Underground excavation in narrow reef PGE deposits with NRE fleet

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UNIVERSITY OF ZAGREB
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UNDERGROUND EXCAVATION IN NARROW REEF PGE DEPOSITS WITH NRE FLEET

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Faculty of Mining, Geology and Petroleum Engineering

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Thesis completed at: University of Zagreb
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Abstract

This work presents the NRE Fleet and testing results from two underground mines: the Zimplats Mupani mine in Zimbabwe and the Tumela 15E mine in Amandelbult, South Africa, owned by Anglo American Platinum. The test results have clearly demonstrated that breast mining is a more effective compared to the room and pillar layout in narrow reef mining. The thesis is conducted as part of project 23024 - NRE-ElectRA (Electric, Remote Control, Automatic Narrow Reef Mining Equipment), funded by EIT RawMaterials.

Key words: Platinum Group of Elements, NRE fleet, Dok-ing, NRE Electra

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Rad izrađen: Sveučilište u Zagrebu
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Sažetak

Rad predstavlja NRE flotu i rezultate testiranja iz dva podzemna rudnika: rudnika Zimplats Mupani u Zimbabveu i rudnika Tumela 15E u Amandelbultu, Južnoafrička Republika, u vlasništvu Anglo American Platinuma. Rezultati ispitivanja jasno su pokazali da je otkopna metoda koja koristi panele veće duljine bolja u odnosu na klasičnu komorno stupnu metodu iskopa tankoslojnih ležišta platine. Diplomski rad je izveden u sklopu projekta 23024 - NRE-ElectRA (Electric, Remote Control, Automatic Narrow Reef Mining Equipment), koji financira EIT RawMaterials.

Ključne riječi: Platinski metali, NRE Flota, Dok-ing; NRE Electra

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LIST OF USED SYMBOLS AND UNITS

Symbol	Unit	Description
t	h, min	time
l, d, r	mm, cm, m, km	distance, length
A	m^2, km^2	area
θ	°	angle
	ppm	parts per million

1. INTRODUCTION

Due to the wide range of applications for Platinum Group Elements (PGE), the challenging geology of these deposits, and the difficult mining conditions, the development of new methods and equipment for their excavation has become essential. Traditional underground excavation methods are not always suitable for Narrow Reef Deposits, prompting leading companies in the mining equipment industry, such as Sandvik and Epiroc, to develop equipment and technology specifically for narrow reef mining, with a focus on safety, efficiency, and sustainability.

The Croatian company DOK-ING has invested significant time and effort in developing equipment suited for the excavation of Narrow Reef PGE Deposits, securing its position in the mining market. DOK-ING's NRE fleet comprises three machines that together complete the drilling, cleaning, and anchoring process. Drilling is performed by the NRE Drill Rig, which is designed to drill panels in preparation for blasting. The NRE Dozer handles the cleaning of backlog ore/sweepings, roadway cleaning, and panel entrance (holing) cleaning. Finally, the NRE Support Rig is used to install self-drilling roof bolts (SDR) in the hanging walls of narrow reef stopes.

This work presents the NRE equipment and testing results from two underground mines: the Zimplats Mupani mine in Zimbabwe and the Tumela 15E mine in Amandelbult, South Africa, owned by Anglo American Platinum. The hypothesis of this study is that by implementing an optimized mining method and layout, refining shift schedules, and enhancing machinery, overall performance and operational efficiency can be significantly improved.

The thesis is conducted as part of project 23024 - NRE-ElectRA (Electric, Remote Control, Automatic Narrow Reef Mining Equipment), funded by EIT RawMaterials.

2. PLATINUM GROUP OF ELEMENTS

The platinum group of elements consists of six structurally and chemically similar elements; Ruthenium, Rhodium, Palladium, Osmium, Iridium and Platinium. Their value lies in their wide range application, from industrial to medical (Bohanek et al., 2023 and references therein).

Figure 2-1 shows placement of PGE in the Periodic Table of the Elements, placing them in the Transitional metal group.

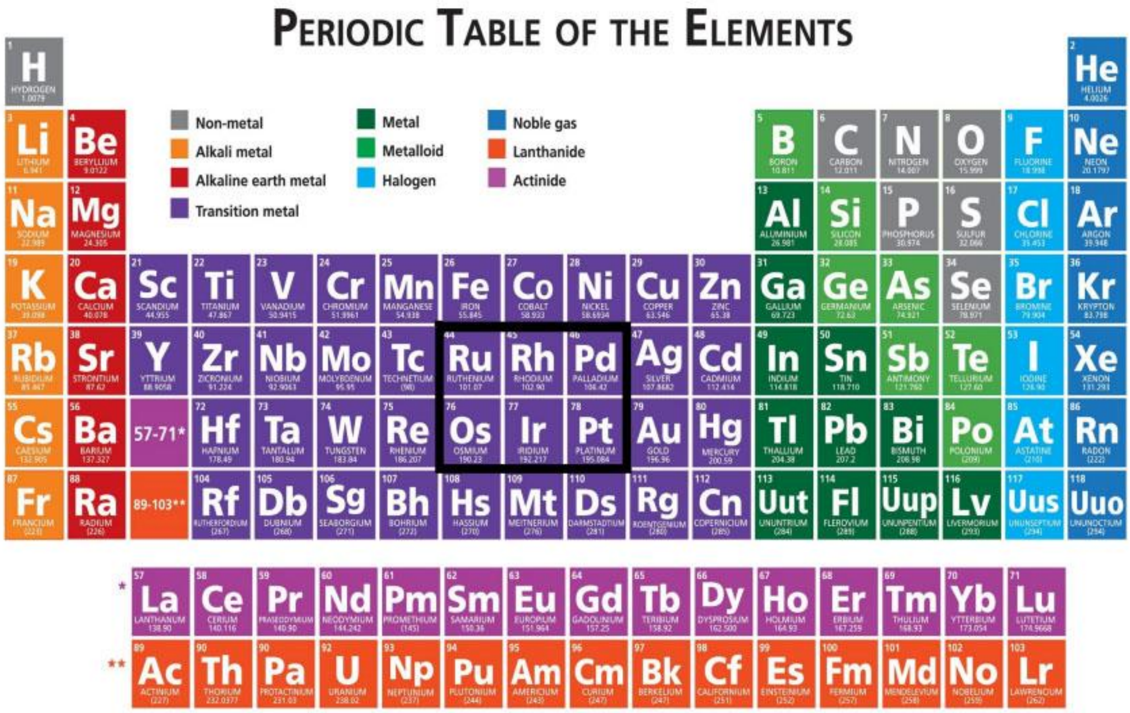


Figure 2-1 PGE placement in Periodic Table of Elements (GraniteShares, 2019)

Mineral deposits containing the main reserves of PGE are found in three countries of the world. Most of them are hosted in mafic and ultramafic rocks in South Africa and Zimbabwe, in large, layered intrusions called the Bushveld Complex and the Great Dyke. The world's primary sources of platinum and rhodium are found in reef-type and contact-type deposits in the Bushveld complex in South Africa. Reef-type deposits are also mined in the Stillwater complex, USA and, before mentioned, Great Dyke, Zimbabwe. In the past, most of these elements were exploited in Russia, Colombia and Canada, but since the 1920s, most of the PGE elements have been obtained in South Africa and Russia, as much as 90% of the world's reserves (Zientek et al., 2014).

2.1. Geological features of PGE deposits

2.1.1. *PGE reef deposits*

PGE reef deposits are associated with large, layered ultramafic and mafic intrusions. Those intrusions are stratified; ultramafic zone with dunite, harzburgite, pyroxenite and chromitite is the lowermost zone, following by central mafic zone with norite, gabbro, pyroxenite and chromitite and uppermost mafic zone with Fe-Ti-rich gabbro and diorite. Most of PGE mineralization occurs in or in close contact with central mafic zone, as shown on figure 2-2 for four significant cases. Rocks that usually carry PGE mineralization are often chromitites but can also be pyroxenite or late-stage pyroxenite pegmatites (associated with Cu-Ni-Co ore). Intrusions bearing PGE are Archean to Proterozoic in age (Bohanek et al., 2023 and references therein).

Origin of PGE mineralization can be:

a) Sulfide immiscibility caused by magma mixing
b) Crustal contamination
c) Upwards migration of hydrothermal fluid through the thick pile of crystallized cumulates (Bohanek et al., 2023 and references therein).

PGE mineralization is stratiform and synergetic, occurring in the form of mineralized lenses or layers. Mineralization is present as a dismantled chalcopyrite-pyrite-PGE assemblage, with average concentration of PGE usually lower than 10 ppm. Significant intrusions with PGE Reefs are the Merensky Reef and UG2 in the Bushveld complex, The Great Dyke intrusion PGE Reefs, Muni Muni intrusion in Australia (Bohanek et al., 2023 and references therein).

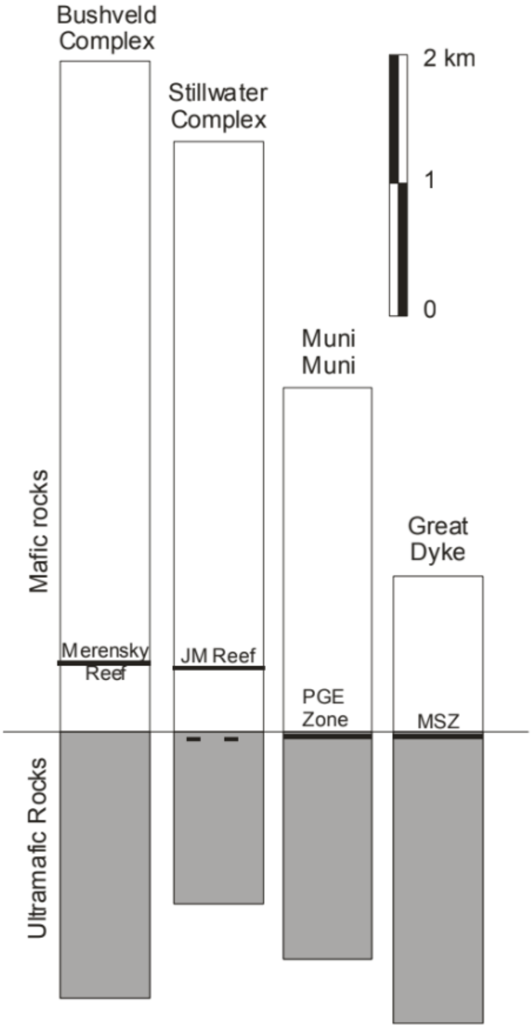


Figure 2-2 Locations of PGE mineralization in some intrusions (Boudreau et al., 2015)

2.2. The Bushveld Complex

The Bushveld Complex was previously known as Bushveld Igneous Complex. It is located in South Africa. It hosts approximately 63% of all known world platinum reserves and if we consider platinum together with PGE, it hosts 87% of all global PGE resources and reserves (Musingwini, 2010).

The complex is covering area of some 67 000 km^2.

The Bushveld complex is made from three main parts:

a) the Lebowa Granite Suite, large A-type granitic intrusions,
b) the Rustenburg Layered Suite and
c) the Rashoop Granophyre Suite.

The Rustenburg Layered Suite is subdivided into a basal Marginal Zone, overlain by the Lower, Critical, Main and Upper Zones. Marginal Zone is thick up to 250 m and consists of massive, fine to medium grained norite and gabbronorite. Lower Zone is 900 - 1600 m thick and consists of olivine and orthopyroxene rich layered cumulates, also chromitite layers (northern and far western parts of complex) (Zientek et al., 2014).

Several major chromitite seams are located within the Critical Zone of the Bushveld Complex. These seams are categorized into three groups:

a) The lower Group (LG1 to LG7),
b) The Middle Group (MG1 to MG4) and
c) The Upper Group (UG1 to UG3).

The LG6 chromitite seam is the most critical for production and reserves, extending over 160 km across both the western and eastern parts of the complex (Robb, 2005).
The Critical Zone is divided into two sub-zones:

a) The Lower Critical Sub-zone, 500 m thick, consisting of ultramafic cumulations
b) The Upper Critical Sub-zone, 450 - 1000 m thick, characterized by repetitive sequences of rock layers

Overlaying Critical Zone, Main Zone is 1600 - 3500 m thick, mainly consisted of norite and gabbronorite (anorthosite layers make up to 5% of rock). The Upper Zone, 1000 - 2700 m thick, consists of gabbro and anorthosite (Zientek et al., 2014). Figure 2-3 shows the stratigraphic column of the Rustenburg Layered Suite, with its zones.

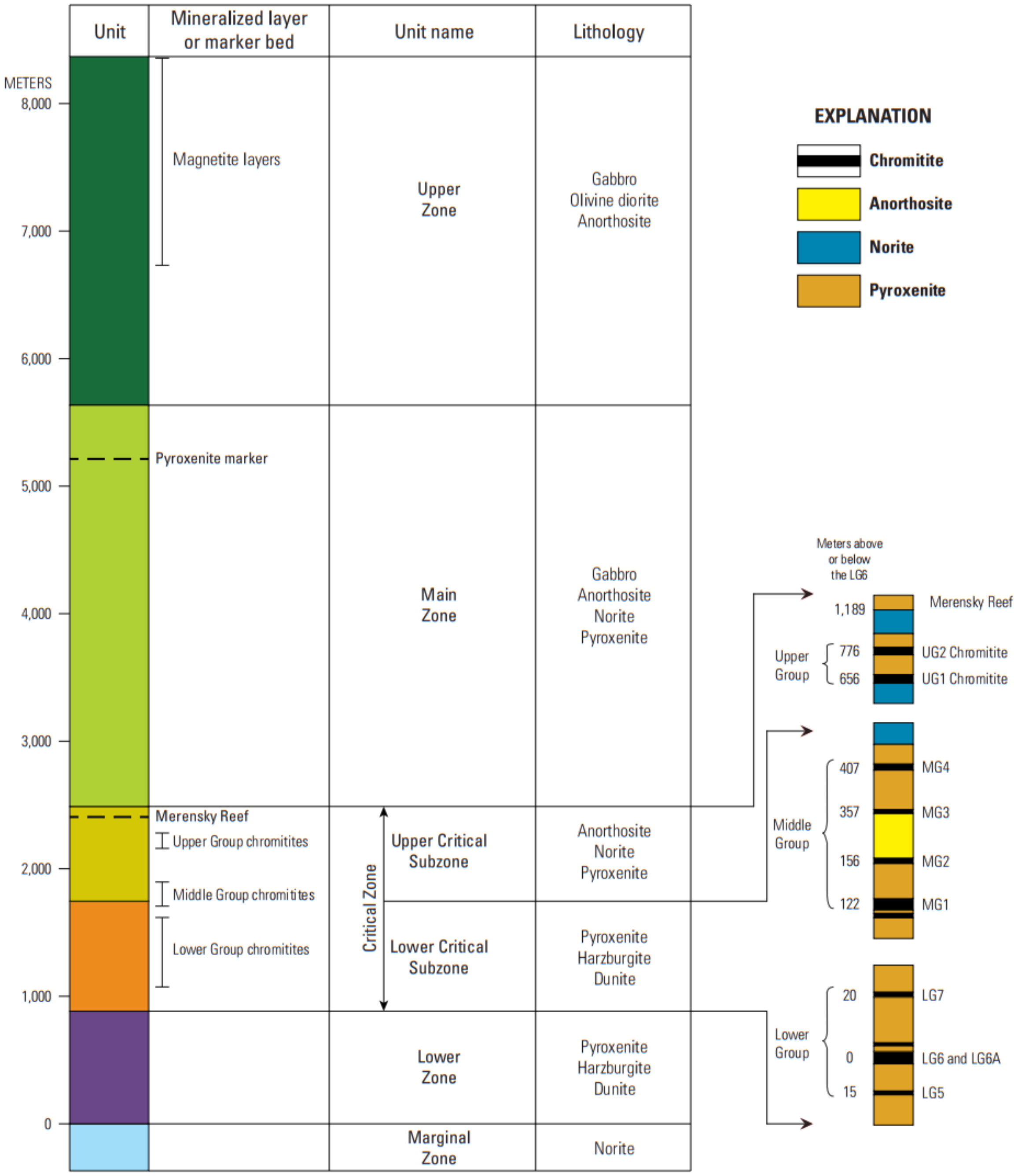


Figure 2-3 Stratigraphic column of mafic to ultramafic layered igneous rocks in the Rustenberg Layered Suite (Zientek et al., 2014)

Bushveld complex is also divided in so-called limbs or lobes. Most of PGE deposits in Rustenburg Layered Suite are in eastern, western and northern limbs. Near the top of Upper Critical zone, in the eastern and western limbs, are located two PGE-enriched stratigraphic intervals; Upper Group Chromitites (UG2) and Merensky Reef. Merensky Reef was discovered by A. F. Lombaard and Hans Merensky in 1924. In the western limb, occasionally are found some other, less PGE-enriched layers (e.g. Pseudoreef located between UG2 and Merensky Reef). In the northern limb, pyroxenite, norite and gabbro are enriched in copper-nickel-PGE minerals, creating a rock structure called Platreef. Platreef was also discovered by Hans Merensky a year after the discovery of the Merensky Reef. Large scale mining of Merensky Reef started in the 1950s, while for the UG2 it stared in the 1970s, after processing developments for extraction of PGE from these ores (Zientek et al., 2014).

In the north-west limb of Bushveld complex, we find Anglo American's Tumela mine. Figure 2-4 shows locations of mines, limbs and zones of the Bushveld complex.

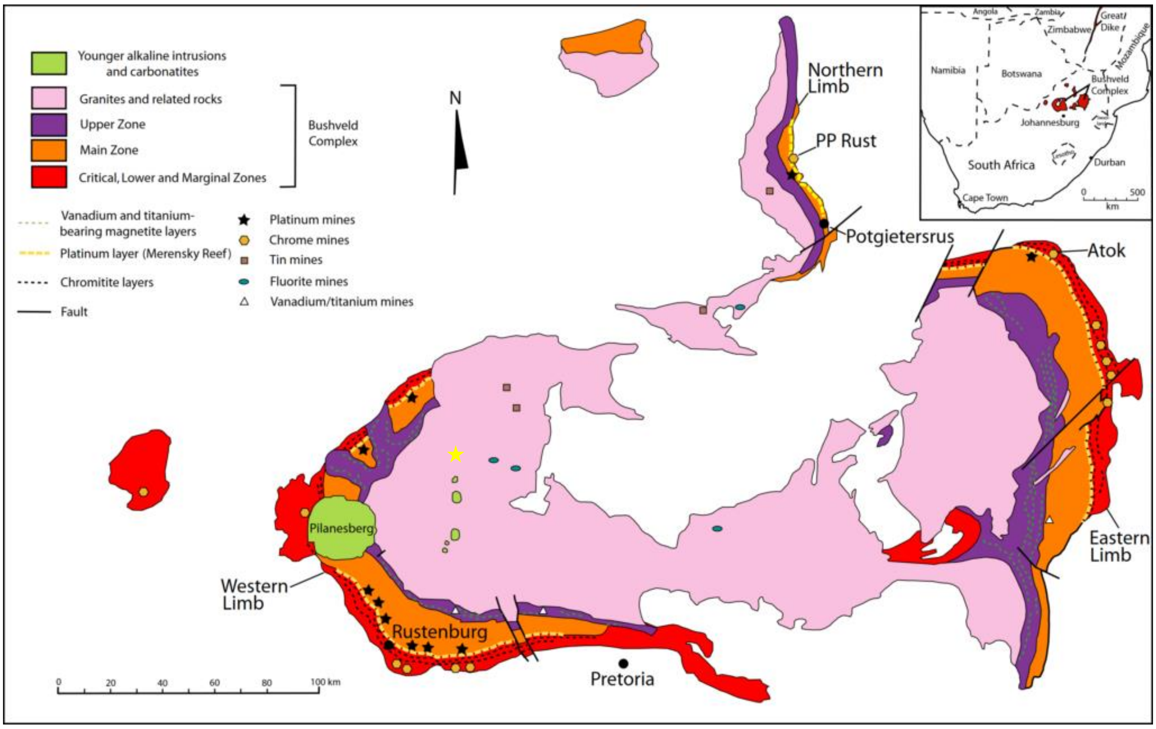


Figure 2-4 Geological map of Bushveld complex (Deseta, 2020)

Amandebult mine is labeled with yellow star on figure 2-4.

2.2.1. Merensky Reef

In addition to large chromite reserves, the Bushveld Complex also contains the largest reserves of the platinum group of elements (PGE). Around 80% of the world's PGE reserves are located within this complex, concentrated in three specific horizons, the most well-known of which is the Merensky Reef, which alone holds about 22% of the world's PGE reserves. Merensky reef was formed at the time when a major injection of new magma occurred into the chamber. This reef also separates the Critical Zone from the Main Zone. The Merensky Reef is typically represented by a 1-meter thick, coarse-grained (or pegmatoidal) feldspathic pyroxenite, which extends along a strike of approximately 250 km. The origin of the Merensky Reef is a subject of debate, with theories ranging from purely magmatic processes to those involving interaction with magmatic-hydrothermal fluids. There is substantial evidence indicating that the Merensky Reef and its associated PGE mineralization have interacted with hydrothermal fluids. Mineralization in the Merensky Reef is evident in the presence of disseminated base metal sulfides, mainly chalcopyrite and pyrrhitite-pentlandite, with which minor PGE sulfides and PGE metal alloys are associated (Robb, 2005).

2.3. The Great Dyke

The Great Dyke is about 550 km long and narrow layered igneous intrusion in Zimbabwe. Present rock types are stratigraphically divided into two sequences; lower Ultramafic Sequence consisting of cyclic repetitions (10 - 100 m thick) of dunite, harzburgite, pyroxenite and chromitite, and upper Mafic Sequence consisting of olivine-gabbro, gabbronorite and norite, and is up to 1150 m thick. Ultramafic Sequence is present throughout the whole intrusion. Much of Mafic Sequence was lost due to erosion and is now present in four areas called complexes or chambers (Zientek et al., 2014).

a) The Musengezi Subchamber,
b) The Hartley Complex and
c) The Southern Chamber, consisting of the Selukwe and Wedza Subchambers.

10 - 15 m below the contact of Ultramafic and Mafic Sequence, a Reef-type PGE deposit, the Main Sulfide Zone (MSZ), occurs. It is typically 2 - 3 m thick, but in some locations can be up to 20 m thick. MSZ was discovered in 1925 (Zientek et al., 2014).

Mupani mine is in Ngezi area, at the heart of the Hartley Complex. An illustration of chambers' placement of the Great Dyke is shown on figure 2-5 and location of Mupani mine is labeled with red star.

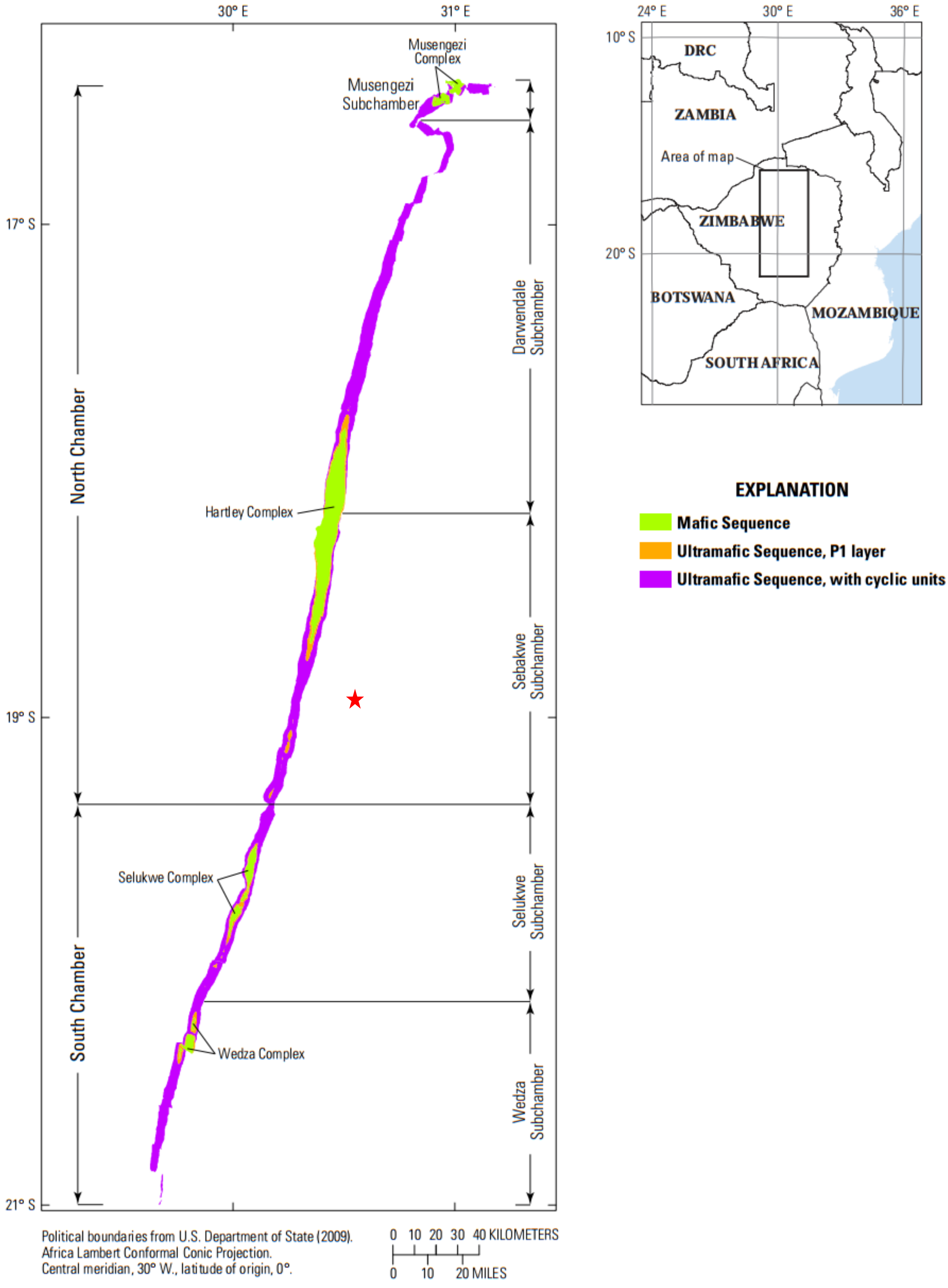


Figure 2-5 Geological map of The Great Dyke (Zientek et al., 2014)

Figure 2-6 shows stratigraphic column of rocks found in Mafic and Ultramafic sequence of the Great Dyke.

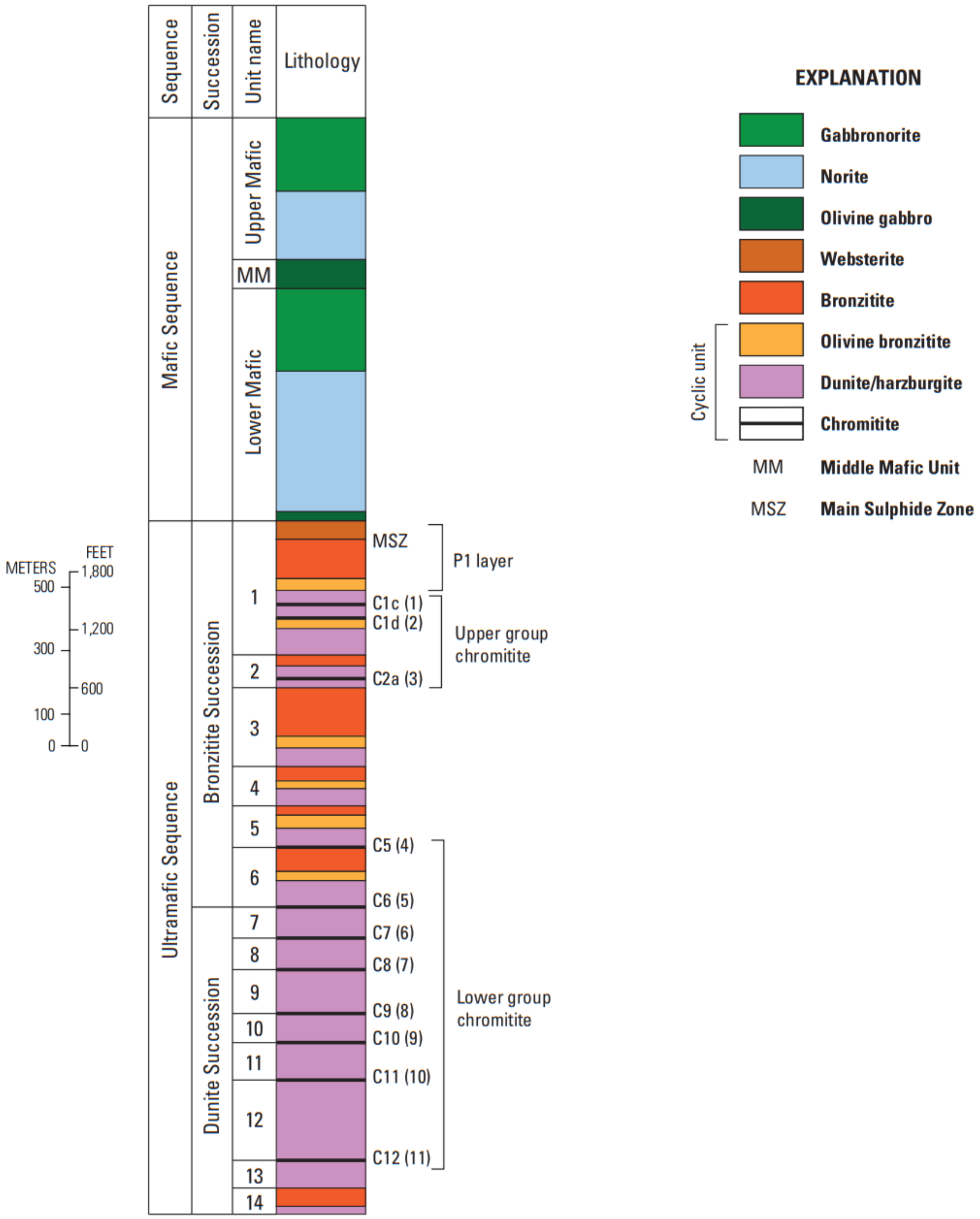


Figure 2-6 Stratigraphic column of mafic to ultramafic igneous rocks (Zientek et al., 2014)

3. MECHANIZED NARROW REEF MINING METHODS

Traditionally, until some twenty years ago, conventional mining methods were used for underground hard rock mining. Although conventional mining is still the dominant mining method, the mining companies are trying to implement more in use of mechanized mining. Main reasons for use of mechanized mining are increased productivity, improved safety and higher quality work. Mechanized mining, can be divided into two categories:

a) Mechanized rock-cutting of the platinum-bearing reefs, and
b) Mechanized drill-and-blast mining methods.

3.1. Mechanized rock-cutting of the platinum-bearing reefs

Mechanized rock-cutting eliminates the need for a re-entry period since no blasting is employed. There is therefore potential for continuous operations 24 hours per day, which results in higher utilization of mining infrastructure. The cutting of reef is much less labor-intensive, and therefore lower labor costs are expected. The major cost component for the mechanized rock-cutting system are cutter costs and engineering maintenance (Van Den Berg, 2014). The largest mining companies trying to implement innovative rock cutting solution for mechanized rock cutting of platinum reef. The solution for continuous cutting offered from Epiroc is named Mobile Miner and Sandvik developed Reef Miner. Mobile Miner and Reef Miner are shown on figures 3-1 and 3-2.

Figure 3-1 Mobile Miner 22H (Mobile Miner 22H | Epiroc, n.d.)

Figure 3-2 Reef Miner MN 220 (Bergbau, 2021)

3.2. Mechanized drill-and-blast mining methods,

Development of underground hard rock mechanized equipment came true by application of knowledge gained from evolution of technology for open pit mining. Three types of equipment were developed:

- LP-low-profile equipment
- XPL-extra-low-profile equipment
- ULP-ultra-low-profile equipment (Fourie et al., 2017).

Room and pillar mining is an effective and widely used method for extracting platinum from underground ore bodies, especially those with narrow, tabular formations. It offers a good balance between ore recovery and mine stability, making it the preferred choice for many platinum mining operations. Breast mining is a similar method, but longer panels are used. The difference between the two methods is in the panel length, but also in the way of organizing mining operations. Graphical illustration of room and pillar mining and breast mining are shown below on Figure 3-3 and Figure 3-4.

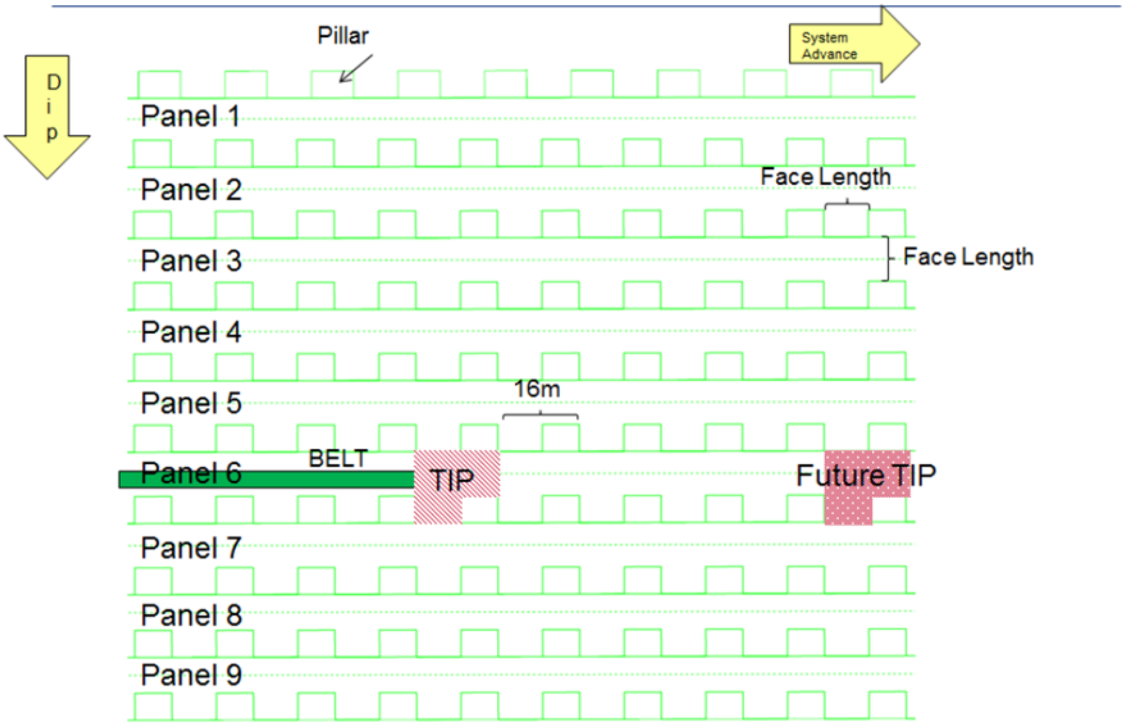


Figure 3-3 Room and pillar mining method (Valicek et al., 2012)

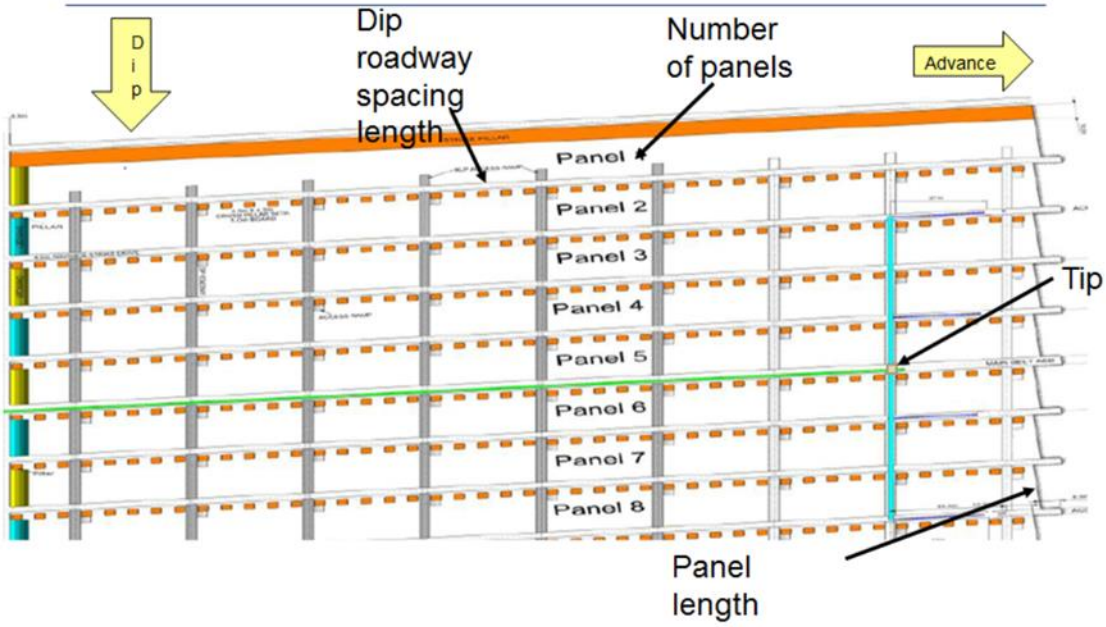


Figure 3-4 Breast mining method (Valicek et al., 2012)

The breast mining method is based on the concept that on-reef development takes place on the strike, prior to stoping, thereby ensuring that all necessary services and infrastructure are in place prior to stoping. This results in an improvement in the overall efficiency of the section and assists in providing a better understanding of the geology, which in turn will ensure better planning for the section before stoping commences (Fourie et al., 2017).

3.2.1. Low-profile equipment (LP)

The LP equipment is mostly used for room and pillar mining in consistent ore deposits without major faults. For the past fifteen years, there have been improvements in LP's production and safety. LP is used for depths up to 400 meters with stoping width from 1,8 to 2 meters and dip less than 10°. Monthly production of ore using LP equipment is from 2100 to 3000 square meters. The biggest advantage is low-level operating complexity, but there are several disadvantages of LP equipment such as high-volume tonnages, low-grade ore, high operating costs and need for complex infrastructure (Fourie et al., 2017).

3.2.2. Extra-Low-profile equipment (XPL)

After the development of LP equipment, XPL equipment was developed for breast mining of consistent orebody with high extraction ratio. It is used in depths from 350 meters to 1800 meters, where we have a dip in range from 0° to 22° and the stoping width variate from 1,3 to 1,8 meters. Monthly production for XPL equipment is the same as it is for LP equipment, but, in comparison to LP equipment, XPL equipment gives less dilution and less waste introduction into plant. However, XPL equipment is very robust, it requires a highly skilled workforce and a complex infrastructure. Additionally, due to high costs of XPL equipment and the inconsistent results of production, the profit margins for XPL were minimal in comparison to LP operations (Fourie et al., 2017).

3.2.3. Ultra-Low-profile equipment (ULP)

ULP equipment has a lot of similarities to XPL equipment It is also used for breast mining, for consistent orebody with high extraction ratio, in depths from 350 meters to 1800 meters, dip from 0° to 22°, but the stoping width is smaller, from 0,9 meters to 1,2 meters. Monthly production is again like both LP and XLP operations: from 2000 to 3000 square meters. Although ULP equipment uses advanced technologies and needs a highly skilled workforce, some of its advantages are the ability to deal with complexities of ore body and high-grade ore (Fourie et al., 2017).

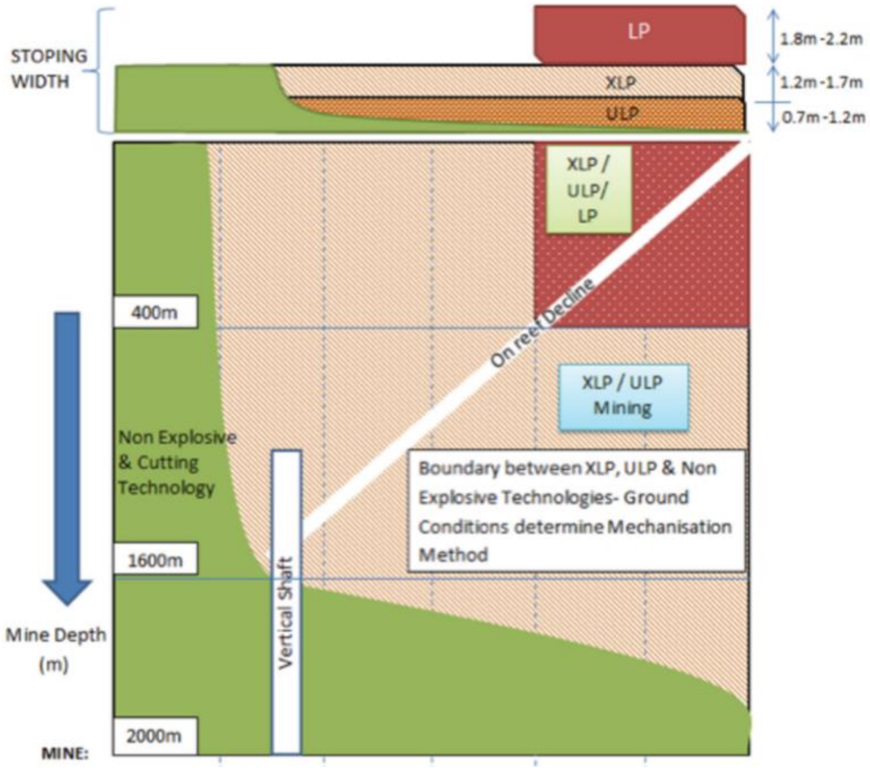


Figure 3-5 Different underground platinum mining methods (Fourie et al.,2014)

Table 3-1 Summary of stopping method (Fourie et al., 2017)

	LP	XLP	ULP
Depth	0-400 m	350-1800m	350-1800m
Stopping width	1,8 - 2 m	1,3 – 1,7 m	0,9-1,2 m
Mining method	Room and pillar	Breast mining	Breast mining
Dip	Approx 10°	0°-22°	0°-22°
Production	2100-3000 m^2	2100-3000 m^2	2000-3000 m^2
Orebody	Consistent ore deposits without major faulty	Consistent orebody, high extraction ratio	Fairly consistent orebody, high extraction ratio
Advantages	Low level operating complexity	Less dilution when compared to LP. Low wastage introduced into plant.	High grade ore, able to deal with orebody complexity
Disadvantages	High volume tonnages Low grade High operating costs Complex infrastructure	Robust equipment Labor intensive Highly skilled workforce Complex infrastructure	Advanced technology Highly skilled workforce Technology in POC phase

*POC- proof-of-concept

4. NRE EQUIPMENT

NRE equipment is innovative, remote-controlled, electric-powered equipment that has the main function of mechanized mining of precious metals from Ultra-Low mining profiles ranging from 0,9 to 1,7 meters. It has robust design, small dimensions, small turning radius, low noise level and nil gaseous emission make these machines the most suitable tool for underground applications. Its lightweight, standalone remote control allows the operator to remain at a safe operating distance during the production process. NRE Fleet consist of 3 machines:

a) NRE Dozer,
b) NRE Drill Rig and
c) NRE Support Rig.

Figure 4-1. NRE Fleet (Dok-ing, 2024)

The NRE Dozer is designed to work in stoping widths from 0,9 m and can work in reef inclinations of up to 25°. The main purpose of NRE Dozer is to push ore from a blasted panel into the advanced strike drive (ASD). The NRE Dozer can also be used to perform cleaning backlog ore/sweepings, roadways cleaning and panel entrances (holing) cleaning (Dok-ing, 2024).

DOK-ING

NRE DOZER TECHNICAL CHARACTERISTICS

DIMENSIONS	
Prime Mover	3460 x 1558 x 652 mm
Prime Mover with Dozer blade	3650 x 1600 x 652 mm
Prime Mover with Sweeper	4660 x 1620 x 652 mm
BLADE	
Clearance	130 mm
WEIGHT	
Prime Mover	4115 kg
POWER SYSTEM	
Battery Type	LiFePO4
Nominal Voltage	308 V DC
Battery Capacity	Up to 8 h
ON BOARD FAST CHARGER	
Charging time	3 hours
Charging source (voltage)	380 – 550 VAC 3ph
BRAKES	
Braking System	Spring Applied Hydraulic Release
OPERATING CAPACITY	
Sweeper cleaning rate in m2	40 m2/h
Dozer Cleaning rate	50 -120 t per hour

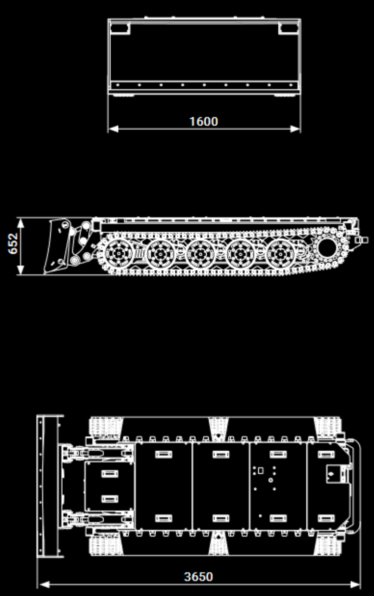
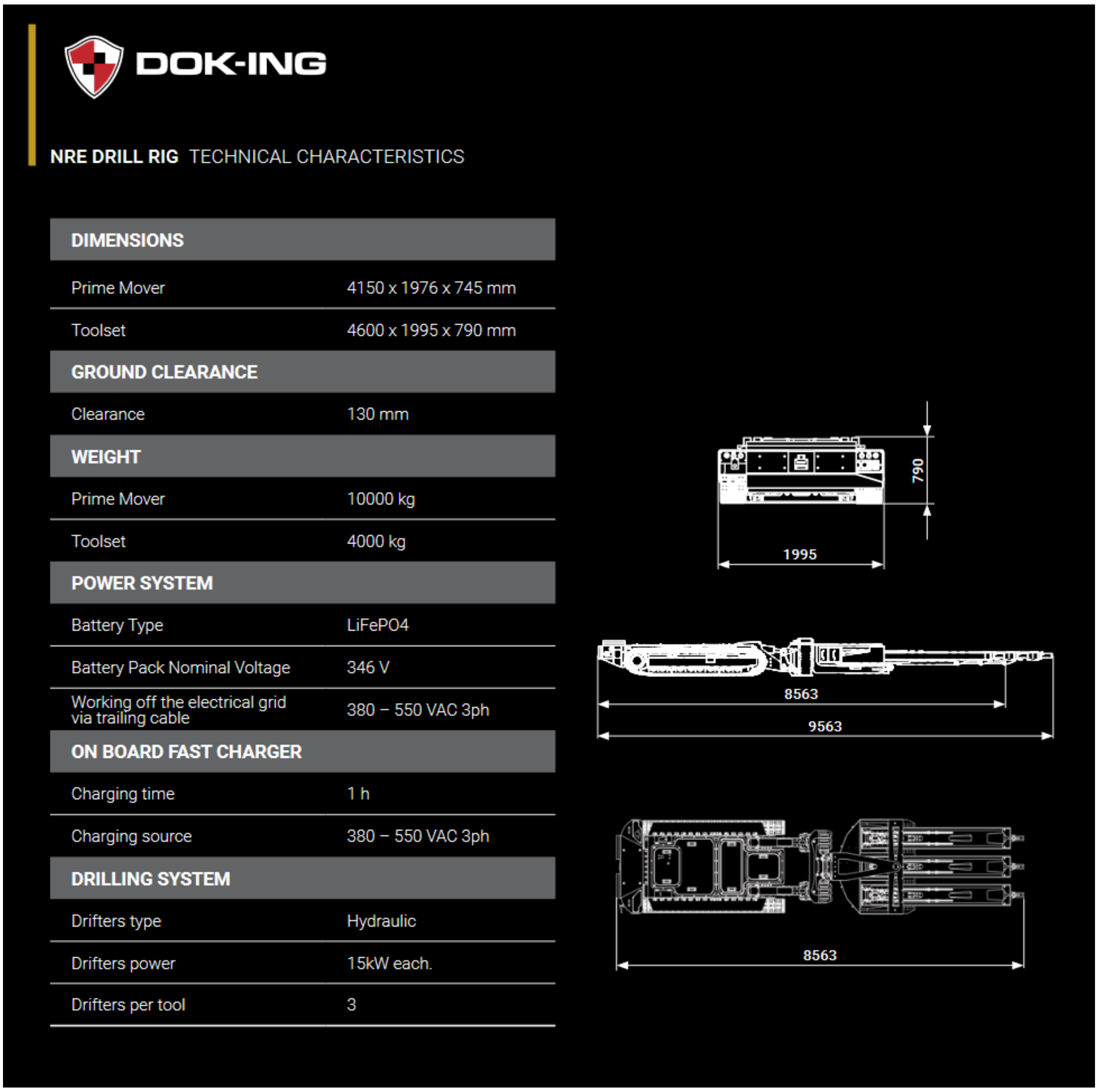


Figure 4-2 NRE Dozer (Dok-ing, 2024)

The purpose of **NRE Drill Rig** is to drill the panels to prepare them for blasting. The operator can perform all the functions from a safe operating distance. The NRE Drill Rig is designed to work in stoping widths from 0,9 to 1,7m and can work in reef inclinations of up to 22°. The NRE Drill Rig has a 3-drill drifter configuration, allowing 3 face holes to be drilled simultaneously. (Dok-ing, 2024).



DIMENSIONS	
Prime Mover	4150 x 1976 x 745 mm
Toolset	4600 x 1995 x 790 mm
GROUND CLEARANCE	
Clearance	130 mm
WEIGHT	
Prime Mover	10000 kg
Toolset	4000 kg
POWER SYSTEM	
Battery Type	LiFePO4
Battery Pack Nominal Voltage	346 V
Working off the electrical grid via trailing cable	380 – 550 VAC 3ph
ON BOARD FAST CHARGER	
Charging time	1 h
Charging source	380 – 550 VAC 3ph
DRILLING SYSTEM	
Drifters type	Hydraulic
Drifters power	15kW each.
Drifters per tool	3

Figure 4-3 NRE Drill Rig (Dok-ing, 2024)

The purpose of **NRE Support Rig** is to install self-drilling roof bolts (SDR's) to the hanging wall of narrow reef stopes. It is possible for an operator to perform all functions from a safe operating distance. The NRE Support Rig is designed to work in stoping widths from 0,9, to 1,7m, and can work in reef inclinations of up to 22°. The NRE Support Rig has a dual tool configuration, allowing 2 bolts to be drilled, installed and resin injected simultaneously. (Dok-ing, 2024).

DOK-ING

NRE SUPPORT RIG TECHNICAL CHARACTERISTICS

DIMENSIONS	
Prime Mover	4150 x 1976 x 745 mm
Toolset	2185 x 1950 x 793 mm
Tool Width (single)	935 mm
GROUND CLEARANCE	
Clearance	130 mm
WEIGHT	
Prime mover	10 000 kg
Toolset	3000 kg
POWER SYSTEM	
Battery Type	LiFePO4
Battery Pack Nominal Voltage	346 V
Working off the electrical grid via trailing cable	380 – 550 VAC 3ph
ON BOARD FAST CHARGER	
Charging time	1 h
Charging source	380 – 550 VAC 3ph
SUPPORT TOOL CHARACTERISTICS	
Number of tools	2
Type of drilling	Rotary drilling
Maximum drill thrust force	40 kN
Support cycle (2 bolts, 1.6 m ea.)	8 min

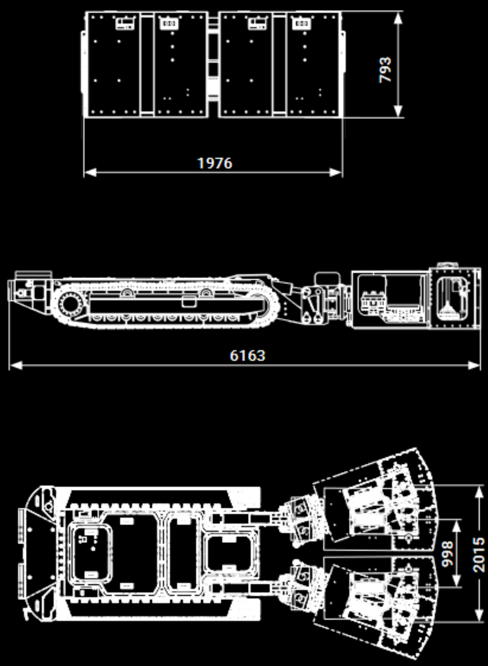


Figure 4-4 NRE Support Rig (Dok-ing, 2024)

5. TESTING

Underground trials have two main components; firstly, is the need to demonstrate that the equipment carries out the function that it was designed for and secondly, that the mining method employed is adequately productive (Pickering & Leon, 2008). When testing the fleet, each machine must reach its targets. If one out of 3 machines do not fulfil the requirements, the mine will not reach the target production. In our case, the NRE fleet is tested in two different underground mines that use different mining methods. In the first mine the room and pillar method were used, in the second mine the breast mining method.

Ore is mined in several separate panels that can be of different lengths and heights, and the mining is performed in mining cycles. Each mining cycle consists of individual mining operations. In both cases, the mining cycle has 4 main operations, as is shown on Figure 5-3.

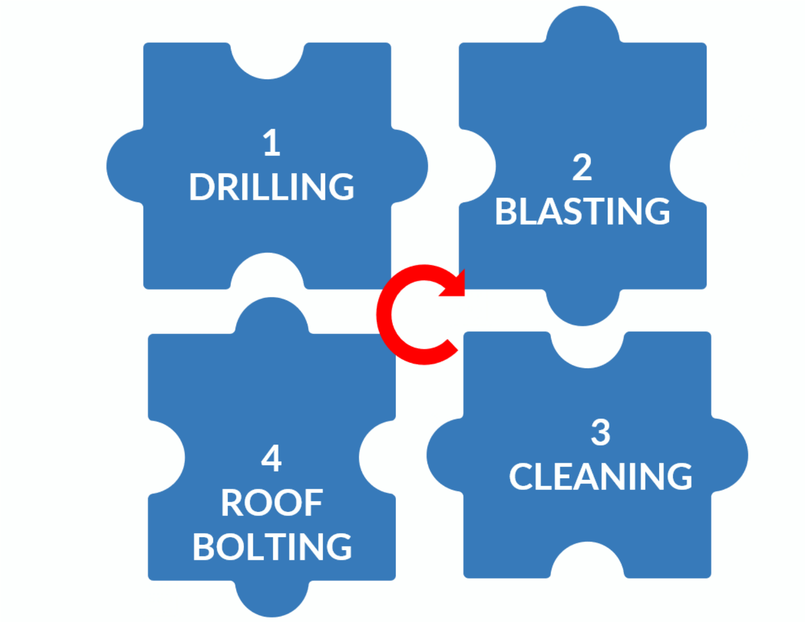


Figure 5-1 Mining cycle operations

Except for blasting, in which blast holes are filled with explosive manually, all other operations can be performed using NRE equipment from a safe distance. NRE Fleet cycle is shown on Figure 5-4.

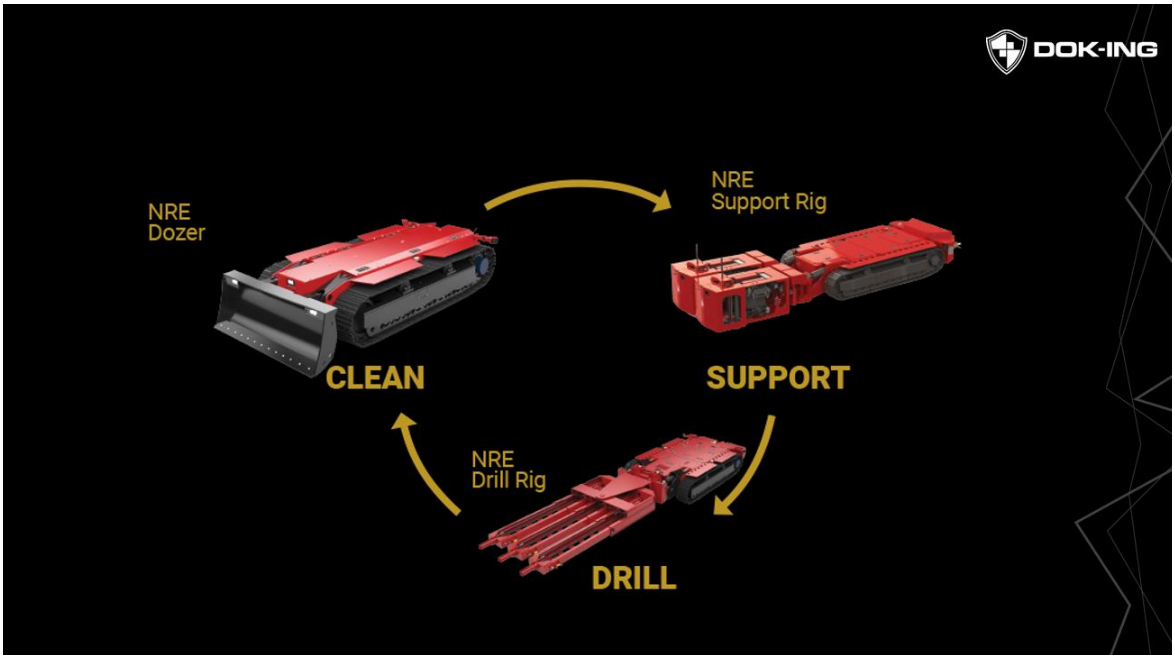


Figure 5-2 NRE Fleet cycle (Dok-ing, 2024)

5.1. Zimplats trial tests

Zimplats is the leading mining company in Zimbabwe specializing in platinum group metals such as platinum, palladium, rhodium, iridium, ruthenium & osmium. The NRE fleet was tested in the upper ores 2 section of the Mupani mine in Zimbabwe. Mupani mine uses room and pillar for the exploitation method. The average reef angle was 15°. The rooms in section are 7,8 m wide, as well as protection pillars. The section is divided into 4 parallel rooms in operation that are interconnected by breakaways. The rooms and pillar pattern are shown on figure 5-5.

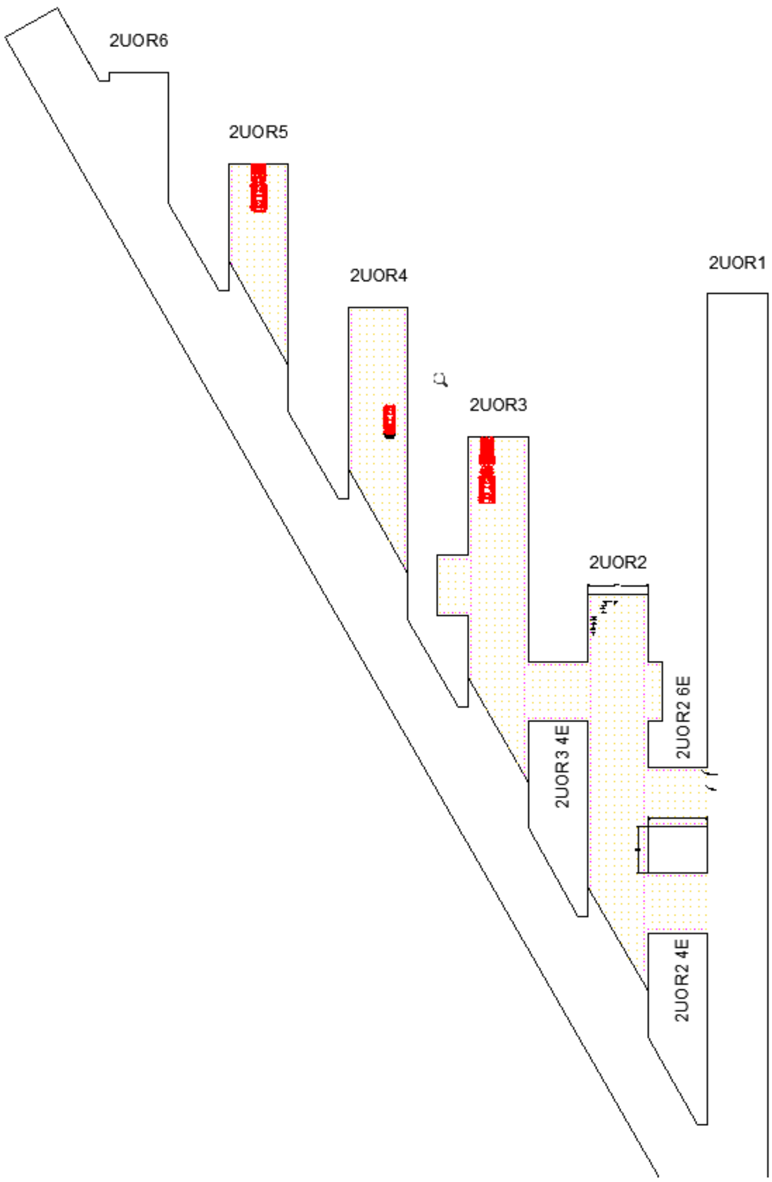


Figure 5-3 Rooms and pillar pattern in Zimplats (Pleše, 2024 unpublished)

The height of the exploited layer is 2,4 meters, while the maximum height at which the fleet operates is 1,7 meters. The fleet operated outside the specified height at which the fleet operates during the entire test period. The number of holes drilled was 63, including the cut holes. Almost all holes were parallel and 2 meters long. The spacing between holes was 0,6 meters and the spacing between rows was 0,45 meters. The cut had 13 boreholes according to a predetermined pattern and the distance between the boreholes was 0,15-0,225 meters.

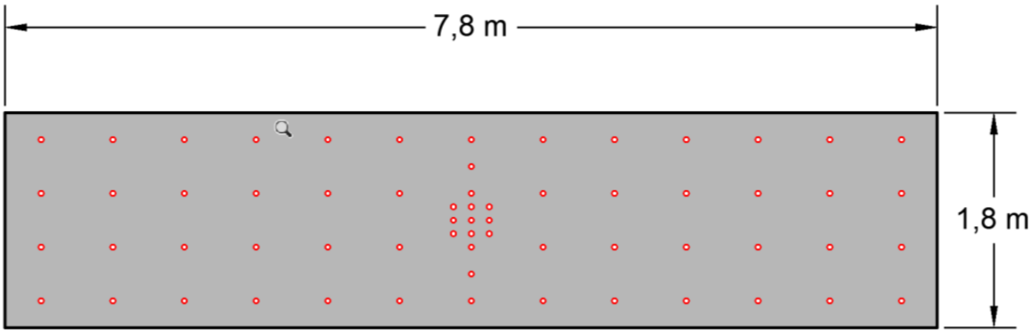


Figure 5-4 Panel with blastholes pattern

The rock mass in which the rooms are located is blocky, due to this factor, overbreak often occurred, therefore the height of the room was usually higher than the targeted room height of 1,7 meters. The position of the drill rig length of the holes and hole angles are shown on figure 5-7.

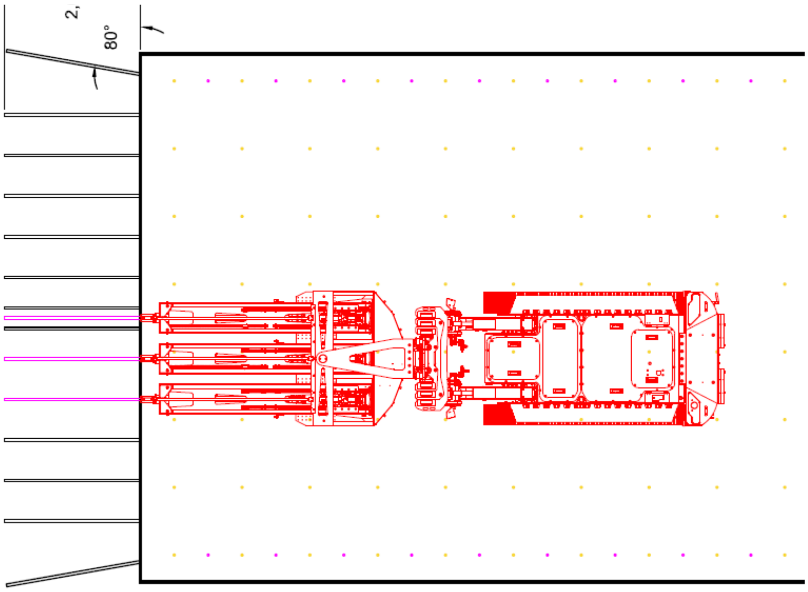


Figure 5-5 Drill Rig postion in Zimplats (Pleše, 2024 unpublished)

Blastholes are manually charged with explosives and detonators and blasting is performed. Blasted material must be cleaned and pushed from the panel by NRE Dozer.

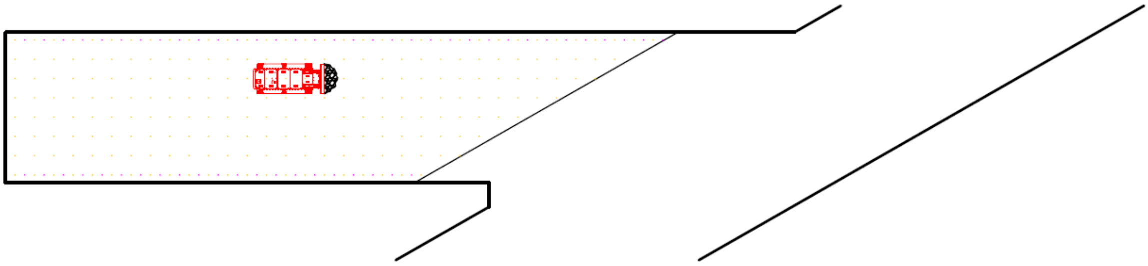


Figure 5-6 Dozer work in Zimplats (Pleše, 2024 unpublished)

After cleaning of panels, the NRE Support Rig can install self-drilling roof bolts (SDR's) to hanging wall of narrow reef stopes. The bolts are drilled on raster 1x1 m except for the lateral sides where additional anchors are inserted at distances of 0,5 m. Diameter of anchors were 32mm and length was 2,0m except for some inserted bolts whose length was 2,4 m.

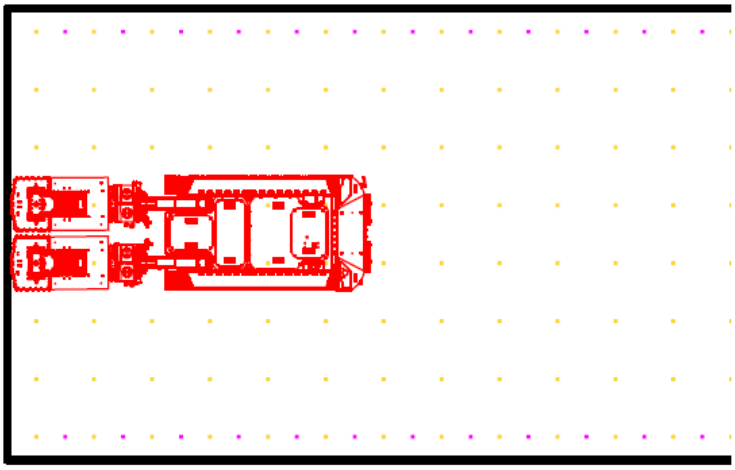


Figure 5-7 Support Rig work in Zimplats (Pleše, 2024 unpublished)

Described testing was performed with one NRE fleet from July 2022 until October 2023.

5.2. Amandebult trial test

The second testing of the NRE fleet was in Amandebult platinum mine in South Africa, owned by Anglo American Platinum. Amandelbult complex comprises Tumela and Dishaba mines, and two operational concentrators with two chrome plants. The currently working mine infrastructure has five vertical and seven decline shaft systems to transport equipment, men and mined material, mining on the Merensky and UG2 Reef horizons (Major Mines & Projects | Amandelbult Complex, 2024). This testing was different from the one in Mupani mine because NRE fleet was already working in the panels where ore body decline at angles ranging from 22° to 30°.

Breast stopping mining method was used in the Tumela mine, Amandebult. This method is used for horizontal and sub-horizontal narrow ore bodies with the thickness of the exploited layer ≤2 m. The thickness of the exploited layer in the Tumela mine varies between 1,4m-1,7m. The section of the mine where the trial period of the NRE fleet takes place is divided into 7 panels. The face of the panel is 25-30m long, the collection drive is positioned next to the lower side of the panel, all mined ore need to be pushed to the collection drive in manner to be removed from work area. The NRE fleet's production cycle starts with a drill rig, depending on the length of the panel, the machine drills about 140 mine boreholes with a depth of 2 m, the rows of boreholes as well as the boreholes in the row are spaced 60 cm apart, except for the first two and the last two boreholes in the row, which are spaced 30 cm.

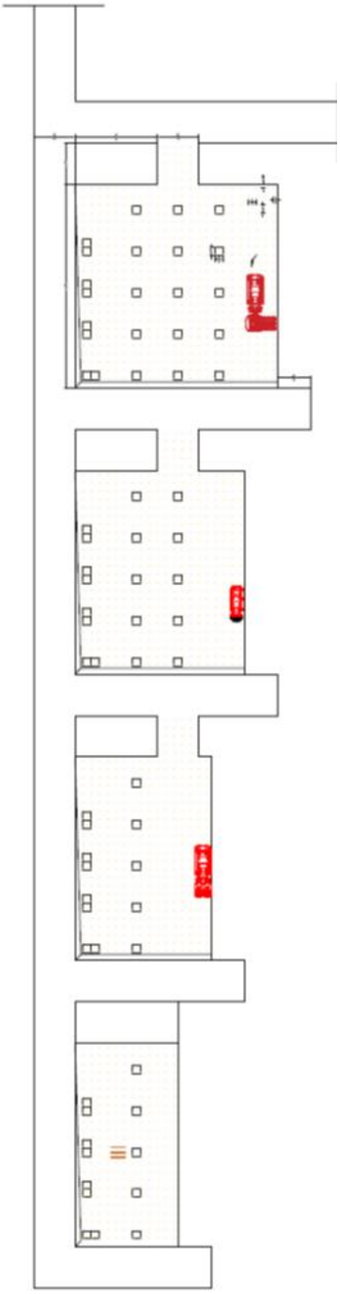


Figure 5-8 Breast mining pattern in Amandebult (Pleše, 2024 unpublished)

The number of holes drilled per each panel was 126. All holes were parallel and 2 meters long. The spacing between holes as well as the spacing between rows was 0,6 meters. Cut holes were not used because blasting fields were initiated from the end of the panel. This is the reason why the distance between two first and last two columns was 0,3 meters. The dimensions of the panel and blasting pattern is shown on figure 5-11.

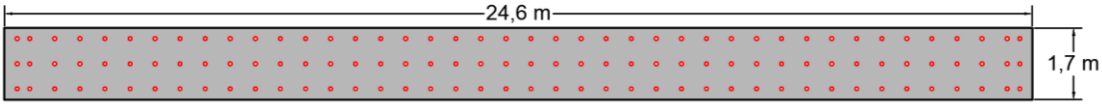


Figure 5-9 Panel with blastholes pattern

The position of the drill rig length of the holes and hole angles are shown on figure 5-12.

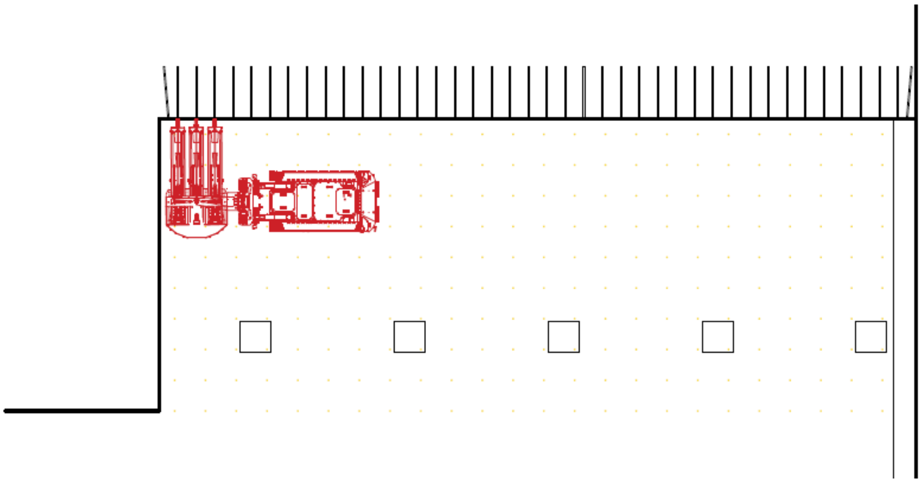


Figure 5-10 Drill Rig postion in Amandebult (Pleše, 2024 unpublished)

After the panel has been drilled, it's time to fill the boreholes with explosives. When blasting is successfully carried out, 60% of the blasted material should be discarded in the collection drive. NRE dozer pushes the material which remain in the panel into the collection drive, from where it is removed with a scoop.

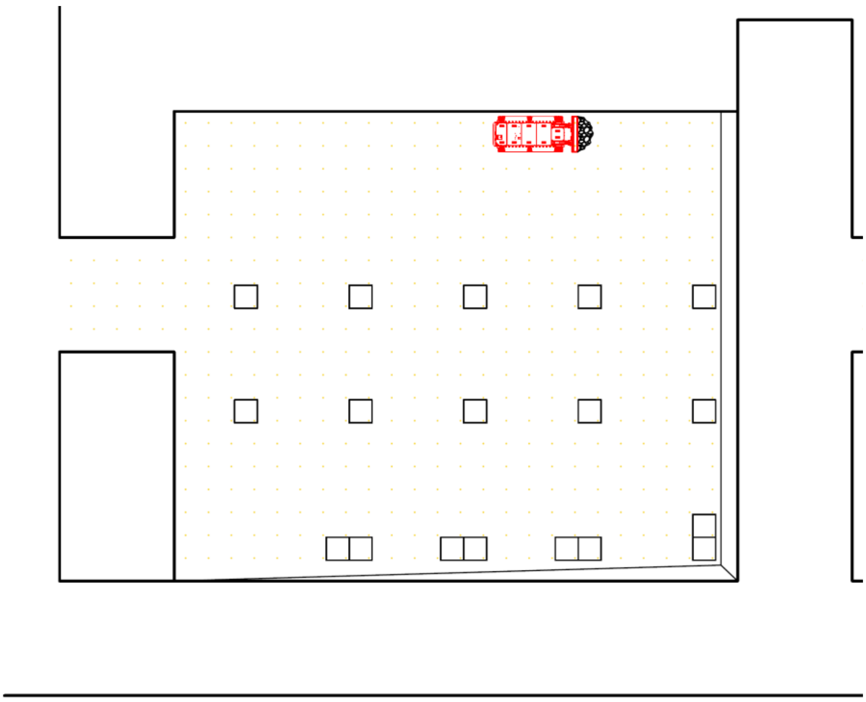


Figure 5-11 Dozer work in Amandebult (Pleše, 2024 unpublished)

After the panel has been cleaned of ore, the newly created space needs to be supported, the support rig uses two tools to install 2 m long anchors in the hanging wall in a manner to support it from collapsing, the anchors are placed in a grid where the rows and the anchors in the row are 1 m apart. The area that needs to be supported after each new blasting depends on the advance created by the blast and the length of the panel, the support rig installs about 50 bolts in the panel to secure the ceiling, the number of bolts depends on the length of the panel, apart from the bolts, concrete pillars with a base of 1x1m are used as a substructure, the pillars are placed in a grid where the distance between the posts is 4m. When the space is secured from collapse, the cycle is repeated.

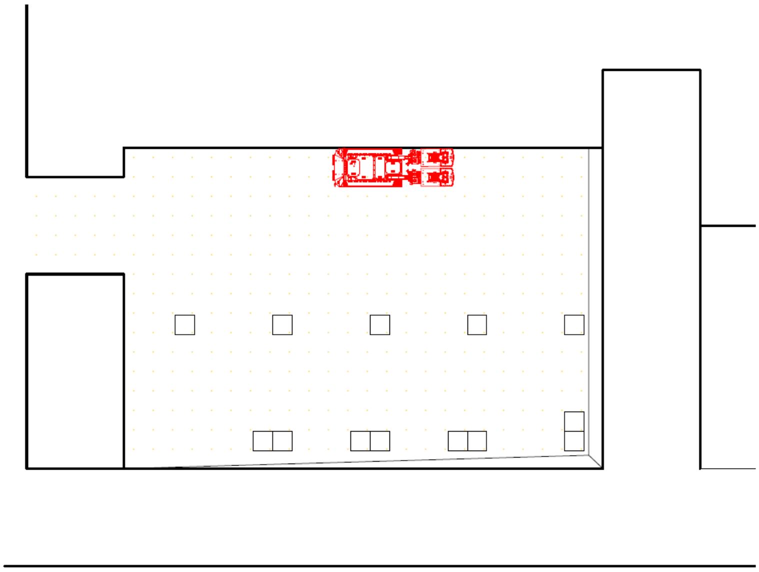


Figure 5-12 Support Rig work in Amandebult (Pleše, 2024 unpublished)

The data about performance of machines are collected for the time from January 2022 until the end of 2023, where availability and utilization were calculated only for period of 2023 year.

6. TESTING RESULTS

In both mines, NRE equipment was tested based on their performance and availability and utilization. Time spent on different activities in mine was also recorded, whether it affected machines utilization or not.

The production performance of mining equipment depends on its availability and utilization. Hence, it is necessary to determine the percentage availability and utilization of machinery with an aim to improve the same. Available is a machine that is fit to perform its duties. Availability can be determined as a fraction of the time in hours the machine is available and time that it is used, plus the time it is available but not used. It is normally expressed as percentages and calculated for one year. Calculations of availability result in easier comparisons of efficiency of maintenance departments of different units (Arputharaj, 2015).

Utilization factor is defined as the ratio of the time in hour the machine is used in a year to the total hours. Total hours can be either total annually scheduled shift hours or total machine available hours. If we calculate Utilization factor with scheduled shift hours, we will get a measure of the efficiency of both maintenance and operational staff, but if we calculate it using machine available hours, we will get a measurement of operational staff efficiency only (Arputharaj, 2015).

6.1. Zimplats trial tests results

During the test's time for each mine, activities during the shift time are recorded and availability and utilization are calculated. The shift working time consists of different activities such as mine procedure, face time, mine not ready, breakdown, maintenance and tramming. Also, the performance for each machine is recorded.

6.1.1. Zimplats NRE Drill Rig results

A summary of Drill Rig performance is shown in table 6-1.

Table 6-1 Summary of Drill Rig performance (Zimplats report, 2024)

Total working shifts	297
Drill Rig + PM working shifts	192
Total drilled holes	9514
Total advance (m)	302
Number of breakdowns	66

Table 6-2 shows ratio between total working time and time when Drill Rig was drilling, on breakdown, time for mine regular procedures (safety talk, checklist, shift down/up; re-entry), tramming and time when mine was not ready. That time represents insufficient water pressure or none of it, charging interruption and when panel was not ready. All the times that are presented were taken from checklist which were filled by the operators.

Table 6-2 Time spent on different activities (Zimplats report, 2024)

Activity	Spent time (h)	(%)
Mine procedure	1030	39
Face time	607	23
Mine not ready	540	20
Breakdown	287	11
Maintenance	96	4
Tramming	90	3
Total	2650	100

Face time drilled blastholes availability and utilization for each month are shown in table 6-3.

Table 6-3 Face time, drilled blastholes, availability and utilization per months (Zimplats report, 2024)

Month	Sum of face time/month (h)	Sum of drilled blastholes/month	Availability/month	Utilization/month
Jul 2022	3	42	100,00%	7,45%
Aug 2022	16	251	87,65%	10,35%
Sep 2022	38	526	94,48%	22,72%
Oct 2022	20	358	93,24%	12,93%
Nov 2022	43	658	82,75%	25,79%
Dec 2022	24	527	88,41%	29,18%
Jan 2023	61	1270	96,97%	44,75%
Feb 2023	42	631	66,33%	28,08%
Mar2023	79	1150	90,82%	48,61%
Apr 2023	32	588	95,35%	24,46%
May 2023	49	821	88,35%	29,07%
Jun2023	36	676	91,93%	21,56%
Jul 2023	61	746	98,12%	35,79%
Aug 2023	36	488	84,04%	20,46%
Sep 2023	63	717	66,01%	40,06%
Oct 2023	6	65	57,33%	32,00%

NRE Drill Rig availability/utilization for testing period are shown in table 6-4.

Table 6-4 NRE Drill Rig availability/ utilization (Zimplats report, 2024)

Activity	Spent time (h)
Breakdown time	287
Utilization time	696
Total time	2650
Availability	89,2%
Utilization	26,3%

6.1.2. Zimplats NRE Dozer results

Summary of Dozer performance is shown in table 6-5.

Table 6-5 Summary of Dozer performance (Zimplats report, 2024)

Total working shifts in Mupani mine	297
Dozer working shifts	205
Total panel cleaned	155
Pushed/pulled ore (t/h)	≈17
Number of breakdowns	59

The time spent on different activities are shown on table 6-6.

Table 6-6 Time spent on different activities (Zimplats report, 2024)

Activity	Spent time (h)	(%)
Mine procedure	1103	45
Face time	810	33
Breakdown	303	12
Other (tramming, Dozer charging)	137	6
Maintenance	120	5
Total	2474	100

Face time and cleaned panels for each month are shown on table 6-7.

Table 6-7 Face time and cleaned panels per month (Zimplats report, 2024)

Month	Sum of face time/month (h)	Sum of cleaned panels/month
Jul 2022	0	0
Aug 2022	31	5
Sep 2022	46	11
Oct 2022	60	4
Nov 2022	81	11
Dec 2022	36	8
Jan 2023	43	6
Feb 2023	63	21
Mar2023	75	22
Apr 2023	85	12
May 2023	44	12
Jun2023	74	8
Jul 2023	64	17
Aug 2023	76	11
Sep 2023	32	7
Oct 2023	0	0

NRE Dozer availability/utilization for testing period are shown in table 6-8.

Table 6-8 NRE Dozer availability/utilization (Zimplats report, 2024)

Activity	Spent time (h)
Breakdown time	303
Utilisation time	892
Total time	2474
Availability	87,75%
Utilisation	36,05%

6.1.3. Zimplats NRE Support Rig results

Summary of NRE Support Rig performance is shown in table 6-9.

Table 6-9 Summary of NRE Support Rig performance (Zimplats report, 2024)

Total working shifts in Mupani mine	297
Total working shifts	195
Total installed bolts	2314
Number of breakdowns	68

The time spent on different activities are shown on table 6-10.

Table 6-10 Time spent on different activities (Zimplats report, 2024)

Activity	Spent time (h)	(%)
Mine procedure	968	37
Face time	598	23
Mine not ready	433	16
Breakdown	406	15
Maintenance	132	5
Tramming	105	4
Total	2642	100

One of the Support Rig advantages is two tools which can be used simultaneously. Sometimes only one tool is used. Face time, sum of installed bolts for each tool (left and right) availability and utilization for each month are shown on table 6-11.

Table 6-11 Face time, sum of installed bolts, availability and utilization per month (Zimplats report, 2024)

Month	Sum of installed bolts SR006L/month	Sum of installed bolts SR006R/month	Sum of face time/month (h)	Availability/month	Utilization/ month
Aug 2022	32	20	16	89,45%	8,68%
Sep 2022	115	0	27	88,37%	14,92%
Oct 2022	58	26	26	80,22%	15,40%
Nov 2022	39	115	51	91,23%	27,88%
Dec 2022	84	55	28	87,16%	31,08%
Jan 2023	151	100	65	93,62%	39,36%
Feb 2023	50	159	57	86,17%	36,44%
Mar2023	115	182	76	88,37%	40,47%
Apr 2023	55	94	46	81,25%	27,66%
May 2023	76	91	40	87,61%	22,13%
Jun2023	119	77	48	82,44%	27,40%
Jul 2023	158	23	48	79,29%	28,54%
Aug 2023	143	0	35	66,51%	18,92%
Sep 2023	158	0	34	94,23%	21,03%
Oct 2023	9	10	6	95,00%	32,50%

NRE Dozer availability/utilization for testing period are shown in table 6-12.

Table 6-12 NRE Dozer availability/utilization (Zimplats report, 2024)

Activity	Spent time (h)
Breakdown time	274
Utilisation time	703
Total time	2642
Availability	89,62%
Utilization	26,60%

6.2. Amandebult trial tests results

The results show the machines' performance for the time from January 2022 until the end of 2023, where availability and utilisation were calculated only for the period of 2023 year. In Zimpalts we had only one fleet which means only one drill rig, dozer and support rig. In Amandebult trial tests data are collected for 3 drill rigs, 2 dozers and

6.2.1. Amandebult NRE Drill Rig results

Three NRE Drill Rigs were used during testing in Amandebult. Drill Rig 004 and Drill Rig 005 are currently in use. Drill Rig 003 has been sent for the refurbishment. Table 6-13 present time spent in the mine and how many blastholes were drilled with each Drill Rig.

Table 6-13 Number of drilled blastholes with NRE Drill Rigs (Amandebult report, 2024)

Drill Rig	Time spent in mine	Drilled blastholes
DR 003	January 2022 – November 2022	1464
DR 004	April 2021 - End 2023	18 868
DR 005	November 2022 - End 2023	13 969

Table 6-14 shows availability and utilization for DR004 and DR005 in 2023. DR003 is currently out of mine, and it did not drill in 2023.

Table 6-14 Availability and utilization of NRE Drill Rigs (Amandebult report, 2024)

	DR004	**DR005**
Availability	64,66%	54,60%
Utilization	15,58%	12,62%

Table 6-15 shows what affected Drill Rigs utilization.

Table 6-15 Activities that affected DR004 and DR005 utilization (Amandebult report, 2024)

	DR004	**DR005**
Standby	40,66%	42,28%
Breakdown	39,96%	32,62%
Service	2,68%	4,53%
Production delays	4,06%	5,73%
Maintenance	2,89%	4,03%
Other	9,76%	10,81

6.2.2. Amandebult NRE Dozers

There are two NRE Dozers on the site D009 and D010. Dozers are pushing blasted ore down the dip in the ASD and the transportation distance depends on the face length. Dozers' performances are shown in Table 6-16.

Table 6-16 Dozers' performance (Amandebult report, 2024)

Dozer	Time spent in mine	Cleaned panels
D009	March 2023 – End of 2023	572
D010	January 2022 – March 2023	23
	May 2023 - End of 2023	428

Table 6-17 shows Dozer's availability and utilization.

Table 6-17 Dozer's availability and utilization (Amandebult report, 2024)

	D009	**D010**
Availability	80,84%	55,42%
Utilization	32,79%	11,91%

Table 6-18 shows what affected Dozer's utilization.

Table 6-18 Activities that affected Dozer's utilization (Amandebult report, 2024)

	D009	**D010**
Standby	52,91%	45,03%
Breakdown	16,31%	32,78%
Service	3,54%	1,98%
Production delays	0,94%	1,08%
Maintenance	1,16%	1,81%
Other	25,14%	17,32

6.2.3. Amandebult NRE Support Rigs

Three Support Rigs were used during trial in Amandebult. Support Rig 003 and Support Rig 004 are currently in use. Support Rig 005 was sent for refurbishment. Table 6-19 presents time spent in the mine and how many bolts were installed with each Support Rig.

Table 6-19 Drill Rigs performance (Amandebult report, 2024)

Machine	Time spent in mine	Installed bolts
Support 003	April 2022 – July 2023	400
	September 2023 - End 2023	13
Support Rig 004	January 2022 – March 2022	119
	June 2023 – End 2023	590
Support Rig 005	March 2022 – End of 2022	540

Table 6-20 shows availability and utilization for SR003 and SR004 in 2023. SR005 was in mine until May 2023, but none of the bolts weren't installed in 2023.

Table 6-20 Support Rigs availability and utilization (Amandebult report, 2024)

	SR003	**SR004**
Availability	57,17%	59,30%
Utilization	5,57%	6,93%

Table 6-21 shows what affected Support Rigs utilization.

Table 6-21 Activities that affected Support Rigs utilization (Amandebult report, 2024)

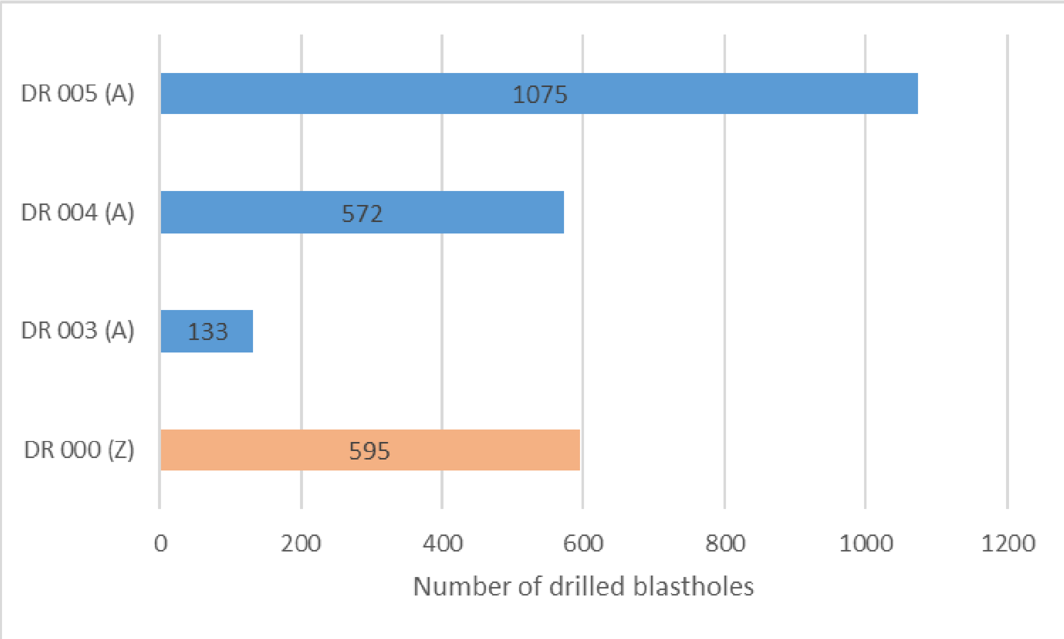
	SR003	**SR004**
Standby	51,45%	44,91%
Breakdown	42,08%	26,62%
Service	2,47%	3,86%
Production delays	1,13%	2,28%
Maintenance	2,23%	1,41%
Other	/	20,91%

7. ANALYSIS AND DISSCUSSION

Although the data collection and the level of information are different at Zimplats and the Amandebult mine, the test period was long enough to compare and analyze the data. However, the data from Zimplats is better, more numerous and more detailed, while the data for Amandebult is more general and collected monthly. The data comparison was carried out separately for each machine.

7.1. NRE Drill Rig results analysis and discussion

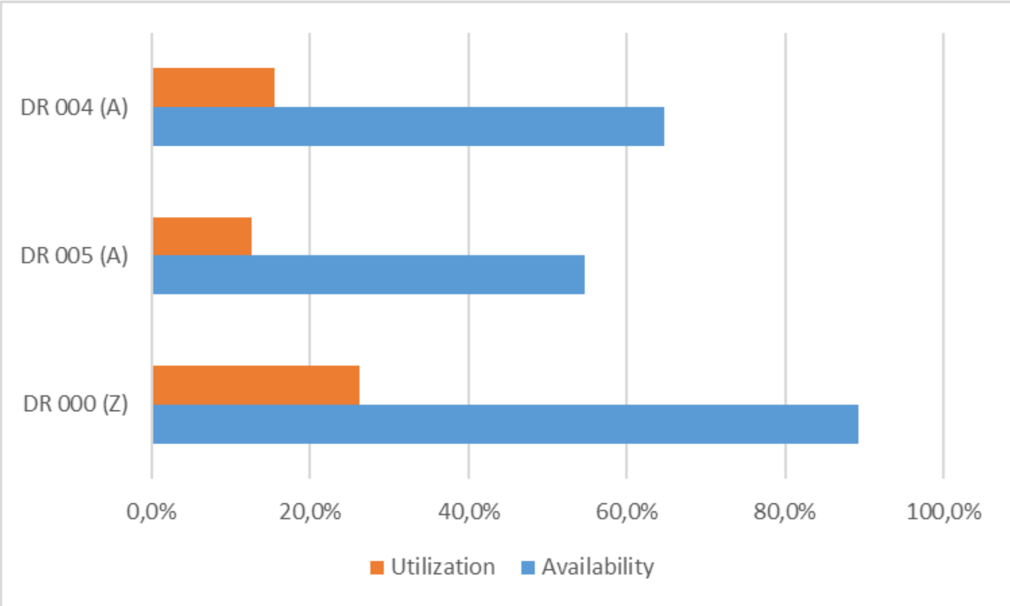
In Zimplats only one drill rig was on site. Total number of drilled holes during the period was 9514 and number of holes per month varies from 42 up to 1270 and time per one hole varies from 2,7 min up to 5,5 min, In Amandebult tree different drill rigs were working and drilled altogether 34301 boreholes. Average number of drilled boreholes per month for each drill rig is shown on figure 7-1.



DR 005 (A)- Drill Rig 005 in Amandebult
DR 004 (A)- Drill Rig 004 in Amandebult
DR 003 (A)- Drill Rig 003 in Amandebult
DR 000 (Z)- Drill Rig 005 in Zimplats

Figure 7-1 Average number of drilled blastholes per month

It can be seen that highest number of drilled boreholes is DR 0005 in Amandebult, and it is almost double the number of holes in Zimplats. The highest number of drilled holes we achieved in the last year of testing when operators became familiar with machines. Results in the first period of testing were not so good. Availability and utilization are calculated only for year 2023 which means that DR 003 is not taken into consideration. Comparison of results is shown on figure 7-2.



DR 005 (A)- Drill Rig 005 in Amandebult

DR 004 (A)- Drill Rig 004 in Amandebult

DR 000 (Z)- Drill Rig 005 in Zimplats

Figure 7-2 Availability and utilization of NRE Drill Rigs

It can be seen from figure 7-2 that availability and utilization is highest for DR 000 which worked on Zimplats mine and achieved similar results as DR 004 which have much less availability and utilization. The reason for the reduced efficiency lies in the choice of the appropriate mining method for the operation of the machine. The room and pillar method with short panel cause that very often only one borehole can be drilled instead of three boreholes at the same time. High numbers of drilled holes by Drill rig 004 and 005 in Amandebult were caused by simultaneously drilling with 3 drills in most drilling lines (all except first drilling line). That was possible because panels were 25 m to 30 m long, making them suitable for simultaneous drilling. Results clearly indicate that brest mining method is more appropriate for Drill Rig.

The most effective drill rig was DR 0005 with an average number of 1075 drilled bore holes per month, and lowest availability and utilization. The reason of increased efficiency can be that the DR 005 is the last machine that worked in the mine. DR 005 was installed in the mine in November 2022 almost one year after the testing started leading to conclusion that local operators gain sufficient skills for handling the machine.

The number of drilled holes can be increased if the panel time is prolonged. The panel time is the time when the machine is in front of the panel and ready for drilling.

Figure 7-3 shows time distribution of activities for Drill Rig in Zimplats mine. Drill Rig spent most time in mine procedure (39%), followed by face time (23%) and mine not ready (20%). It was mentioned in the report that a lot of time was lost for preparations and on waiting for water or electricity or for panels to be ready.

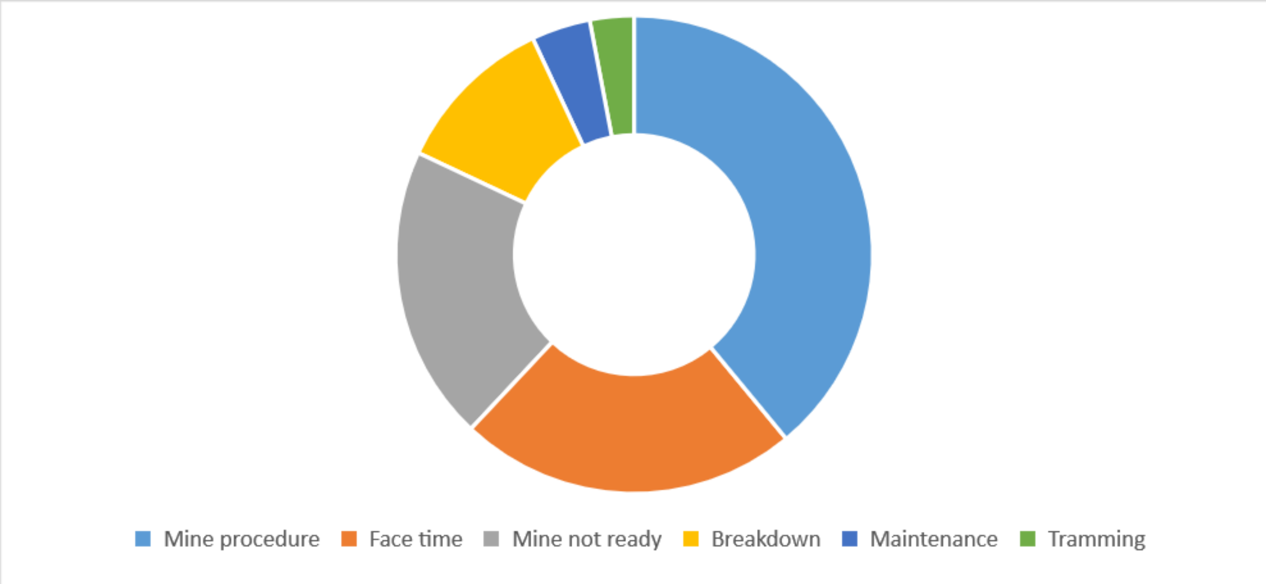


Figure 7-3 Time distribution of Drill Rig activities in Zimplats

Mine procedure includes safety talk, pre-checklist and risk assessment which takes about 1,5h per day. During that time machines are not able to drill. By rearranging shift schedules machines can spend more time on the face and drill more boreholes. Data how the time when the mine was not ready and time, we decreased safety talk by 45 minutes influence on number of drilled blast hole per shift is shown on figure 7-4.

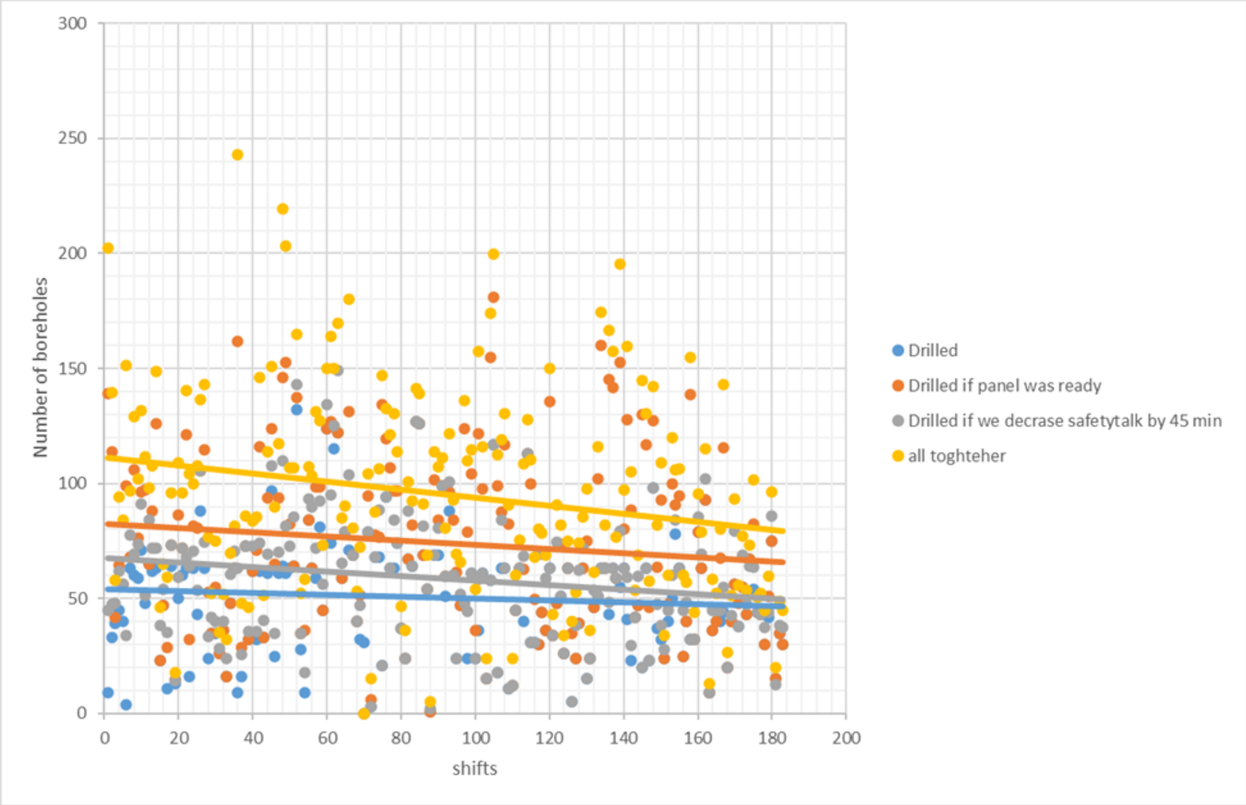
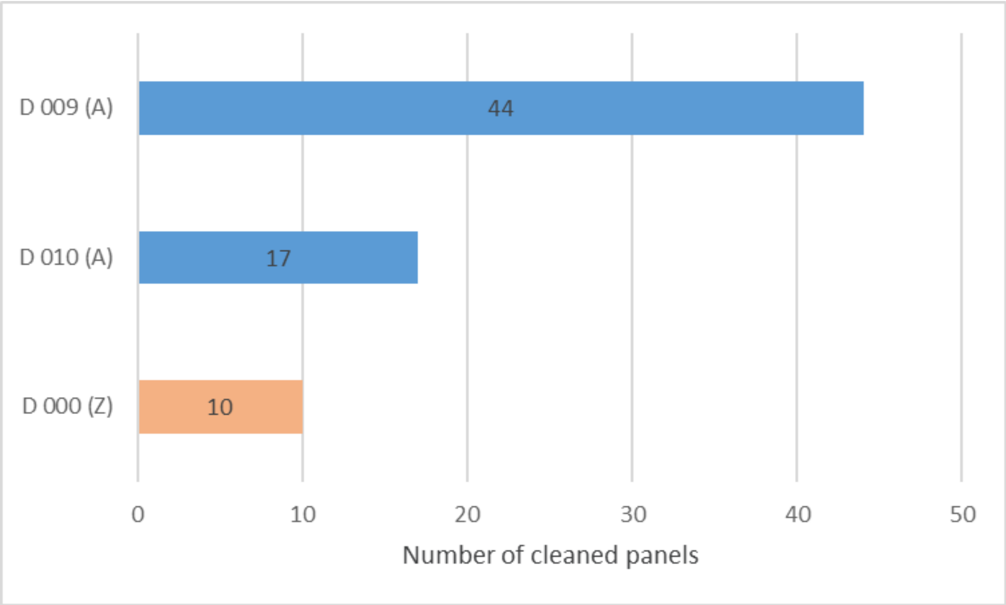


Figure 7-4 Influence of optimizing mining work and time shift on number of drilled blastholes

Data can be only calculated for Zimaplats trial tests where we have high level of data per shift collected. Unfortunately, the same calculation for Amandebult is not possible.

7.2. NRE Dozer results analysis and discussion

In Zimplats only one dozer worked on site. Total number of cleaned panels during the period was 155 and number of cleaned panels per month varies from 0 to 22 and time per one panel varies from 180 min up to 900 min. In Amandebult two different dozers were working and cleaned altogether 1023 panels. The average number of cleaned panels per month for each dozer is shown on figure 7-5.



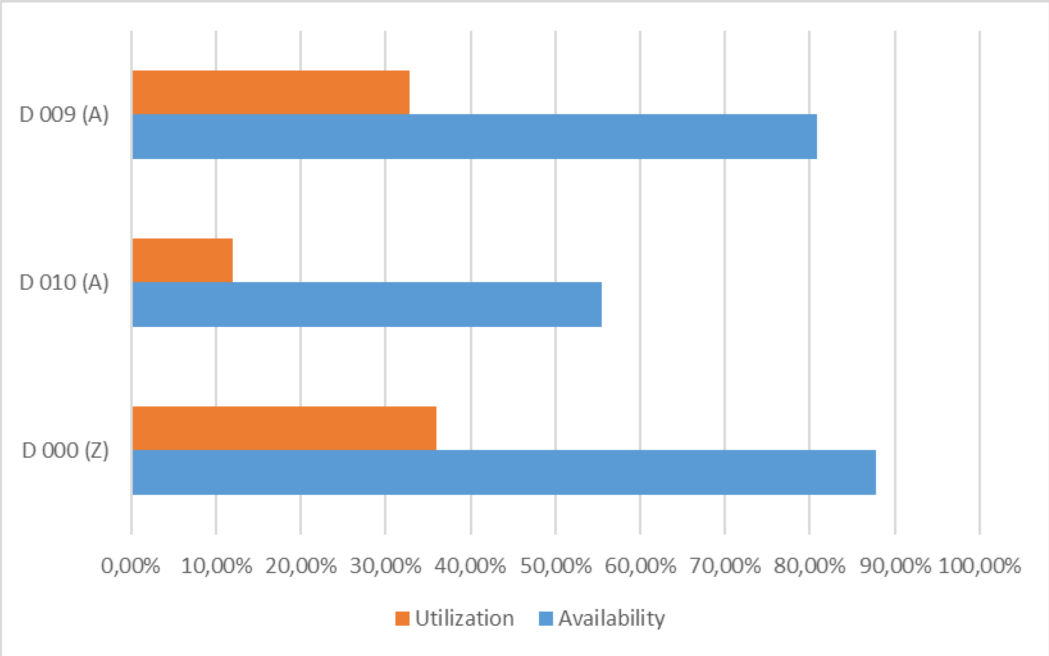
D 009 (A)- Dozer 009 in Amandebult

D 010 (A)- Dozer 010 in Amandebult

D 000 (Z)- Dozer 000 in Zimplats

Figure 7-5 Average number of cleaned panels per month

It can be seen that the highest number of cleaned panels is accomplished by D 009 in Amandebult, and it is around four times the number of panels in Zimplats. Results in the first period of testing were not well but have gotten better over time. Availability and utilization are calculated only for all tree dozers. Comparison of results is shown on figure 7-6.



D 009 (A)- Dozer 009 in Amandebult

D 010 (A)- Dozer 010 in Amandebult

D 000 (Z)- Dozer 000 in Zimplats

Figure 7-6 Availability and utilization of NRE Dozers

It can be seen from figure 7-6 that availability and utilization are highest for D 000 which worked on Zimplats mine and achieved similar results as D 009 which have slightly lower availability and almost the same but still a bit lower utilization. In Amandebult, dozer pushes down the dip into ASD which improved its results, while in Zimplats, ore had to be pulled more often and because the blade tool was designed to push, pulling increased the wear and tear of tool. Zimplat's mine layout was not suitable for NRE dozer.

The most effective dozer is D 009 with an average number of 44 cleaned panels per month.

Figure 7-7 shows time distribution of activities for Dozer in Zimplats mine. Dozer spent most time in mine procedure (45%), followed by face time (33%) and breakdown (12%).

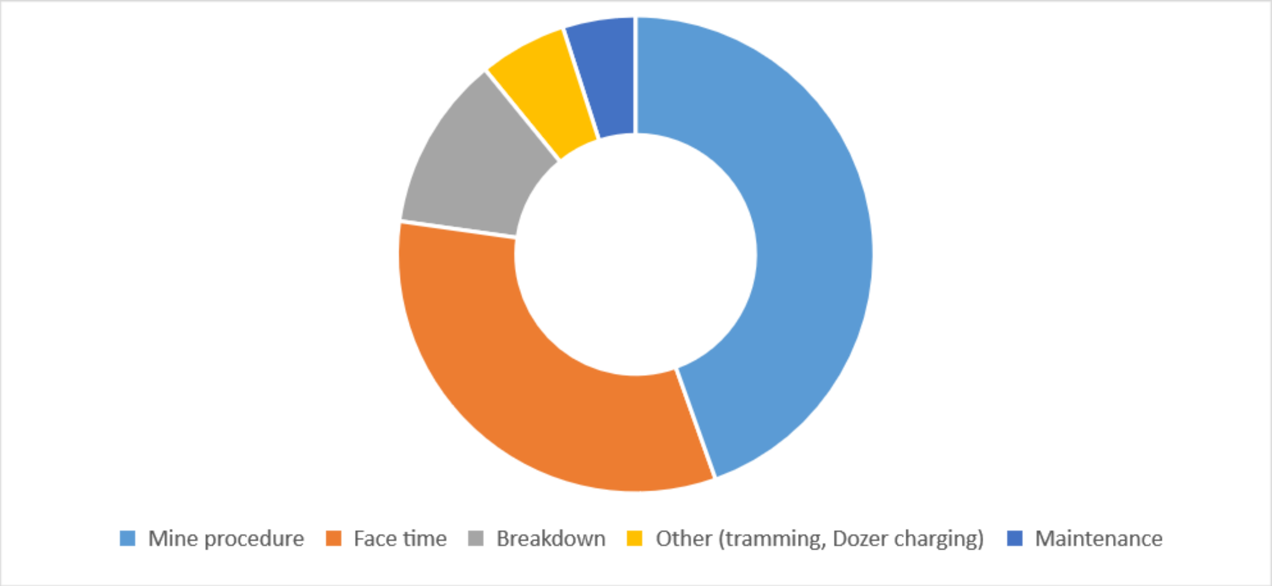


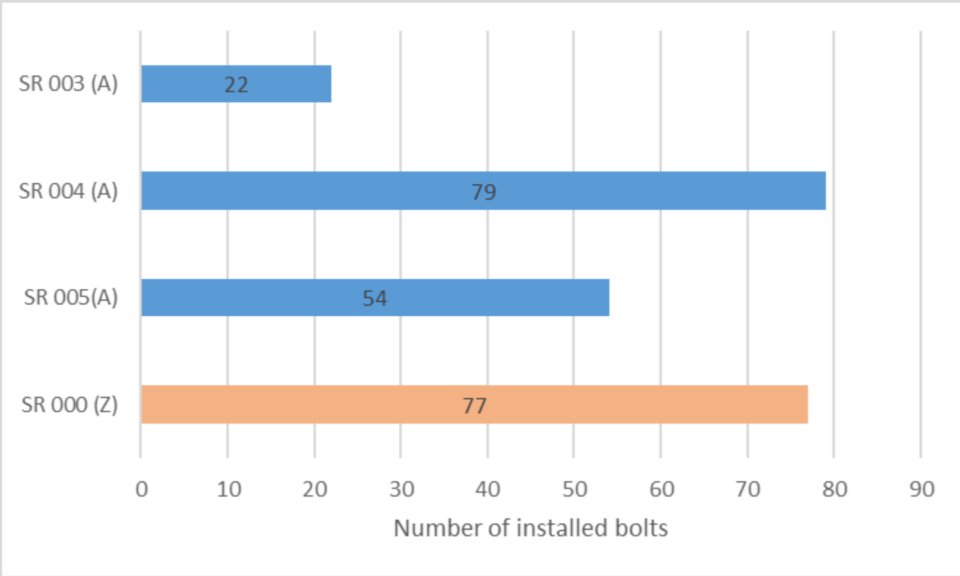
Figure 7-7 Time distribution of Dozer activities in Zimplats

Same as the previous case, the dozer method achieved better results in breast mining compared to the room and pillar layout. However, while the dozer D000 at Zimplats had the highest availability and utilization percentages, it did not achieve the highest number of cleaned panels.

The maximum number of panels cleaned per shift was two. The number of panels cleaned is closely connected to the performance of the drill rig. Unfortunately, if the drill rig experiences issues, the panels cannot be drilled and subsequently cannot be blasted, leaving no work for the dozer. This situation results in high availability for the dozer but low utilization.

7.3. NRE Support Rig results analysis and discussion

In Zimplats, as it was the case with NRE Drill Rig and NRE Dozer, just one support rig worked on site. Total number of installed bolts from both left and right tool during the period was 2314 and number of installed bolts per month varies from 0 to 182. In Amandebult three different support rigs were working and installed altogether 1662 bolts. The average number of installed bolts per month for each support rig is shown on figure 7-8.



SR 003 (A)- Support Rig 003 in Amandebult

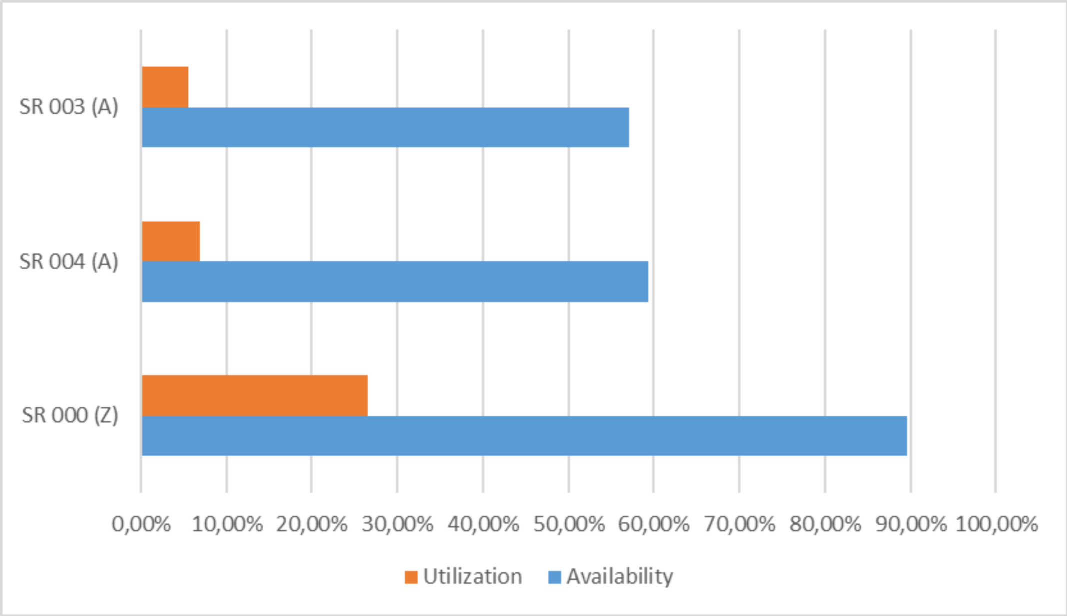
SR 004 (A)- Support Rig 004 in Amandebult

SR 005 (A)- Support Rig 005 in Amandebult

SR 000 (Z)- Support Rig 000 in Zimplats

Figure 7-8 Average number of installed bolts per month

Even though SR 004 installed the highest average number of bolts per months working, SR 000 in Zimplats installed the highest total number of bolts, 2314 as mentioned before. SR 004 slightly bigger average number of installed bolts can be explained by the fact that it worked nine months in total, installing 709 bolts, while SR 000 worked fifteen months. Availability and utilization are calculated only for all tree support rigs. SR 005 installed all its bolts in 2022, so availability and utilization are not calculated for it. Comparison of results is shown on figure 7-9.



SR 003 (A)- Support Rig 003 in Amandebult

SR 004 (A)- Support Rig 004 in Amandebult

SR 000 (Z)- Support Rig 000 in Zimplats

Figure 7-9 Availability and utilization of NRE Support Rigs

It can be seen from figure 7-9 that availability and utilization are highest for SR 000 which worked on Zimplats mine. In Amandebult, support rigs have similar availability and utilization. Zimplats support has better performance than support rigs in Amandebult due to improved machine design and better trained personnel in Mupani.

In Amandebult, both SR 003 and SR 004 worked on two occasions. SR 003 showed good results in the first period, installing 400 bolts, but disappointed in the second period, while SR 004 got way better results in the second trial period. The utilization of the support rig in this case was particularly disappointing, ranging between just 5.57% and 6.93%, which clearly indicates that the machine's performance needs to be significantly improved. These low utilization figures suggest that despite the machine's availability, it was not being put to effective use in terms of its core function, likely due to the operational issues tied to the drill rig and the general mining cycle.

Although the support rig was equipped with two units, one on the left and one on the right, for bolting operations, in most cases, only one of these units was operational at any given time. This limitation significantly impacted the rig's overall efficiency. Ideally, both units would work simultaneously to maximize productivity, but operational constraints or mechanical issues often left one unit idle.

The maximum number of bolts installed per unit was 25, and this was achieved only when a single unit was working on bolting. The fact that this number was reached with just one unit suggests that, under better conditions, the support rig had the potential to achieve much higher bolting rates if both units were functioning properly. The number of bolting per unit for shift for Zimplats is shown on figure 7-10.

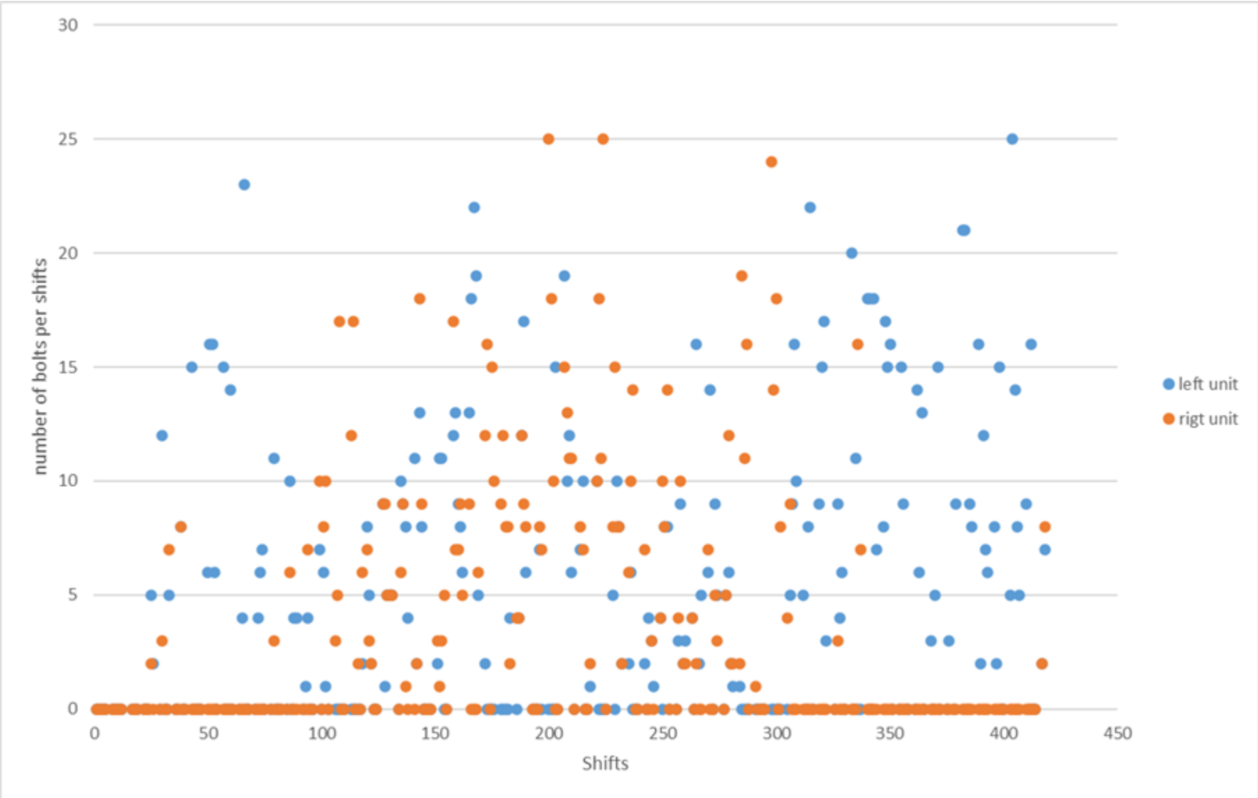


Figure 7-10 Number of bolts pert shifts in Zimplats

This underperformance ultimately led to the decision that the mine would discontinue the use of the support rig. When the support rig failed to operate efficiently—whether due to mechanical breakdowns or delays in drilling—the downstream operations, such as panel cleaning by the dozer, were directly impacted.

Figure 7-11 shows time distribution of activities for support rig in Zimplats mine. Support rig spent most time in mine procedure (37%), followed by face time (23%) and mine not ready (16%).

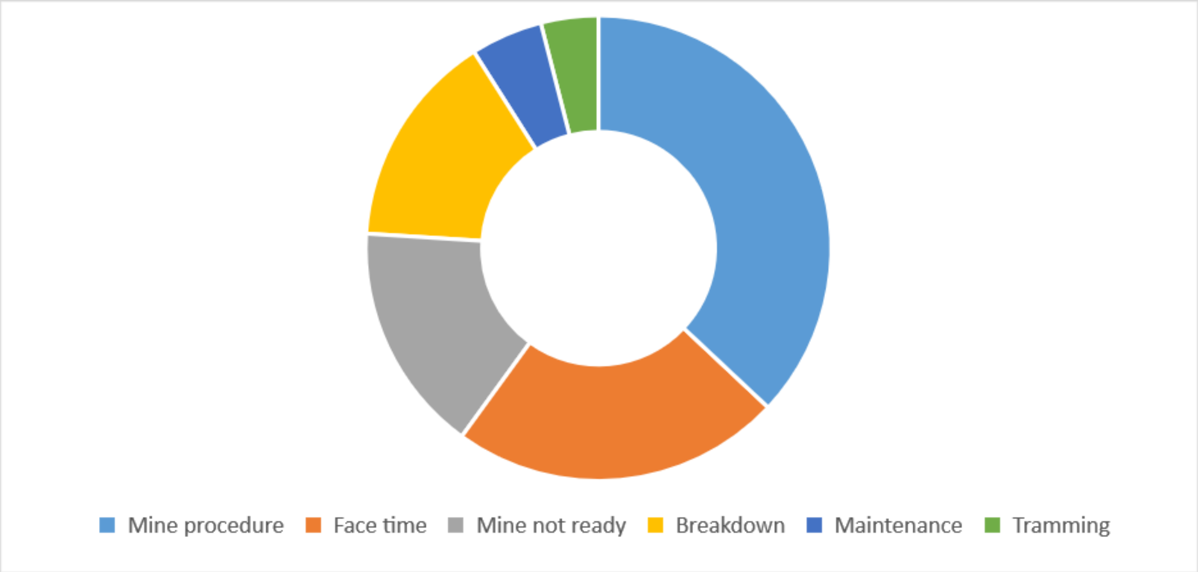


Figure 7-11 Time distribution of Support Rig activities in Zimplats

Mine not ready includes time for activities such as insufficient water pressure, charging interruption and when panel was not ready. Improving the support rig can increase panel time by optimizing mine activities and scheduling. Ensuring both bolting units work simultaneously and aligning tasks better would speed up panel preparation. This, in turn, allows the dozer to operate more efficiently, cleaning more panels per shift. Rearranging mine activities and improving scheduling would minimize downtime, ensuring smoother workflow and better equipment utilization.

8. CONCLUSION

The objective of this analysis is to provide insights into the overall performance of the NRE fleet during the production trial at Zimplats and Amandebult. This analysis serves as a foundational element in achieving the overarching goal of the development of a fully operational prototype of the NRE Fleet. The successful application of mechanized mining in narrow reef platinum deposits is a complex challenge due to the unique characteristics of these deposits. However, with the right machines, suitable mining layout and highly skilled and motivated miners, it is possible to effectively mine narrow reef PGE deposits. the conclusions are in line with the hypotheses of the work presented earlier. The test results have clearly demonstrated that breast mining is a more effective method compared to the room and pillar layout in narrow reef mining. Both the drill rig and the dozer showed significantly higher performance and productivity under the breast mining method during the Amandebult trial tests. This conclusion is also consistent with previous tests conducted using XLP (Extra Low Profile) and ULP (Ultra Low Profile) equipment. In earlier studies, both XLP and ULP machinery demonstrated enhanced efficiency and effectiveness when utilized in breast mining layout. The length of the panels has a significant impact on the performance of the Drill Rig. Longer panels allow the Drill Rig to operate more continuously without frequent repositioning, reducing downtime and increasing drilling efficiency. This leads to higher productivity as the rig can drill more holes in a single setup. The breast mining layout, where the Dozer pushes material down the dip into the Advanced Strike Drive (ASD), significantly enhances the Dozer's performance. This method allows the Dozer to take advantage of gravity, making the material handling process more efficient and reducing the energy required to move the ore. In narrow reef (NRE) mining, the support rig is often considered a bottleneck and the same is concluded during the trial testing of NRE Fleet. Although the support rig performed slightly worse results in breast mining, the primary reason for this is not the mining layout itself, but rather the current capabilities and maintenance status of the machine. Results from Zimplats indicate that the number of bolters can be increased if both units can operate simultaneously at maximum capacity. Currently, only one unit can work at full capacity at a time. The testing of the NRE fleet in Amandebult shows that machines, especially Support Rig, need to be more serviceable and better maintained. The training practices for mine staff should be improved and updated with every new modification which is made on the machine.

During the trial in Zimplats it became evident that with improved mine procedures aimed at achieving six hours of face time each machine's performance could double. Rearranging shift schedules and reducing safety talk time could increase drilling productivity by allowing machines to spend more time at the face, potentially leading to a higher number of blast holes drilled per shift. This will lead to more panels being blasted and cleaned, increasing both the workload for the dozer and overall productivity. Enhancing the NRE fleet and the mine procedures, as well as adjusting the mine planning to accommodate the characteristics of the NRE fleet, holds promise for optimizing the overall production.

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