering et al. (2006) give a detailed update on the ARM1100 project conducted at Lonmin's Rowland Shaft in a paper represented at the International Platinum Conference: "Platinum Surges Ahead", held in 2006. According to the authors, the room and pillar method followed by long hole drilling and blasting in narrow reef mining offers the maximum reef recovery and minimum waste recovery. They believed that non-explosive mining has the potential to be conducted on a continuous basis, with no delays pertaining to the hazardous explosive fumes and in return, maximizing the capital investment.

According to Pickering et al. (2006) the available rock-cutting technology will define the stope width and will need to be considered when designing the mine to maximize output and minimize waste dilution. This will also potentially minimize damage to the hanging and create a safer environment. The authors gave the summary below with trials of several different cutting processes and mining machines over the years to indicate progress made at that time (2006):

- Pick cutting has not been cost-effective in hard rock
- Full-face cutting with solid discs or cutters has successfully been applied to raise boring and TBMs. A narrow reef mining machine with these mechanisms has been developed and tested by Placer Dome in Canada, and a similar machine was tested by Anglo Platinum. It was found that only a few cubic metres of rock were cut at both sites.
- Anglo Platinum has successfully cut a few cubic metres using activated cutting for stoping machines.
- CRC Mining in Brisbane is conducting experiments for oscillating discs
- Undercutting was used by Wirth in the mobile tunnelling machine that mined about 200 m^3 in a Sudbury mine. Its technology is used by SMC in the ARM 1100 and has successfully cut over 5000 m^3 in both UG2 and Merensky reefs.

Voest Alpine Bergtechnik, an Austrian-based company, together with Sandvik Tamrock, were major players in the development of the Icutroc process during the late 1990s. It made it possible for pick-cutting machines to operate cost-effectively in substantially harder rock. After various tests, it was found that the most cost-effective option for reef cutting would be conventional disc-cutting technology. Sandvik Tamrock, Voest Alpine and Lonmin Platinum entered into an agreement to develop and test the Reef Miner. Sandvik Tamrock and Voest Alpine share the intellectual property for the design of the prototype. Whilst Lonmin Platinum funded the manufacturing of the prototype. The design and manufacture schedule of the prototype was estimated to take 12 months and was to be delivered in South Africa in November 2001. During discussions, two high-risk elements were identified that could potentially cause failure of the narrow reef miner. The major technological issue was the cutter life and, consequently, cutter cost per ton. The reef miner uses undercutting technology of which there was limited testing (Pickering et al., 2006)

The ARM1100 was installed on the east side of a raise connection. It was cutting from the solid face to the free face in the raise. The cutting plan was to cut up dip for approximately a 70 m distance and then turn the machine around to cut down dip for approximately 80 m. During the production trail of 2004 and 2005 the aim was to cut 3 m per day for 22 days, yielding a 276 centare production month. Both trails conducted in October and November, respectively, yielded 280 centares in 17 shifts. A production of 3 m per shift for 22 shifts on a two-shift basis was the next target. This trial was ended prematurely due to the stop ventilation being inadequate, and temperatures exceeding 36 ˚C during a blind cut. The tipping point was too far for an XLP loader to make the round trips in time. It was then decided to test the ARM at Impala Platinum in February 2004. Due to the brittleness of the rock in the Merensky Reef, it made cutting easier. Cutter costs reached lows of R 185/t and production rates outperformed that of UG2 by 30% (Pickering et al., 2006).

According to Pickering et al. (2006) there were specific layout requirements essential to achieving production targets, namely:

- Sections need to be as long as possible
- Blasting needs to be kept to a minimum as it causes a substantial loss in production due to the instability of the machine to cut effectively in these areas
- Tipping points should be no further than 130 m from the machine
- Ventilation in the section is preferable

The new layout for the machine being installed to mine Merensky Reef at Lonmin was described by Pickering et al. (2006) as follows:

- In a 260 m long ventilated stope, the machine will cut up and down dip
- Only one tipping point at the up-dip side of the stope
- Multiple shuttles (electrically operated) will handle ore, moving the ore between the machines and the tips.

- Ventilation will be forced up to the machine, where it will be exhausted from the machine to be scrubbed at a remote location further up in the stope

In conclusion, ore handling was highlighted as an important section of the process, handling must be fast, flexible and clean. Some restrictions were encountered using conveyors to handle the ore. These restrictions included not being able to follow the machine into 'blind cuts', away from tipping points, or change direction within the stope. For a higher production output, a more flexible system is paramount. Thus, a multiple-bucket system is being considered for future as mentioned by Pickering et al. (2006). The buckets will contain ore generated from two or more consecutive cuts. A hydraulic system will move the bucket a set distance after each cut to ensure an even spread over the length of the bucket to prevent spillage.

The article: "Continuous mining machines on the verge of a breakthrough in hard rock operations" written by Lopez-Pacheco (2017) dives into the world of hard rock mining and specifically how continuous mining machines seek to enhance the efficiency and safety practices of the hard rock mining process. Lopez-Pacheco (2017) conducted multiple interviews with industry experts; Jens Steinberg (commercial manager of hard rock-cutting for Caterpillar Global Mining), Mikael Ramström (Atlas Copco's director for mechanical rock excavation) and Brad Neilson (president of hard rock mining for Komatsu Mining), to gain a deeper understanding of the potential that continuous mining machines hold in hard rock mining compared to the traditional drilling and blasting approach. The article also lays focus on the technical specifications of each design and how these different approaches to a similar problem can lead to potential breakthrough in the way hard rock mining is conducted.

Similar to the findings of Vogt (2016), indicating a lack of partnership and buy-in from miners, Lopez-Pacheco (2017) discussed the difficulties experienced in transitioning to the new technology and the lack of interest from miners. He discussed how the Robins Company manufactured the first capable mobile miner in the late 1970s and tested it at Mount Isa mine in Queensland, Australia, in 1983 (1.1km at 80m/month) and Pasminco's Broken Hill mine in New South Wales, Australia, advancing 1.4km. In the year 1993, Atlas Copco acquired the tunnelling division of the Robins Company and used the mobile miner for civil works in Japan, proving the technology successful. Albeit, in 1998 Atlas Copco had to shelf the technology because miners did not buy into the mobile hard rock miner.

Details of various projects are discussed by Lopez-Pacheco (2017) through interviews with key industry experts. The machines mentioned in the article include the HRM220 hard rock miner from Caterpillar, the DynaMiner from Komatsu Mining, and Atlas Copco's Mobile Miner. These machines are designed to target the rock's tensile strengths which are only 10 to 20 percent of its compressive strength. The purpose of these machines, as outlined in the article, is to improve efficiency by reducing the energy required to break the rock, to reduce wear on the components and to reduce the operational time required.

Caterpillar launched a fully mechanized longwall system used for continuous hard rock mining in 2016 with the goal of targeting the tensile strength of the rock instead of its compressive strength. Initial research and development were conducted in Australia as well as in platinum mines in South Africa before further development in Luenen, Germany, and commercialisation. The details pertaining to the testing are not found in the public domain. A summary of the project details is shown below.

Table 17. Project Details: Project Rapid Mine Development System (RMDS) with CAT and Anglo American

Project Owner	Caterpillar (CAT)
Strategic Partners	KGHM
Project location	R&D cutting tests in Australia and platinum mines in South Africa before the product was developed Tested at KGHM's Polkowice copper mine in Poland
Project timeline	2016 (commercialize)
Project Objectives	Caterpillar's HRM220 (fully mechanized longwall system for continuous hard rock mining)
Machine Type	Caterpillar's HRM220
Reference	(Lopez-Pacheco, 2017)

As stated by Lopez-Pacheco (2017), the continuous miner from CAT uses picks with the aim of utilizing the tensile strength property of the rock to encourage fracturing. By employing continuous rotational movements of the cutting picks to hit the rock like hammer swings at an angle, the mechanical force required to break the rock is decreased. This makes the process more efficient and leads to a greater longevity of the picks. Numerous picks mounted on two cutting heads hit the rock from an angle designed to exploit the tensile strength. The contact of the picks is short, limiting heat and wearing. The system has a series of hydraulic roof supports similar to the set-up of longwall miners used in coal, as depicted in the images in Figure 40.

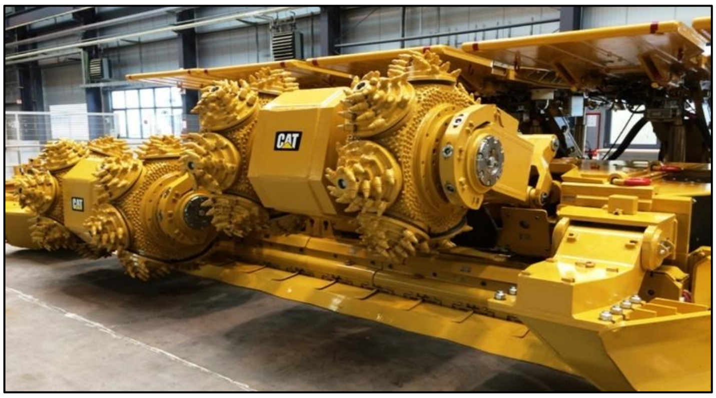


Figure 40. Images of Caterpillar's HRM220 Longwall Hard Rock Mining Machine

The DynaMiner was also discussed by Lopez-Pachenco (2017) and he describes the machine as using an oscillating disc to undercut the rock. The goal of this design is to also target the tensile strength of the rock instead of battling with its compressive resistance. The design of the machine also focussed on the parameters of size and mobility to increase the efficiency of the product whilst decreasing operational costs.

Table 18. Project Details: The DynaMiner continuous mining machine from Komatsu Mining

Project Owner	Komatsu Mining (formerly Joy Global)
Project timeline	2016
Project Objectives	continuous mining machine with more effective energy to cut ratio
Machine Type	Komatsu Mining DynaMiner
Reference	(Lopez-Pacheco, 2017)

Komatsu Mining (formerly Joy Global) has been working on the DynaMiner (Figure 41), which employs the DynaCut technology, since 2006. This machine uses an oscillating disc mounted to a smart boom to chisel rock in a way similar to a high-speed hammer. The DynaMiner prototype is currently being tested at Newcrest's Cadia East Mine in Australia to quantify cutting rates and refine the system for commercial use. Updates on the progress of this machine were not found during this literature study.

Figure 41. Komatsu's DynaMiner Prototype (Lopez-Pacheco, 2017)

Atlas Copco has been developing its Mobile Miner since 2009 in collaboration with Rio Tinto and has also worked with Anglo American on the Rapid Mine Development System (RMDS) since 2012. Testing of RMDS at an Anglo American mine began in 2016 and was nearing completion at the time of reporting. The Mobile Miner uses disc cutters and is equipped with sensors that adjust the force applied to the rock based on its hardness, making it highly efficient.

Table 19. Project Details: Mobile Miner and Project Rapid Mine Development System (RMDS) with Atlas Copco, Rio Tinto and Anglo American

Project Owner	Atlas Copco
Strategic Partners	Rio Tinto, Anglo American
Project location	Tested underground in Anglo American's Twickenham platinum mine in Limpopo
Project timeline	2009-2016
Project Objectives	Continuous mobile mining machine with reduced energy and wear demands
Machine Type	Atlas Copco Mobile Miner
Reference	(Lopez-Pacheco, 2017), (Anglo American, 2017)

A schematic of the Atlas Copco Mobile Miner is indicated in Figure 42 below. In a later study by Lyly et al. (2018), more details regarding the mobile miner were found. The detail of the study is summarised in Table 20 and discussions below.

Figure 42. Schematic of the Atlas Copco Mobile Miner

Table 20. Atlas Copco/ Epiroc Mobile Miner

Project Owner	Epiroc
Strategic Partners	Atlas Copco
Project location	Different locations for the different models
Project timeline	From 1964 - present
Project Objectives	Lower costs, ensure a safe and healthy workplace, meet environmental requirements, and deliver an underground opening that will match the expected quality and strive for improvements. Improving the tunnelling/drifting speed
Machine Type	Epiroc Mobile Miner
Reference	(Lyly, et al., 2018)

The Epiroc Mobile Miner was designed using the combination of geometric flexibility and TBM techniques, which gives it the unique capability of drill and blast to meet variable ground conditions as well as an effective drifting and tunnelling ability. The Mobile Miner operates non-sequentially, creating a good environment for automated working processes. The Mobile Miner should be an ideal machine for underground excavation. However, for the shape and size of the tunnel, the Mobile Miner has a more limited capacity than that of a drill rig. Typically, the excavation is slower than that of the TBM process for similar-sized tunnels.

The curve-taking capability is better than TBM tunnelling, but not as good as drill and blast operations. The Mobile Miner is generally good in small to mid-sized tunnels where flexibility is important, and the tunnel size doesn’t differ extensively.

Features that are normally associated with a mobile miner include, self-propelling capacity (wheels or tracks, etc.), must be able to travel at speeds greater than a few km/h, the ability to handle tight corners, and travel backwards in drifts. Mobile Miners have a cutting system mounted on a boom that can be moved in at least one direction (vertical or both vertical and sideways).

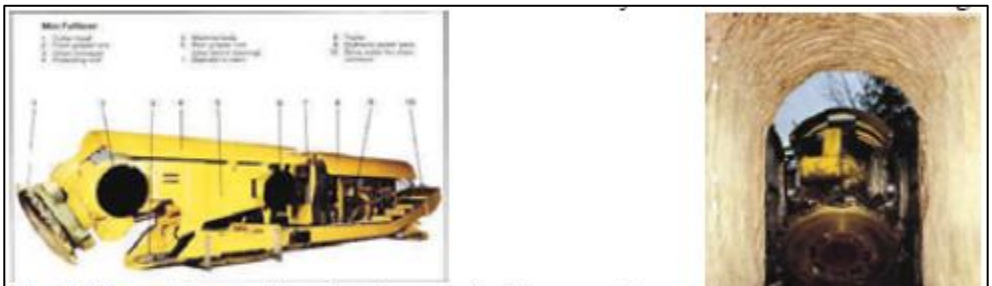
Lyly et al. (2018) discuss the history behind Epiroc’s mobile mining development since the early 1970’s with work done initially by Atlas Copco. The timeline is indicated as follows:

- 1964-1980 Atlas Copco Tunnelbohrmaschinen Ag Thun
- 1980-1985 Altas Copco Jarva Inc Solon Ohio
- 1983-1988 JV with Eickhoff GmbH Road header/loader for mining. Very heavy road headers for civil construction

- 1985-1989 Webster UK small Roadheader/loader for mining
- 1985 -1988 JV with Kvaerner Brug Norway FORO, later Jarva TBM machines
- 1988-1992 JV med Ilbau Jarva type TBMs
- 1993-1998 Atlas Copco owns Robbins Company, Jarva Robbins RBM mobile miners
- 1998-Present RBMs at Epiroc, Sweden

Pioneer machines that paved the way for the Mobile Miner included; the mini midi machines built by Atlas Copco, the Robbins mobile miners (MM120, MM130 and the Taisei tunnelling system), the large tunnelling boring system developed together with Rio Tinto 2011-2014 (Lyly et al., 2018).

TBMs from Atlas Copco Thun from 1970-1980 were basically an undercutting machine equipped with giant TC bits, low revolutions and very high forces.



The Midi machine achieved a clean cut with a very large radius invert and a smooth horse shoe roof.

Figure 43. Atlas Copco TBM's from 1970-1980's (Lyly et al., 2018)

The Robbins Mobile Miners, later owned by Altas Copco, now known as Epiroc. In the early 1990s, the Robbins Company started to develop the Mobile Miner. The first of which was the MM120 (tested in Mount Isa). It was found that there were some design issues due to the extremely strong rock, USA +300 MPa. It was followed up by the MM130 and tested at Pasminco. The MM130 was at a standstill for an extended time while waiting for drill and blast activities.

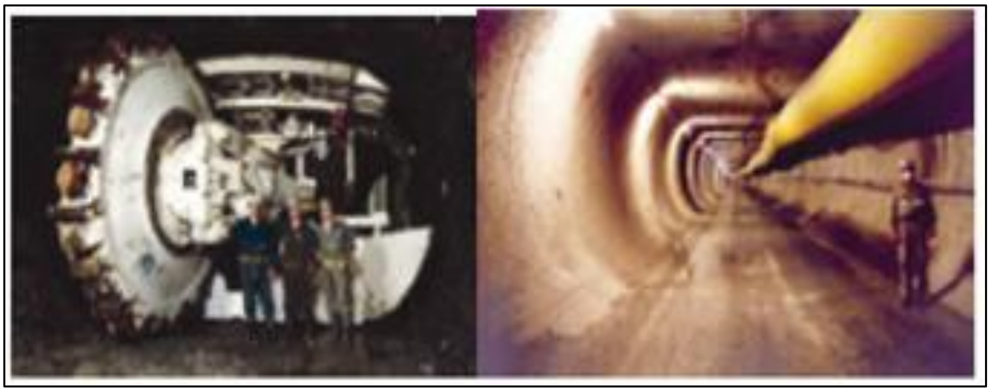


Figure 44. Images of the MM130 and an excavated drift using the MM130 (Lyly et al., 2018)

Around 2010 Rio Tinto planned to open up several very large copper block caving machines, including Resolution and Tolgoi. Block-caving mines have severe drawbacks despite their supposedly low operational costs. This has led Rio Tinto to invite a number of equipment suppliers to propose a mechanical rock-cutting solution for the extensive developments required for block caving operations. The main focus was speed of development as a priority over cost/m^3. The initial testing was done in Finland with factory floor cutting tests. However, the proposal of the testing of the Epiroc (Atlas Copco initially) mobile miner underground was postponed on the back of plummeting metal prices and lower-than-expected copper demand. The machine was later purchased by a Swedish contractor (Bergteamet AB) to develop a research tunnel at SKB's testing facility in Aspo Sweden (Lyly et al., 2018).

As shown in the image (Figure 45), there are several backup units with two different rock bolting stations (shotcrete and wire-mesh station), rescue chambers and all relevant gear like an emergency generator and compressor.

Figure 45. The Epiroc/Atlas Copco Mobile Miner

The rock conditions for the proposed rock caving mines are generally not difficult to excavate (40 – 160 MPa). Other challenges that are faced include high temperatures between 70˚ - 80˚C. The machine has a cutter head with 4.5 m diameter and 1.65 m width. It contains 52 cutters, with two in each position 180 degrees apart. The cutter head power is 650 kW at 12 RPM (variable speed drive). The machine weighs between 700 – 1000 Tons. Drift sizes extend up to 5.5 m high and 4.5 m in width without moving the machine sideways (Lyly et al., 2018).

Lyly et al. (2018) also gave some background on the joint venture RMDS between Anglo American and Epiroc. He stated that more than 90% of Platinum ore is excavated with conventional methods using pusher leg drills for panels, hoisted scrapers etc. These circumstances are extremely dangerous with roof heights of 60cm or less. Due to the concerns about the productivity and safety of these methods, the mining industry has spent the past few decades looking into trackless solutions (LHDs and rig-based drills). Different generations of machines have been developed over the years, with the latest being XLP (lower) to Ultra Low Profile (ULP), with machines to mine at heights less than 80 cm. The focus shifted to full mechanization with the future goal of automation (Lyly et al., 2018).

Lyly et al. (2018) focused on the machine used for the development and gave details regarding the machine configuration and some insight into the project findings. The machine (Figure 46) has a cutter head rotating around a vertical axle, with the head having a diameter of 2.5 m and height of 1.1 m.

Figure 46. Epiroc Mobile Miner tested at Anglo's Twickenham mine (Lyly et al., 2018)

Lyly et al. (2018) describe the set-up of the machine with the cutter head having 32 17'' HD TBM type cutters arranged as two opposites in each kerf, amounting to 16 kerfs. The installed power is 500 kW at an RPM of 12, and the hydraulic linkage allows the machine to advance sideways and vertically (full stoke of 0.7 m). The cuttings and additional muck are removed using a chain conveyor system.

The machine was first tested at a closed mine called Kvarntorp in Orebro, Sweden, on pure sandstone with a UCS ranging between 130 MPa and 150 MPa and high abrasivity. A tunnel length of 70 m, measuring 2.5 to 2.6 m high and 5.5 m wide, was bored with an average rate of penetration recorded as 1.3 m/hr with cutter wear noted as surprisingly low. Albeit, the geological conditions at Anglo's Twickenham mine were very different and proved extremely difficult. Even though initial trials showed good penetration rates, unacceptably high cutter consumption rates were experienced and detrimental to performance and production cost. The lengthy cutter replacement time affected the overall advance rate and new procedures had to be established to bring cutter wear into control. An average of 40-50 m^3 per disc ring was recorded, on par with standard TBM rates, however it was still not within Anglo-American's expectations for cubic meters per hour (Lyly et al., 2018).

5 Current Mechanical Reef Mining Projects in South Africa

There are a few mechanical cutting projects underway in South Africa, with not all being public knowledge at the time of this study. It is known that Impala Platinum is investigating mechanised mechanical cutting, but details regarding this are not readily available. There are three major mechanical cutting trials in South Africa, with two of them being conducted at Anglo American's Mogalakwena and Twickenham operations and the third at African Rainbow Minerals (ARM) Bokoni and Modikwa platinum mines (see Table 21). However, the project at Mogalakwena is focused on the TBM used to develop a decline for underground mine development and not directly for on-reef mining.

Table 21. Current mechanical cutting projects in South Africa

Machine	Location	Reference
Master Drilling MTB	Mogalakwena Platinum Mine, Sandsloot Pit	(Van Rooyen and Carstens, 2022)
Herrenknecht D1000 Reef Borer	ARM Modikwa Platinum Mine, South Africa	(Van der Bijl, 2024)
Master Drilling Reef Miner	ARM Bokoni Platinum Mine	(Van der Bijl, 2024)
SANDVIC MN220 Reef Miner	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)
Atlas Copco Slot Borer	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)

Further details of these projects are covered in the next sections.

5.1 Sandsloot TBM project at Anglo American's Mogalakwena mine

Based on interviews and work presented by Van Rooyen and Carstens (2022), a basic summary of the Sandsloot TBM project at Anglo-American's Mogalakwena mine was developed. The purpose of the project was to develop two declines into the Sandsloot highwall using a different method for each, namely, mechanised drill and blast in the one and continuous cutting using a Mobile Tunnel Borer (MTB) in the other. Project details are indicated in Table 22.

Table 22. Project details: Mobile Tunnel Borer used at Mogalakwena mine Sandsloot

Project Owner	Anglo American
Strategic Partners	Master Drilling
Project location	Mogalakwena Platinum Mine, Sandsloot Open Pit
Project timeline	The project has been effectively running since 2021 after initially being delayed due to the Covid-19 pandemic.
Project Objectives	To investigate the feasibility of highspeed development of a decline using a Mobile Tunnel Borer (MTB) compared to the performance of the conventional drill and blast method.
Machine Type	**Master Drilling Mobile Tunnel Borer:** 5.5m Diameter Cutting head with disc cutters. • 32 x 17-inch cutters • 3-stage machine ○ Cutting module, Power (Step Down Transformer) + Support + Control Module, Cleaning Module + Carrier Car (Electricity) • 8500 kN of Thrust • 2 newly added thrust barrels (Gripper Shoes) • 8 Hydraulic Cylinders position the cutter head • Automated cutter head positioning to ensure all cutting heads have equal contact ○ Previously, this was operator-controlled ○ Reduced wear and increased penetration rate

The project was divided into two main phases:

- ***Phase A***: A total development of 4.1 km with 1.2 km development using the TBM and 2.9 km using Drill and Blast
- ***Phase 2:*** A total of 5.8 km development (using the best option as derived from the results of phase A)

A schematic of the MTB used during the development is shown in Figure 47. The setup is very similar to general TBM's but supposedly boasts higher mobility.

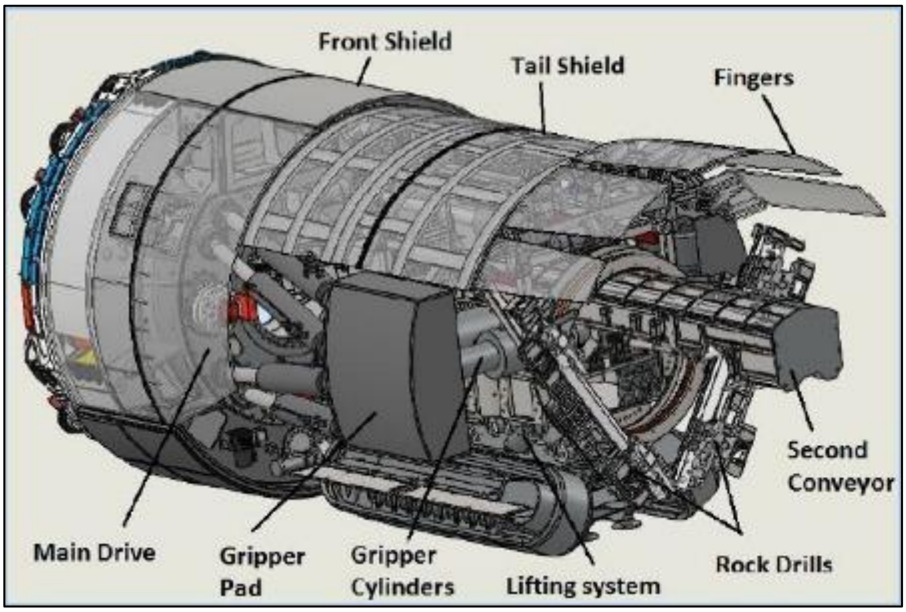


Figure 47. Schematic depicting the MTB of Master Drilling used at Mogalakwena Mine (Van Rooyen and Carstens, 2022)

The staff composition of the MTB was:

- 1 x Operator
- 1 x Millwright/engineer
- 2 x Support Operators
- 1 x Backend Loader (some material left behind TBM as a safety berm)
- 2 x Loading trucks to remove material

Images of the initial installation and setup of the MTB are shown in Figure 48.

Figure 48. Images of the set-up of the MTB at Mogalakwena Mine (Van Rooyen and Carstens, 2022)

Figures 49 and 50 indicate the initial portal development for the two methods, as well as an image of the tunnel shape and condition after initial development into the portal. As noted, there is a difference in tunnel shape and a definite distinction between tunnel walls, as the MTB walls seem smoother and more consistent. However, the MTB tunnel requires an additional phase to undercut the floor of the tunnel to ensure a square, flat surface for people and equipment.

Figure 49. Images of the portal and post development of the MTB heading (Van Rooyen and Carstens, 2022)

Figure 50. Images of the portal and post-development of the conventional drill and blast heading (Van Rooyen and Carstens, 2022)

Typical rock characteristics include a UCS of 140 to 220 MPa with high abrasivity. At least 2 cutter heads are replaced per shift, each weighing 82 kg. The logistics around the replacement of the cutters have been a challenge. At the time of the ongoing development of Phase A, the production statistics were:

- 10 hours of cutting per day
- 5 days of cutting per week
- The goal is an advance rate of 10 m per day, to achieve 200 m a month (blasting at 135 m). The current best achievement is 5 m/day
- Conveyor belt can do 200 tons an hour, in 1 m advance, 200 tons of rock
- Planned Inclination is 11 degrees

The planned cost (fixed and variable) of cutting was set at R 220 000/meter, however, at the time of the trial Phase A (2021/2022), the project cost around R 450 000/day. The MTB was powered using a diesel generator as a precautionary measure for excessive power cuts at the time. This had a big impact on project cost and logistics. Other challenges incurred during the project were water control, the blasting of cubbies, and the round-shaped footwall caused challenges for equipment operability and material handling. Dry cutting is required, but with the excessive water ingress, cover drilling was increased. The initial plan was to cement water features before cutting through them, however, once the excavations advanced underneath the water table, the water issues intensified. Cubbies and refuge bays are being blasted concurrently with the declines, further impacting the slower advance rate and continuity of the MTB operation. The footwall profile needed to be flattened to improve equipment operability, resulting in the use of diamond wire cutting to flatten the footwall. The installed conveyor was too small and therefore inefficient to remove the material timeously. This leads to additional grinding and excessive fines of the rock material. Other challenges, such as ventilation and dust, also caused significant issues.

5.2 Bokoni and Modikwa Platinum Mines, African Rainbow Minerals

The reef boring project currently in progress at Bokoni and Modikwa platinum mines is promising as this is being done in partnership with experienced OEMs Herrenknecht and Master Drilling. Multiple tests have been completed using full-scale production cutting heads, with the proof-of-concept testing at the Bokoni Platinum mine set to start within the next two years, depending on the completion of the remaining system modules (Van der Bijl, 2024). A summary of the project details can be seen in the table below.

Table 23. Project Details: ARM Mechanised Reef Mining Projects

Project Owner	African Rainbow Minerals (ARM)
Strategic Partners	Herrenknecht Master Drilling
Project location	Modikwa and Bokoni Platinum Mines in the Eastern limb of the Bushveld Complex in South Africa
Project timeline	The project has been running since 2020 (for the past 4 years), with the current progress suggesting full-scale proof-of-concept testing within the next 2 years (by 2026).
Project Objectives	1. To match the production performance of a mechanised bord and pillar crew (±1600 Oz/month) 2. To Improve overall grade through selective mining 3. Improve safety (removing people from stopes) 4. To reduce total mining unit cost 5. Enable the opportunity for improved mechanisation and ultimately, automation
Machine Type	**Herrenknecht:** 3-overlapping circular profile roller bit boring system. This system has effectively tripled the production rates of current single circular profile boxhole borers due to improved cross-sectional cutting area. **Master Drilling:** Horizontally orientated rotating cutters with cutting discs, producing a rectangular excavation of 3 m by 0.6 m.

In an interview with Creamer Media, Jacques van der Bijl (executive for growth at ARM) discussed the reasons behind the project, the objectives of the trials, the methodology followed, the progress made, and the current status of the project. According to van der Bijl (2024) the main motivation behind the reef boring project was to find mechanised solutions to mine UG2 reef more selectively and efficiently, especially in narrow tabular orebodies.

ARM identified two operations with the potential for reef boring namely Modikwa and Bokoni mine, with Bokoni mine being the most likely location for the proof-of-concept testing and full implementation due to its consistent narrow tabular reef. The reef boring project has been running for the past four years (since 2020), with a focus on mining high-grade at 70 cm UG2 reef, without mining high quantities of pyroxenite waste. As seen in Figure 51, the current conventional methods mine at heights of approximately 1.2 m, which leads to dilution and a lower mined grade of 6 g/tonne. If the autonomous machine is used to ideally mine the UG2 reef exclusively, the high grade of 9 g/t can be maintained with the added benefit of removing employees from the stoping area (Van der Bijl, 2024).

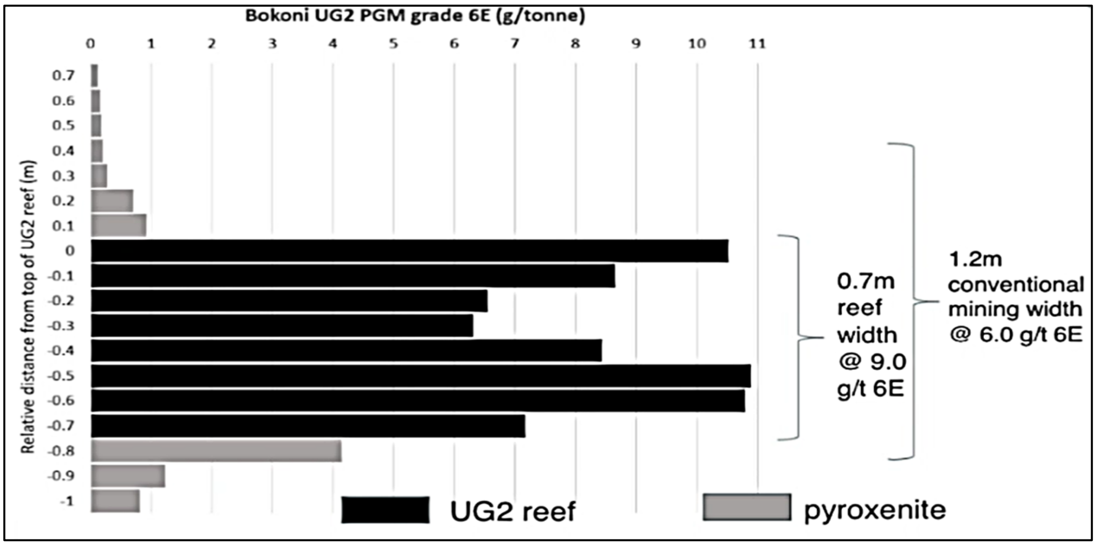


Figure 51. UG2 PGM grades at Bokoni Mine (Van der Bijl, 2024)

ARM tasked Herrenknecht and Master Drilling to develop a technical solution to mine the UG2 reef at Bokoni and Modikwa based on the following criteria (Van der Bijl, 2024):

- A mechanised stoping solution that does not require labour to enter the stoping area.
- Ability to mine the UG2 reef selectively to minimise the dilution of grade from the pyroxenite.

- Mining unit cost needs to be comparable to a mechanised stoping fleet in a narrow bord and pillar operation such as Two Rivers Mine.
- The ability to produce at a rate of approximately 7000 tonnes of UG2 reef (approximately 1800 ounces of 6E) per month.

Herrenknecht based their solution on their 1m diameter box-hole boring machine which already has a commercially proven record. The newly proposed D-1000 reef-cutting machine has three overlapping box-hole boring cutter heads that are joined together into a single cutting frame (see Figure 52).

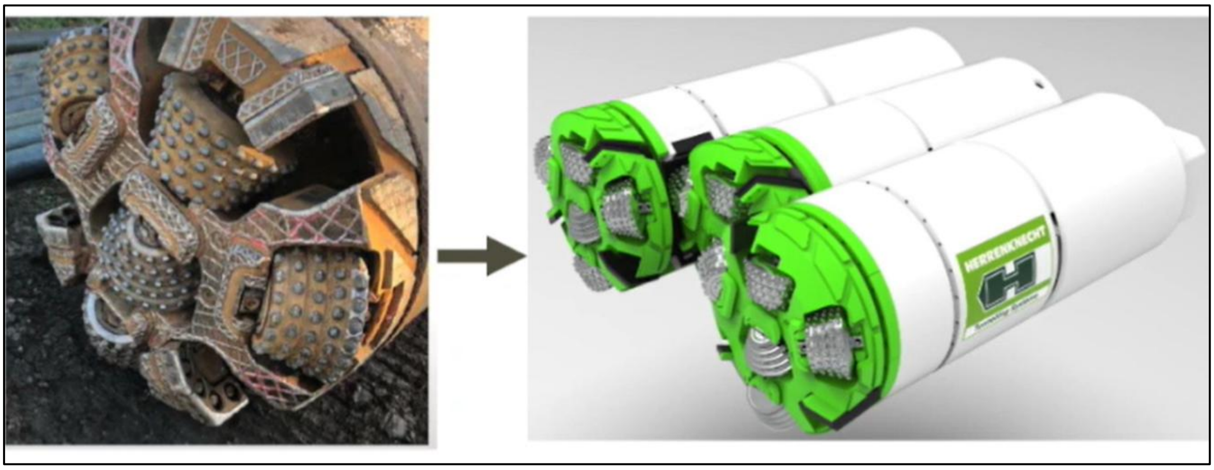


Figure 52. Herrenknecht 3-ovelapping boxhole boring concept (Van der Bijl, 2024)

Herrenknecht targeted the challenge of limited cross-sectional cutting area for circular reef boring solutions. The 3-overlapping cutting heads increased the cutting cross-sectional area and production rates effectively 3 times compared to current single circular borers, improving the ore production rate per meter drilled. This cutting profile provides a mixed cut of UG2 and pyroxenite (Figure 53) with the cutter head having the capability of autonomous steering (to follow the reef). The material cut from the face is transported using a vacuum suction system. The benefit of consistent fragmentation on full profile boring also allows for the potential of pumping the mined material directly to plant facilities on the surface, simplifying the ore transportation process and reducing overhead costs. Due to the concept being based on commercially proven machinery and Herrenknecht extensive expertise in boxhole boring and pipe jacking, the development risk of this newly proposed boring solution is significantly lower, enhancing the probability of success (Van der Bijl, 2024).

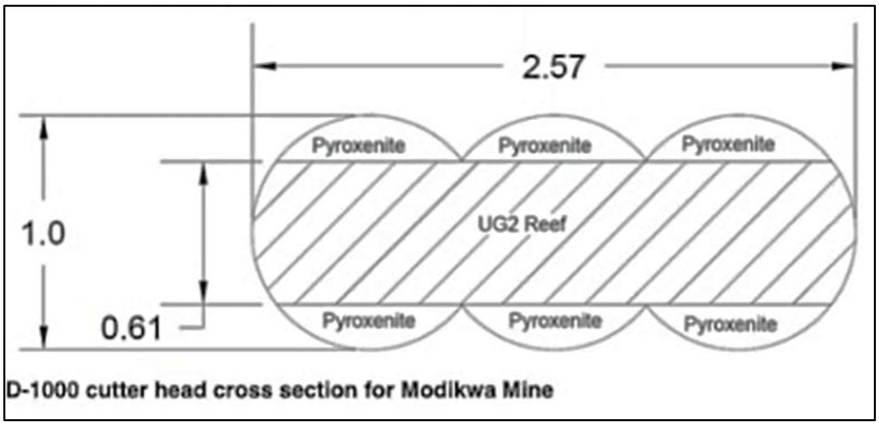


Figure 53. Herrenknecht 3-overlapping cutter head (D-1000) cross section

Master Drilling focused on the challenge of mining the UG2 reef without mining additional pyroxenite waste by developing an innovative cutter head layout. As shown in Figure 54, the cutter wheels are orientated perpendicular to the direction of drilling with a central vacuum suction system to remove cuttings to the reef drive.

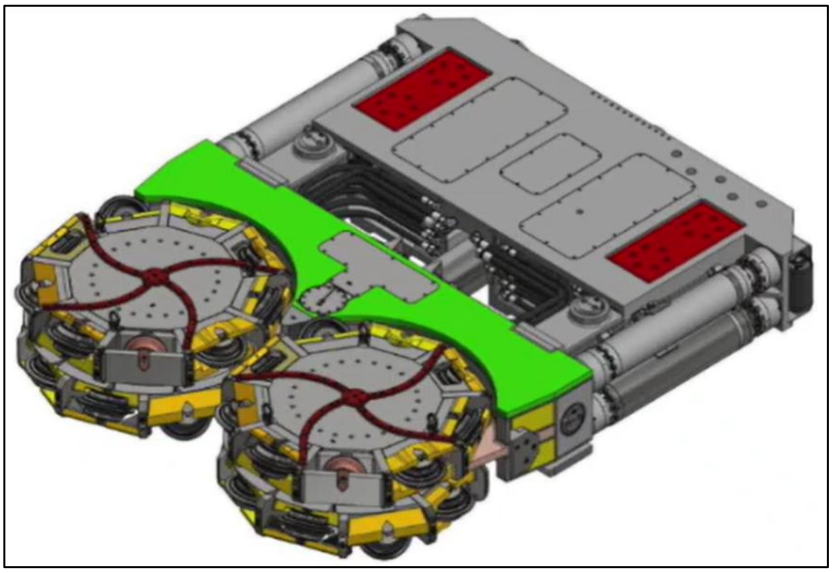


Figure 54. Master Drilling Reef Boring Machine (Van der Bijl, 2024)

The orientation of the cutter heads provides a rectangular cross-sectional cutting surface, yielding an excavation with dimension of 3 m wide by 0.6 m high. The larger cutting wheels allow for the use of disc cutters with the cutting profile allowing for maximum UG2 extraction with little to zero pyroxenite waste. An additional advantage is the ability to mine in the softer UG2 reefs (typically 60 to 70 MPa – Bokoni Mine), whereas the pyroxenite has a hardness of about 130 MPa. Staying in the UG2 reef means the boring machine can mine at improved rates and improves the possibility of self-steering (Van der Bijl, 2024).

Master Drilling developed a testing platform (Figure 55) to cut into 85 MPa concrete blocks (total length of 15 m) with the objective of testing the functionality of the cutting head and the vacuum system. The machine set-up included the cutter head, product separator, filter module, vacuum blower, and a hydraulic power pack. The concrete block properties were based on the UG2 and pyroxenite rock types (Van der Bijl, 2024).

Figure 55. Master Drilling production cutter head testing (Van der Bijl, 2024)

The findings from testing indicated the need for design changes to both the filter module and product separator, but also revealed that the performance of the cutting head exceeded planned cutting rate targets by 160%. A hydraulic test frame with a single disk cutting head was then tested underground where the rig was mounted on a pillar with thorough testing done on torque, thrust and penetration rates on both UG2 and pyroxenite waste. The data gathered were valuable in designing the final cutting head design for the reef boring solution (Van der Bijl, 2024).

Most historic machines were not properly tested before underground trials and had a single circular profile, which means the cutting was not optimised for the material being excavated and the diameter of the machine yielded a cutting area limited to the height of the reef. The cutting surface areas were too small to be economical as it required a drilling rate three times higher than current boring solutions to obtain sufficient production tonnes per meter drilled. ARM's methodical and systematic risk-adjusted approach, followed by the key strategic partnerships with the OEMs, greatly improves the probability of success compared to historic attempts. However, there is still a lot to do before the technology can be fully commercialised (Van der Bijl, 2024).

Compared to the conventional mining method employed at Modikwa and Bokoni mines, the reef boring technology has the potential to improve PGM grades by approximately 50%. The technology is also well suited for mechanisation and, ultimately, automation for future improved mining unit costs. The benefits of uniform fragmentation size produced from mechanical cutting include improved conveyance and transfer shoots, improved downstream processing of the material, and no need for grizzlies, rock breakers or crushers. The Herrenknecht cutting set-up allows for the pumping of material directly from underground to processing facilities on the surface, reducing overall infrastructure capital. Reef boring also has the potential to impact tailings management, which also impacts overall mining costs and environmental impact. The improved unit cost of selective mining justifies the cost of backfilling mined-out areas, which increases the extraction ratio to above 90%, extending the life of the mine and improving the stoping-to-development ratio (enhancing ROM grades and reducing the amount of development required). The tailing storage facilities (TSF) required for these operations have significantly smaller footprints which relates to reduced risk and reduced environmental impacts (Van der Bijl, 2024).

The current status for next steps (as of July 2024) is:

- Numerous tests for both concepts using full-scale production cutting heads have been done on high-strength concrete and granite blocks (replicating rock qualities of UG2 reef and Pyroxenite layers). The results have been encouraging with the teams managing to double the performance compared to design objectives.
- Currently the construction of the remaining modules to complete the full-scale reef boring system is underway
- The aim is to conduct proof-of-concept testing at Bokoni mine. Depending on the outcome of the proof-of-concept testing, the final objective is to fully implement the reef boring system at Bokoni Mine. The technology will be continually tested with the aim of achieving the targets over the next two years.
- This project has been running for the last 4 years, with significant progress being made.

5.3 Twickenham Platinum Mine, Anglo American

The project at Anglo American's Twickenham platinum mine forms part of the group's "FutureSmart MiningTM" approach to re-imagine how underground mines can operate by utilising mechanised mechanical cutting technologies. Together with strategic partner Atlas Copco, they have created the Rapid Mine Development System (RMDS). The RMDS is in the proof-of-concept phase and aims to quickly, safely, and cost-effectively excavate low-profile hard rock ore excavation. The trials at Twickenham platinum mine consist of three main segments, namely the SANDVIK Continuous Haulage

System (CHS), the SANDVIK MM220 Reef Miner, and Atlas Copco Slot Borers. The proof-of-concept for the SANDVIK MN220 Reef Miner was completed in 2013 and resulted in a production rate up to three times faster than conventional drill and blast methods. This machine also boasts the capability of roof bolting. The current status of this machine is the optimisation of the machine specifically for platinum mining conditions (Anglo American, 2024).

Images of the rear and front view of the Sandvik MM220 reef miner being trailed at Twickenham mine are depicted in Figures 56 and 57.

Figure 56. Rear view image of the Sandvik MM220 reef miner underground at Twickenham mine (Anglo American, 2024)

Figure 57. Front view image of the Sandvik MM220 reef miner underground at Twickenham mine (Anglo American, 2024)

6 THE VALUE OF APPLYING MECHANICAL ROCK-CUTTING

The study found that mechanical rock-cutting has a rich history in South African mines since the 1950s. Albeit the technology has been successfully implemented in coal mining, the development and implementation of hard rock-cutting applications have been slow due to the lack of appropriate funding for research in this domain as well as some technological constraints.

Most of the developments in hard rock-cutting were focused on off-reef development such as shaft sinking, decline tunnels, ventilation shafts and box holing. However, there have been studies on on-reef cutting with less success. The key historical studies found for on-reef cutting included:

Table 24. Summary of historic on-reef cutting projects in South Africa

Machine	Location	Reference
Wire Saw	Anglo Gold Ashanti mines	(Barnes, 1969)
Prototype rock-cutting machine (COMRO)	COMRO Laboratory and Underground mines	(Cook et al., 1968a), (Cook, 1969), (Gibs, 1969)
Reef Boring	Vaal Reefs	(Lundstrom, 1985)
Rock-cutting Machines (rock cutter, reef borer, swing-hammer and impact ripper)	Gold Mines of South Africa	(Joughin, 1976)
TBM (Jarva MK6 -1976 model)	Bafokeng Rasimone Platinum Mine (BRPM)	(Stander et al., 2001)
ARM1100	Lonmin Platinum Rowland Shaft and Impala Platinum mines	Pickering and Ebner, 2002), (Moxham, 2004), (Pickering et al., 2006)
Narrow reef miner, oscillating disc cutter, activated drum system.	Anglo Platinum Mines	(Croll, 2004)
Mechanised XLP Fleet	Anglo Platinum	(Fourie et al., 2017)
Epiroc Mechanical Miner	Anglo American, Twickenham mine	(Lyly et al., 2018)

The study also found that key projects in the reef-cutting domain is underway at three major South African platinum mines. There is presumed to be more, however, details regarding these projects are not available in the public domain. These projects are listed in the table below.

Table 25. Current mechanised cutting projects in South Africa

Machine	Location	Reference
Master Drilling MTB	Mogalakwena Platinum Mine, Sandsloot Pit	(Van Rooyen and Carstens, 2022)
Herrenknecht D1000 Reef Borer	ARM Modikwa Platinum Mine, South Africa	(Van der Bijl, 2024)
Master Drilling Reef Miner	ARM Bokoni Platinum Mine	(Van der Bijl, 2024)
SANDVIC MN220 Reef Miner	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)
Atlas Copco Slot Borer	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)

6.1 MECHANICAL ROCK-CUTTING APPLICATION GUIDELINES

The number of tunnelling machines utilised over the past decade has escalated, testimony to their continuing success and flexibility for application on projects of different diameters, lengths, and ground conditions. There are various guidelines available for machine selection and for developing a suitable specification for a machine for a given project. Proper application of these guidelines is an essential part of machine selection to ensure optimal performance of these machines in a given project. However, available guidelines are very general, and based on past experiences, they cannot take into account the many intricacies of a specific upcoming project including site setup and geology. Figure 58 illustrates a mechanical rock cutter being designed for a specific mining application.

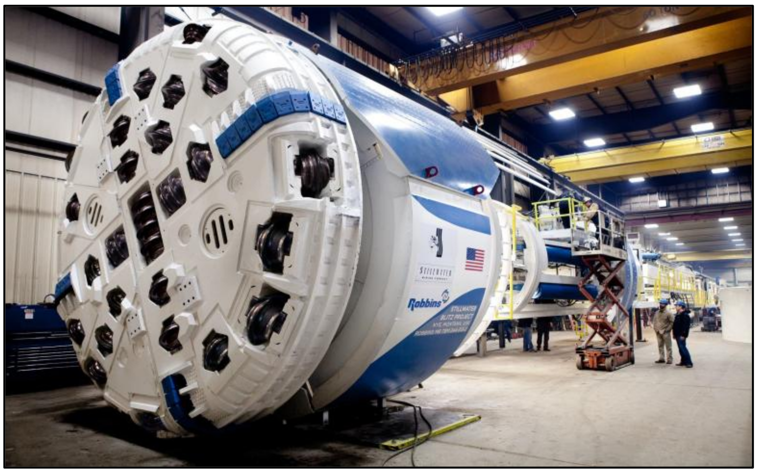


Figure 58. Image showing a TBM for a specific mining application (Robbins, 2024).

The success of tunnel boring machines (TBMs) in projects has proven the use of TBMs to be a promising approach to meet these challenges. In order to better understand the possible gains when using mechanised rock-cutting, some of the important factors governing and influencing the machine's performance are set out and explored in this report. The Current trends and main challenges in the tunnelling industry are to go ‘faster, larger, deeper and longer’.

The performance of the TBM is represented by the advance rate, which is a function of the penetration rate (PR) and utilization factor (U). Both PR and U parameters are impacted by the ground conditions and operational parameters, while U is also impacted by site set up, maintenance, ground control, and experience of the crew.

The typical value of U ranges from 5% to 55%, with the most common range being 20 to 30% (Rostami 2016). This indicates that typically, TBMs work only for a few hours per shift, with the rest of the time being recorded as downtime involving other tunnelling activities. Paltrinieri (2015) noted that utilization factor estimation requires a combination of both ground conditions and/or machine factors. The estimation of U requires careful consideration of the various tunnelling activities occurring at the project site, including machine maintenance, ground support, surveying, muck transportation systems, cutter change, unexpected breakdown, and so on. Interdependence among these various activities makes the estimation of U a complex process. A general schematic diagram depicting some of the considerations of a mechanical rock-cutting project is shown in Figure 59.

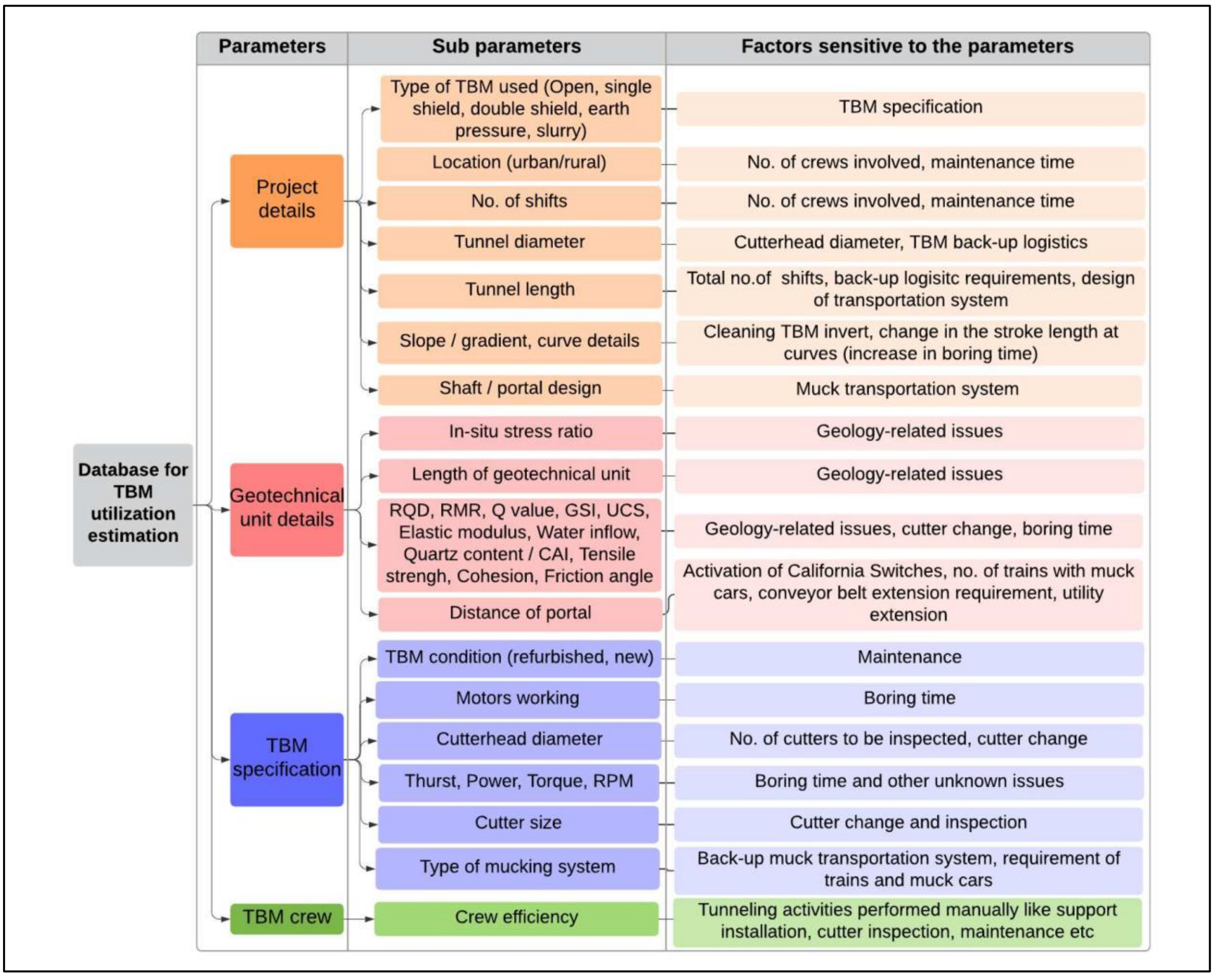


Figure 59. Figure showing some of the considerations of a mechanical rock-cutting project. (After L. Eide, 2014)

Predicting the performance of a mechanical rock-cutting machine is paramount to the proper selection of the machine specifications, operation of the machines, and estimation of time of completion, hence the cost of tunnelling. The performance of a machine can be assessed by estimating its utilization for a given period, like a shift or a day. Equipment performance can be influenced by factors such as slope curvature of tunnels, geology, and ground condition, or design factors throughout the entire project. While various models can predict TBM utilization, it seems as if there is no single model that was built to contain all the possible variations. The existing models are empirically based models that do not account for uncertainties like the variation in the support installation time, utility extension requirements, transportation system, and so on.

Discrete event simulation has proven to be a promising approach, as can be seen in the DAT simulation software (Einstein, 2002) and by Abd-Al Jalil (1998) in predicting TBM utilization. DES approach can consider events as individual activities and determine their interdependencies. The uncertainties in the input parameters are taken into account by assigning the activity time through stochastic modelling to see the impact of various site settings on TBM utilization.

In a study by Khetwal et al., the performance influencing factors of a mechanised cutting machine were analysed. The overall results show that the utilization factor value decreased with an increase in delays, as anticipated, however, at a non-uniform rate. Maintenance-related delays showed maximum impact on the utilization factor with a reduction in the range of about 6 %. The impact of other delays was limited to around 3 % utilization reduction, but the influence of the geotechnical conditions can create more extensive ground-related delays.

The sensitivity analysis modelling showed that the system utilization, while excavating in geotechnical units with lower RMR values, had very low sensitivity to machine-related downtimes because major delays were caused by the ground-related issues and therefore the time required for ground stabilization overshadowed the delays due to other activities. In fair to good ground, the ground-related delays are not significant and therefore, logistic management is the key to controlling the utilization factor.

The study further indicated that in fair to poor ground ratings, maintenance delays showed maximum impact with a 6 % variation in utilization factor. The analysis, however, indicated that the U value was not very sensitive to cutter change. Transportation delays were the crucial factor and unexpected breakdowns, on the other hand, comprising of many other activities like hydraulic, mechanical, and electrical problems, non-availability of materials, and conveyor issues did not show any general trend with variation in the utilization. Figure 9 is an image showing some of the sensitivities as modelled by Khetwal et al. The findings of their study are important as it has a direct influence on the performance of such a system and would hence affect the value and benefit of cutting when compared to blasting.

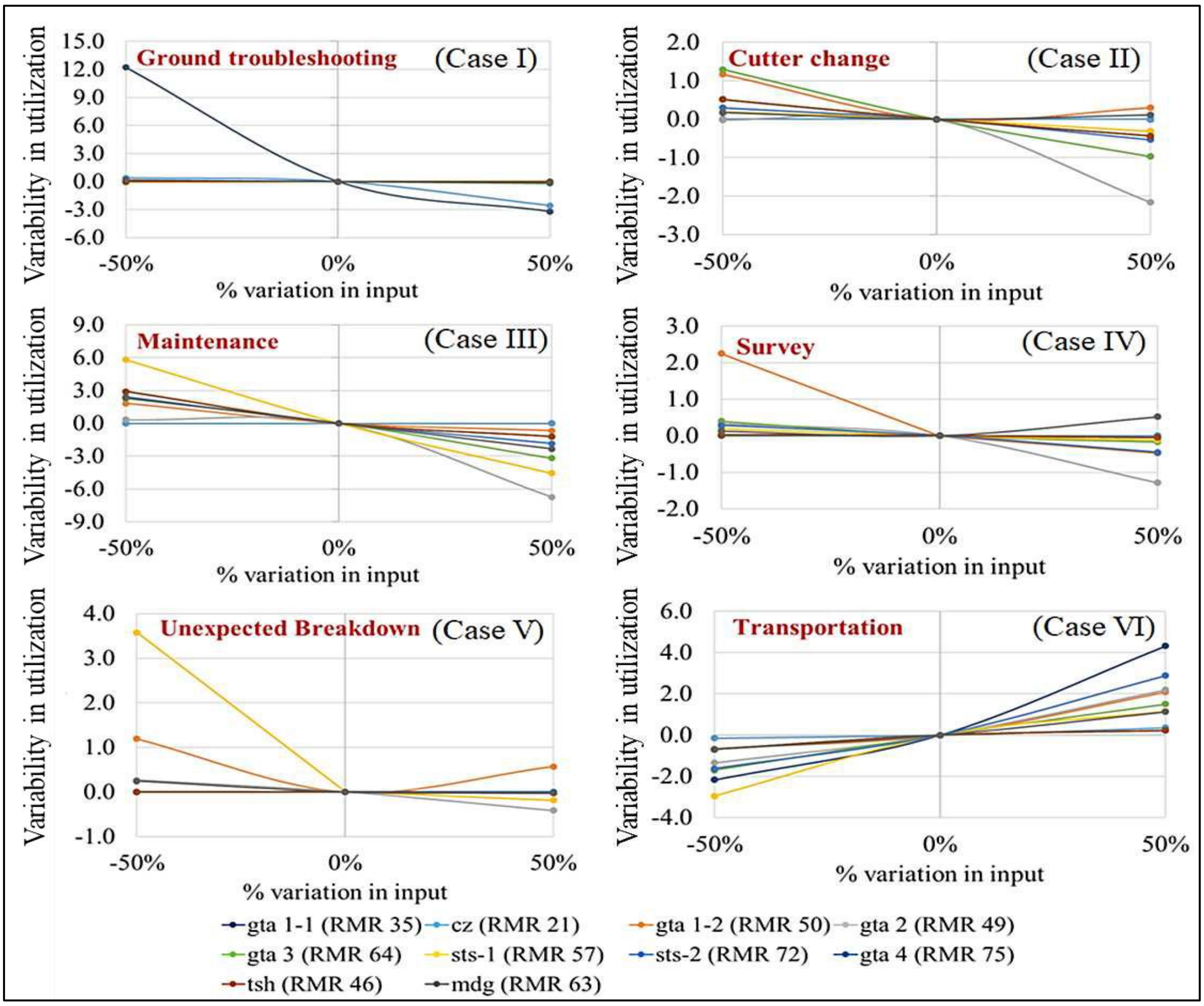


Figure 60. Figure showing the modelled sensitivities (Khetwal et al.,2012)

6.2 DETERMINING THE VALUE OF APPLYING GUIDELINES

The next step of this study was to determine the value of a mechanical rock-cutting project when applied in an international hard-rock mine environment. The operation had a good understanding of the geology, where the rock strengths were more than 140 MPa. The probe drilling program was vital to provide more detailed information about the conditions ahead of the TBM in the areas beyond the existing mine infrastructure. (Stillwater Mining Company, 2011).

6.2.1 Determine mechanical cutting efficiencies

To determine the efficiencies and ultimately determine the project value, the collected data from TBM operator's written shift logs were used, as there was no computer logger on the TBM in question. These shift logs have been digitalised into an Excel spreadsheet. Each shift log contains information regarding the following:

- Time and date of boring operations
- Machine hours at the start and end of each shift
- Averaged TBM data for selected strokes during a shift
    - Amperage
    - Propel Pressure
    - Gripper Pressure
    - RPM of the cutter head
- Distance bored each stroke
- Amount of rock support installed

Based on the input given in each shift log the following is calculated and used as parameters to assess the TBM performance:

- Boring time in machine hours
- Meters per shift
- Average amperage per shift
- Average torque per shift
- Gross average cutter thrust in kN/cutter
- Penetration rate in m/h
- Basic penetration in mm/cutterhead revolution
- Utilization of the machine in percentage boring time

The following key indicators were explored to determine their role and impact on the project value. These indicators are:

Monthly Advance Rate

The study by Eide, 2014, found that the TBM had a cumulative average advance rate of 137 meters per month as shown in Figure 61. The TBM's monthly advance rates weren't very high, but as it's a mine tunnel, it can't be directly compared to other civil construction projects of a similar nature. Only one shift is used to drive this tunnel, and each shift lasts 11.5 hours from Monday to Thursday, with roughly 10 hours of excavation time available. This equates to 40 hours of excavation time every week. This also explains why the advance rate is shown monthly rather than weekly, as is more typical, as the weekly advance rate would have been significantly impacted by TBM downtime. The best daily advance rate achieved was 20.12 meters, while the greatest monthly advance rate achieved was 183 meters.

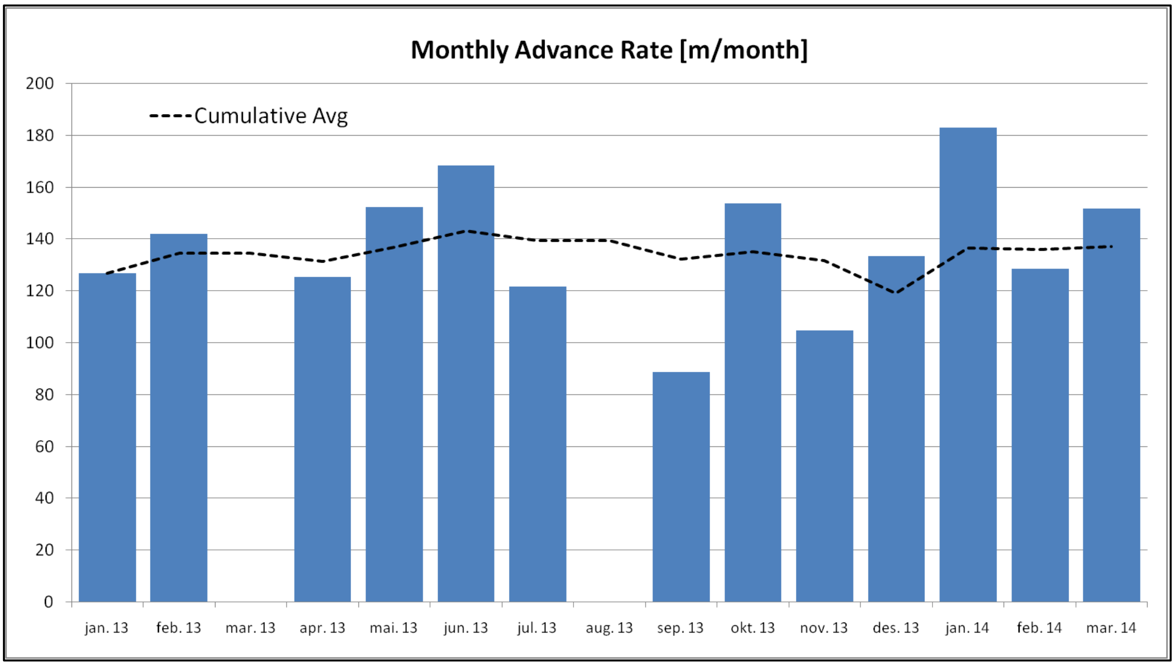


Figure 61. Figure showing the observed advance rates (after N. Eide, 2014)

Machine Utilisation

The average monthly utilization of the machine in percent boring time is shown in Figure 62. As described previously in the report, this utilization is based on an available excavation time of 10 hours per shift for the crew. Utilization over the observed period was 31% in the best month and 17% in the worst month.

The machine's overall average usage throughout all months is assessed to be 26%. Although this isn't a particularly high number, it should be remembered that this isn't a civil tunnelling project where efficiency and time are the primary concerns. Geological conditions may influence the use; for example, a high penetration rate and more strokes made in a day mean more time spent waiting for the train to return to the TBM so that additional excavation can begin or for the installation of rock support. This is particularly evident during the month of November, which has the lowest utilization but also the highest average penetration rate.

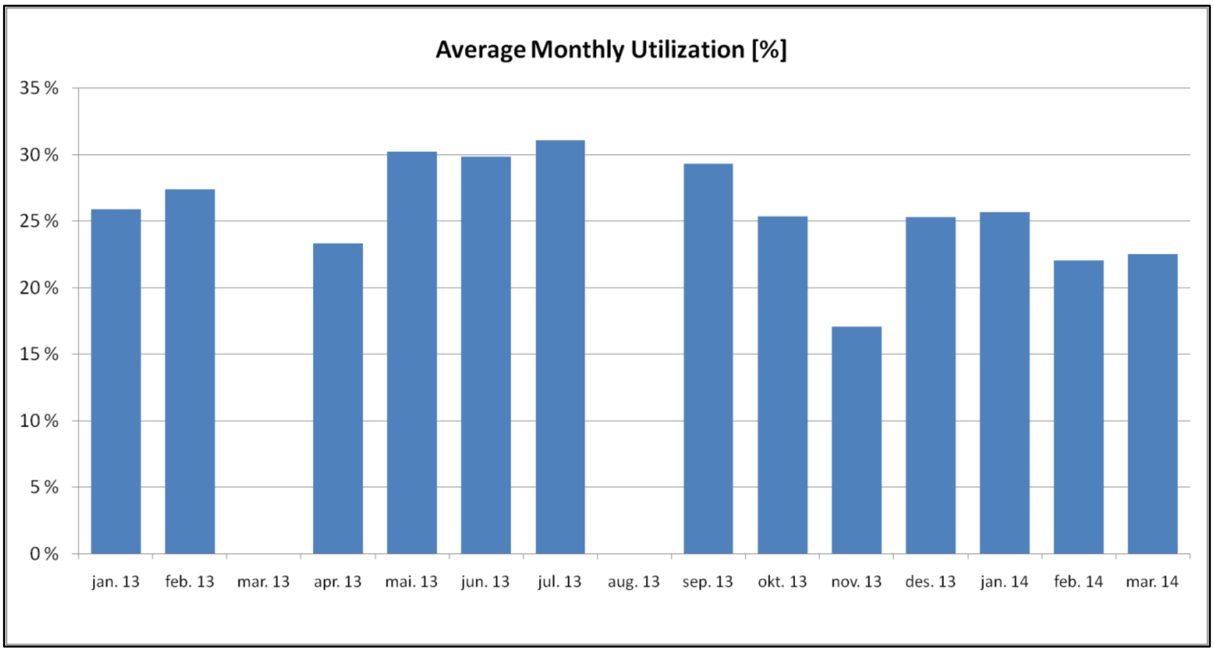


Figure 62. Figure showing the machine utilization (after N. Eide, 2014)

RPM versus Basic Penetration Rate

Another two key indicators to be examined from the TBM's daily shift logs data were the influence of revolutions per minute (RPM) on basic penetration rate (mm/rev). The fundamental penetration rate and RPM data gathered from the shift records are displayed in Figure 63. The average value from every observed shift is represented by each data point. The TBM's most frequently used cutter head-turning speed is 10 RPM. This would, however, differ significantly between projects as it would depend on the geology and machine design.

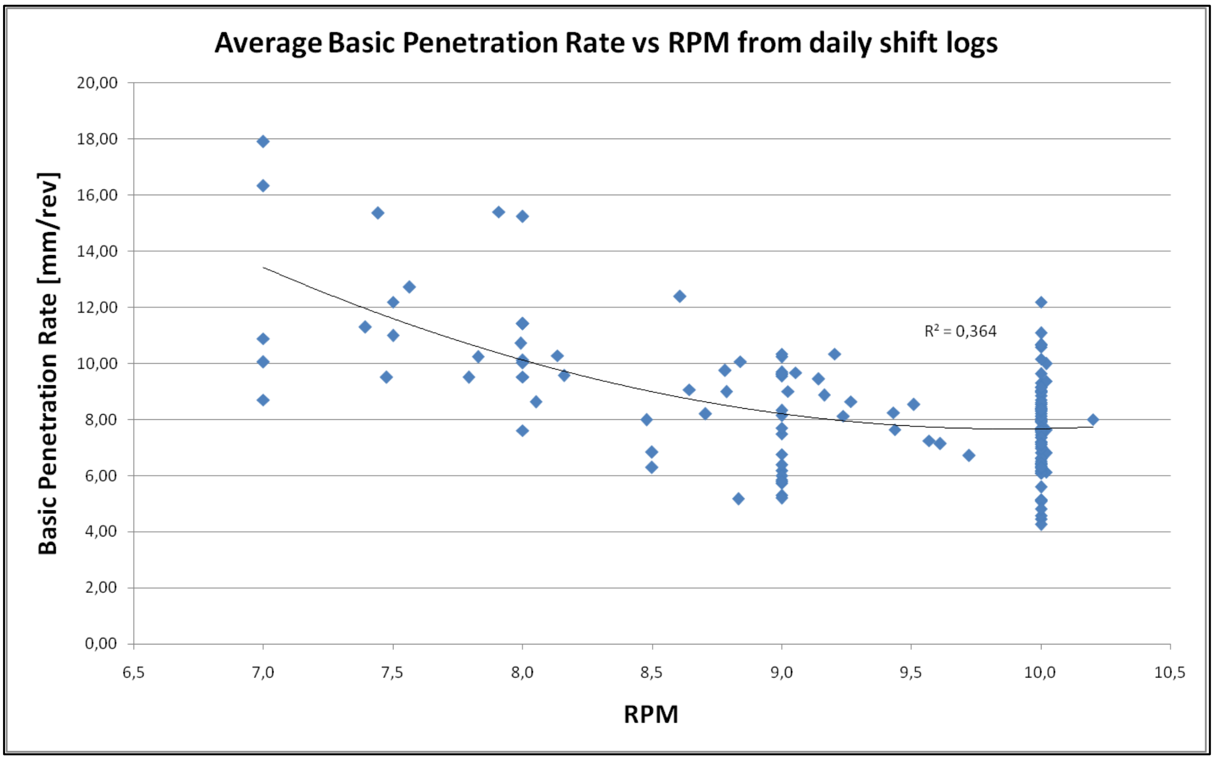


Figure 63. Figure showing the penetration rate compared to turning speed (After N. Eide, 2014)

Cutter Life

Assessing the cutter life is a very important factor as some projects indicated that it could be one of the major contributors to operational costs. In order to determine the actual cutter life, the following needs to be recorded. Unfortunately, the cutter life was not a focus area of the study by Eide, 2014, and hence no conclusion can be reached from his work.

- Date of cutter change
- Position of cutters changed
- Chainage at cutter changes
- Machine hours at cutter changes
- Meters bored for cutters changed
- Amount of wear (mm)
- Reason for cutter change
- Serial numbers of cutters

6.2.2 Comparison of drill and blast operations

Concurrently mining a conventional and TBM drive has made it possible to collect enough data to compare the development methods in terms of capital costs, development rates, and direct operating costs. The prices and expenses listed below are based on the conditions that existed during the specified time of measure; because of shifting situations, they might not be indicative of rates and expenses in the future.

For comparison purposes, data from January 2013 through March 2014 were considered. Included in capital costs were equipment such as the diesel locomotive, twenty-two muck cars, and eight rail cars required for the TBM tunnel. The equipment for the drill and blast (5600E) incline, included a 4.5 m^3 LHD, double boom jumbo, mechanical bolter, scissor deck, and two 18-tonne haul trucks. Two miners, each with three crews, were working in the drill and blast headings on average, working a 4 on/4 off, 11.5 hr/shift schedule.

The data presented in Table 4 provides strong evidence that a TBM's faster progress rates can offset longer tunnels' higher initial capital costs, resulting in lower direct operational costs for mechanized tunnelling.

Table 26: Comparison of TBM and Drill and Blast

Heading	Heading Size	Avg. Advance Rate (m/shift)	Capital Cost ($ USD)	Direct Operating Cost ($/m)
5000E TBM	5.5 m Diam.	7.0	14,300,000	260
5600E Incline	4.6 m x 4.6 m	1.2	4,000,000	302

6.4 Advantages of TBMs

The main advantages of the use of TBMs for mining projects are as follows:

- Significantly higher and sustainable progress rates for generally good quality hard rock conditions.
- Less rock support due to less damage caused to tunnel profile;
- Long single drives where no intermediate access drives are possible;
- Lower ventilation requirements;
- Reduced exposure to blast movement and fumes.

Figure 64 indicates a side-by-side comparison of an actual tunnelling project consisting of parallel drives being drilled and blasted, and mechanically excavated.

Figure 64. Image showing a side-by-side comparison of a twin tunnelling project.

6.5 Challenges of TBM applications

Mechanical rock-cutting does not come without its challenges. Some of the disadvantages and challenges are listed below;

- Significant geological investigations and information are necessary;
- Detailed planning required;
- High capital investment is necessary;
- Longer lead time for design and building of the machine;
- Circular excavation profile for TBM equipment;
- Limitations on curve radii and change in diameter;
- Sensitive to varying rock types and high-water inflows;
- Transportation and 'launching' of the machine are a significant undertaking.

6.6 Conclusions from Value Determination

It is clear that there are several complicated parameters and factors influencing the rock-breaking process in a TBM drive. The indentation seems to be of high importance, as it determines how efficiently energy is transmitted from the cutterhead to the rock, and thereby how efficient the rock chipping will be. This, in turn, will influence the penetration rate of the TBM.

It seems that there is an agreement among a multitude of researchers that the chipping mechanism in a TBM is caused by a tensile mode of failure, and not by shear failure, as has been believed by some. The processes of indentation, chipping and penetration are highly influenced by several geological and machine factors. Regarding the geological conditions it seems obvious that the degree of fracturing is of special importance alongside the drill ability of the rock.

Through the performance data collected from the TBM it is found that the average penetration rate of the TBM, after 1828 meters being bored, is 4.8 meters per hour, which is a relatively high value. The high value is most likely due to beneficial geological conditions with a high degree of fracturing throughout the tunnel drive.

The 26 % average utilization is not very high for TBM tunnelling, but this relates to the concurrent drill and blast mining, which often require additional rock support in areas where needed.

Luxner (2014) states that the use of the TBM at the mine has been a great success so far, as it has been 46 % cheaper and 5.1 times faster than constructing a similar drive by the use of conventional methods at the mine, the capital required is however 3 times more. One must keep in mind that this comparison is done based on experience data from this specific mine. Nevertheless, this supports the findings by Macias and Bruland, 2014; Maidl et al., 2008 showing the substantial advantage of using a TBM instead of conventional Drill & Blast Tunnelling.

The economics and dynamics of a TBM over conventional development are dependent on each situation; these factors include tunnel length, tunnel alignment, and other variables. In the case of Stillwater Mine, however, TBMs have had a long and successful history. Their decades of proven excavation with TBMs in mines provided a strong case for other worldwide mines developing deep ore bodies that must be accessed through long tunnels.

Table 27 indicates a summary of key projects with some statistics regarding results and costs. This is to be used to demonstrate the value of applying a mechanical rock-cutting methodology by analysing applicable case studies identified in the literature review of the initial milestone.

Table 27. Case Study summary to be used as a guideline for mechanical rock-cutting projects

Project Location	Project Timeline	Machine Type and Method	Challenges and Findings	Capital Cost (ZAR)	Running Cost ZAR/m	Reference
Anglo American: Mogalakwena Mine	2021-2023	Master Drilling Mobile Tunnel Borer 5.5 m diameter, disc cutters. High-speed development of one of the twin-decline tunnels to compare with drill and blast activities in the other.	- Slower than planned advance rate - Challenge with materials handling (not sufficient in removing material fast enough) - Water challenges (machine got flooded as soon as it hit the water table making it difficult to advance and conduct maintenance) - Cutter wear and breakdown frequency higher than anticipated. With no space to get to the cutting face the TBM had to be retracted 2 m to get to the front of the machine	Not Specified	Planned Cost (Fixed and Variable) at: R220,000.00/m Actual cost on average: R450,000.00/day	(Van Rooyen and Carstens, 2022)
Stillwater Mining Company	2014	Comparison of TBM and drill and blast development. 5000E tunnel boring machine used for reef mining 5600E incline (conventional)	The Blitz TBM has driven the 5000E footwall lateral 5.75 x faster Crew consisted of non-miners than the comparatively sized 5600E drill and blast incline. TBM advance: 7 m/shift Conventional advance: 1.2 m/shift	TBM operation required 3.6 times the capital of conventional headings, however direct operational; costs are lower than conventional development TBM CAPEX: $14.3million Conventional CAPEX: $4million	Direct TBM operating cost: $260/m Direct conventional drill and blast operational cost: $302/m	(Willis, et. al., 2014)

Impala Platinum	2004	ARM1100 on Merensky Reef	Merensky reef was found to be easier to cut compared to UG2 with the results indicating production rates by around 30% higher than UG2 cutting rates. Due to the high cutter cost compared to other mining costs, the advancement in cutter technology is now seen as the driver to achieve more cost-effective cutting solutions. The integration of a reef miner into existing operations proved difficult as the continuity of operation is broken by other mining activities (taking up to 70% of available time).	Mentioned the "Placer Dome Narrow Reef Miner" developed for a cost of $20million	Cutter costs reached lows of R185/t Total labour cost of the ARM system totalled 12% at full production with cutter costs at 55% of total mining cost.	(Pickering, et al., 2006)
Lonmin	2005	Sandvik boxhole-borer Borer / raise-boring machine / ABH 1600 (prototype) Hydraulically powered by a 280kW powerpack 6x off-the-shelf cutter heads, with a tricone bit Remote operation with cameras for operator visuals Spoil removal through a vacuum and hopper system	Although the direct cost of mechanical boring is higher it is still on par with drop-raising and has a host of advantages that may tip the scale in favour of mechanical tunnelling - No top-access requirement - Can do 1.5 to 2 m per hour whereas conventional drop-raising can only mine about 4 m at similar cost - No explosives required - Smoother sidewalls less prone to scaling - Limited haulage sliping and no heavy-duty concrete civils required to set-up the borer	Sandvik boxhole-borer with a price-tag of R8.5million	Not Specified	(Lanham, 2005)
Anglo Platinum	2004	The role of mechanization in platinum mines	To ensure cost competitiveness of rock-cutting or other mechanised systems, and/or enhanced margins look at: - reduced unit cost (cost per ounce) - supplier partnerships, strategic alliances - supplier efficiencies - increased volumes - quality of operation with minimal dilution and optimised stoping width.	Not specified	Not Specified	(Croll, 2004)
Lonmin Platinum	2001-2004	ARM1100 on UG2 reef	The nature of the UG2 reef does not support effective fracture propagation resulting in low cutter efficiencies.	Not Specified	Cutter cost estimated as 70% of total production	(Moxham, 2004)

			The number of cutterheads (6) was also identified as too little and adjustments had to be made to improve cut depth and enhance the smoothness of the cutting process. Ore handling was also identified as a critical constraint. Inefficient muck removal led to regrinding and excessive fines.		cost per to produced	
Bafokeng Rasimone Platinum Mine	2000-2001	Jarva MK6 (TBM) – Built in 1972	The best results were achieved in the least disrupted reef The scraper cleaning system did not work successfully, alternative solutions like conveyors needed The method of service installation and operator selection is key in avoiding delays and poor performance Relook into ventilation in confined spaces required Extensive pre-planning required before the implementation of a TBM project. Average penetration rate of 0.47m/h achieved: Anorthosite (0.36 – 0.40) Norites (0.60) Merensky Reef (0.90 – 1.10) Better than anticipated, achieving a life of 12.21 m^3 rock/ring. Initial centre cutters had a low life but was mitigated by the use of carbide cutters. Best advance/day = 13.8 m Best advance in a week = 47.6 m Best advance in a month = 104.7 m Best ROP = 1.33 m/h TBM availability = 82.5% TBM utilisation = 22.3%	Not Specified	Not Specified	(Stander et al., 2001)
Vaal Reefs South	1983	Blind hole boring was implemented as an experimental basis with the 52 RH hydraulic driven machine equipped with cutter head 1.52 m in diameter.	The initial progress was slow and costs were high.	Overall cost: R1,613,027.00	Overall cost of 690.51 R/m	(Lundstrom, 1985)

Trials on blindhole boring in South African Gold Mines	1976	Cralweld BH. 60 blindhole borer. The BH60 has dimensions of 1,52 m (H) x 1,52 m (W) x 2,59 m (L). The wheels are fitted to the main frame and the cutter head is transported specialized car that raises the head to the height of the machine head frame.	Advantage in rotating the borer. Blind hole borers experienced problems with drill-string stabilization. The object was to test the feasibility of boring stope boxholes with a full-face blind hole-boring technique, as a proof of concept. The technique was found to be suitable with improved boring performance expected as experience is gained and relevant modification are made.	Not Specified	R230,87 per metre	(Van den Berg and Taylor, 1978)
Gold Mines in South Africa	1974	Mechanized reef cutting using rase borers	Increased penetration rates and possibly reduced costs could be obtained if higher thrusts were available at the reaming head. At the time of the study (1974) the necessary technology was not available, especially not the machines with the capacity required to achieve high penetration rates in the hard abrasive quartzite formations. The cutters available were also not suitable as they were not really developed for high loading.	Not Specified	Overall cost between 48.95 R/ft to 78.80 R/ft	Wilson and Graham, 1974)
South African gold mines	1968-1976	Drag bit cutting	Mechanization can significantly improve stoping efficiency, but costs and feasibility depend on reef characteristics. Selective mining technologies (rock cutters, reef borers) show potential but need improvements in speed and cost-effectiveness. Machines relying on face stress-fracturing (swing-hammer miner, impact rippers) are promising, with expected productivity of 5–10 ca per shift. Face conveyors are highly effective and could transform mining operations by enabling faster face advances and better rock clearance. The potential demand for mechanized stoping machines is high, given the industry's need to increase productivity and reduce labour costs.	Not Specified	R15.00 R/m^2	(Joughin, 1976)
South African gold mines	1968-1976	Boring methods		Not Specified	R40.00 R/m^2	(Joughin, 1976)
South African gold mines	1968-1976	Swing hammer		Not Specified	R10.00 R/m^2	(Joughin, 1976)
Goldfields South Africa	1968	Prototype Continuous Rock Cutter (similar to early crawler tractors)	For rock-cutting to be economical the cutting of rock is to be continuous as a means to offset the extreme capital cost with lower operational cost.	Not Specified	R22.00 R/m^2	Cook et al., 1968a)

From Table 27, the above-mentioned examples indicate that if the design methodology is correctly applied, the machine is fit for its designed purpose. Therefore, it can add significant value, or in the absence of the guideline applications, can result in significant production loss and associated costs.

7 CONCLUSIONS FROM THE STUDY

The study found that mechanical rock-cutting has a rich history in South African mines since the 1950s. Albeit the technology has been successfully implemented in coal mining, the development and implementation of hard rock-cutting applications have been slow due to the lack of appropriate funding for research in this domain as well as some technological constraints.

Most of the developments in hard rock-cutting were focused on off-reef development such as shaft sinking, decline tunnels, ventilation shafts and box holing. However, there have been studies on on-reef cutting with less success.

Table 27. Table of prominent mechanised rock-cutting projects in South Africa

Machine	Location	Reference
Wire Saw	Anglo Gold Ashanti mines	(Barnes, 1969)
Prototype rock-cutting machine (COMRO)	COMRO Lab & Underground mines	(Cook, et al., 1968a), (Cook, 1969), (Gibs, 1969)
Reef Boring	Vaal Reefs	(Lundstrom, 1985)
TBM (Jarva MK6 -1976 model)	Bafokeng Rasimone Platinum Mine (BRPM)	(Stander, et al., 2001)
ARM1100	Lonmin Platinum Rowland Shaft	(Moxham, 2004)
Narrow reef miner, oscillating disc cutter, activated drum system.	Anglo Platinum Mines	(Croll, 2004)
Continuous mining hard rock-cutting machine, Mechanised XLP fleet.	Lonmin Platinum	(Pickering & Ebner, 2002), (Pickering & Moxham, 2006) (Pickering, et al., 2006)
Mechanised XLP Fleet	Anglo Platinum	(Fourie, Smith, Valicek, & Krafft, 2017)
Epiroc Mechanical Miner	Anglo American, Twickenham mine	(Hiyate, 2018)

The study also found that key projects in the reef-cutting domain is under way at three major South African platinum mines. There is presumed to be more, however, details regarding these projects are not available in the public domain. These projects are listed in the table below:

Table 27. Table of current rock-cutting projects in South Africa

Machine	Location	Reference
Herrenknecht D1000 Reef Borer	ARM Modikwa Platinum Mine, South Africa	(Van der Bijl, 2024)
Master Drilling Reef Miner	ARM Bokoni Platinum Mine	(Van der Bijl, 2024)

SANDVIK MN220 Reef Miner	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)
Atlas Copco Slot Borer	Anglo American, Twickenham Platinum Mine, South Africa	(Anglo American, 2024)

The study found that the root causes of failure for reef cutting technology in the past included:

- Geological constraints;
- Technological constraints;
- Economic climate;
- Mining layout and support challenges;
- Poor pre-implementation research, testing and/or planning;
- Low production levels and uneconomical unit costs due to low advance rates, high running cost and poor utilisation of machines;
- Lack of mobility and flexibility due to size and weight of machines as well as steering limitations.

With the current economic climate, available technology and renewed focus on research to rescue the South African Platinum industry, new studies on rock-cutting on-reef seems much more promising. The change in approach to a risk-based methodology, strategic partnerships and using proven technology has reduced development risk.

In projects where the appropriate cutting was achieved, the success of the project was mostly haltered by supporting services such as maintenance, ore handling and rock support. Initially, projects in the UG2 reef failed due to the challenges associated with the inability to effectively fragment the rock, whilst later attempts failed due to changing economic- and ground conditions as there was a lack of appropriate system adaptability. The initial key to rock-cutting success seemed to have lied with the advancement of cutter technology, however, it seems that the latest drivers are:

- Achieving a cutting system that is truly continuous in its totality;
- Capable of adjusting to ground conditions;
- Compact and high manoeuvrability;
- Simplistic design and easy maintenance.

Apart from high capital expenditure, other factors identified included the lack of interest from the industry to purchase developed technology or to form meaningful partnerships that share both the risk and the reward with machine suppliers. Overall, the table indicates that disc cutters seem to be the most effective, with the best cost performance associated with smaller, mobile cutting machines.

Guidelines for future rock-cutting projects should include:

- Establish meaningful partnerships between miners and suppliers where both the risk and reward of rock-cutting technology developments are shared;
- Geological considerations for machine design should not just include geotechnical parameters for cutting feasibilities or tunnel support but should include information relating to i.e., hydrogeology and reef variations to enable improved adaptability of cutting systems to everchanging ground conditions;
- Ensure appropriate ore handling systems are in place and vigorously tested during development phases;
- Ensure improved integration with other mining activities to mitigate the risk of disruptions. A review of layouts to best suit continuous cutting is critical. Achieving continuous cutting is the key to the success of the cutting system and achieving desired advance rates;
- Ensure an appropriate water management strategy is employed for the cutting set-up;
- Ensure that the cutting system has high manoeuvrability;
- Component reliability is also key as high wear and breakdowns can impact overall performance.

8 WAY FORWARD

The Mechanical tunnelling of hard rock does hold significant value for the South African Mining Industry. In order to leverage and optimise on past experience and work done – it would be ideal to establish a panel consisting of industry leaders, OEMs, tunnelling experts and operation managers. Such a panel would prove to be of great value to the advancement of mechanised rock-cutting in the mining industry.

9 LINKAGES TO OTHER MILESTONES

This milestone summarises and concludes the work done for project MMS24WP3.

10 RECOMMENDATIONS

Apart from the immense potential of establishing an industry panel the current phase does not have any specific recommendations.

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