UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

IMPACT OF SECONDARY ROCK-BREAKING EQUIPMENT AVAILABILITY ON MINING PLAN IN BLOCK CAVE MINING

Martin Sphiwe Nyarela

(2402607)

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DECLARATION

I declare that this report is my own, unaided work. I have read the University Policy on Plagiarism and hereby confirm that no plagiarism exists in this report. I also confirm that there is no copying nor is there any copyright infringement. I willingly submit to any investigation in this regard by the School of Mining Engineering and I undertake to abide by the decision of any such investigation.

________________________________ 23 August 2024

Signature of Candidate Date

ACKNOWLEDGMENT

I would like to express my gratitude to my Lord and Saviour Jesus Christ for the wisdom, persistence and ability to carry out this research. *"Now unto the King eternal, immortal, invisible, the only wise God, be honour and glory for ever and ever. Amen"*- 1 Timothy 1:17 (KJV).

I dedicate this research to my late Mother, Xolelwa Evelyn Nyarela, who taught me patience, endurance, love, and dedication. May her soul rest in peace. To my wife Mpho Nyarela, and my two sons Ntsako and Tshiamo, thank you for the support and love.

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ABSTRACT

Block caving is one of the massive mining methods that has become increasingly popular due to its low operating cost, improved safety, and high production output. The low operational cost is attributable to minimal blasting, which is only focused on secondary rock-breaking activities. Once caved, the material flows continually and is loaded from the drawpoint to the tipping areas using LHDs and other means, such as scraper winches. Different rock fragmentations register in the drawpoint as loading continues. The sizes range from fine to medium fragmentation and the undesirable oversized rocks that cause hang-ups and blockages.

Blockages and hang-ups disturb the flow of material, which negatively impacts compliance with the mining plan and draw control schedule. The hang-ups are treated with secondary rock-breaking equipment to make drawpoints available for loading. However, if the mechanical availability of rock-breaking equipment is low, drawpoints remain idle beyond acceptable limits. Additionally, factors such as the availability of experienced miners to address challenging hang-ups, in instances where treated hang-ups remain unresolved as a result of treatment failure, and the prioritisation of adjacent draw points for loading to restore macro material flow, especially in cases of high hang-ups, can significantly contribute to longer idle periods as well. In this regard, this research aimed to understand the impact that secondary rock-breaking equipment has on the mining plan at the PMC block cave.

The research conducted an empirical study of the Secondary Breaking Unit, which forms part of the Mining Operations responsible for all secondary rock-breaking activities at the Palabora Mining Company (PMC). The secondary rock-breaking equipment types that this study investigated include the Medium Reach Rigs, Water Cannons, and Mobile Rock-Breakers. A 52-week data obtained from PMC was used for this study, covering

the period from January to December 2021. The data pertain to secondary rock-breaking equipment availability and utilisation, cave availability, loading compliance, downtime contribution factors, and in-situ grade.

The correlation and regression analysis methods were used for the analyses of data to answer the research questions. In this study, the copper content derived from the mined tonnes and in-situ grade was used as a proxy for the mining plan and it excludes uncontrollable factors such as recovery, pricing, and exchange rates. Firstly, the study sought to determine whether the PMC's Lift 1 block cave is behaving as predicted and it was concluded that it is. Secondly, the study sought to determine if there is a relationship between the mining plan, using the deviation from the mining plan, and cave availability and loading compliance respectively. It was established that the correlation between the deviation from the mining plan and cave availability was not strong enough whereas the correlation between the deviation from the mining plan and loading compliance was strong enough to derive a predictive equation which was validated.

Thirdly, the research sought to establish the minimum acceptable rock-breaking equipment availability at PMC. It was found that the minimum acceptable availability was cautiously 60% based on the historical data. Fourthly, the research sought to determine the research strategy that can improve the rock-breaking equipment availability from the low of 42% in 2021 to at least 60%. The mine's target availability is 65%. To achieve this, categories of downtime for MRR, MBR and WC with high impact were identified using the Pareto principle. The maintenance overrun downtime category which was one of those with a high-impact downtime was found to be common in all three equipment types with a combined duration of 10 695 hours or 44.4 days per operational equipment per year. In this regard, the Schedule Maintenance strategy was suggested.

Keywords:

Block caving, Secondary rock-breaking equipment, Hang-up, Mining plan, Draw control, Availability

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Definition / Meaning
CAv	Cave availability
Cor (r)	Correlation coefficient
Dtp	Deviation to plan
LHD	Load Haul Dumper
LoM	Life of Mine
MRB	Mobile Rock Breaker
MRR	Medium Reach Rigs.
OEE	Overall equipment effectiveness (OEE)
PCBC	Personal Computer Block Cave
PIC	Palabora Igneous Complex
PMC	Palabora Mining Company
SBU	Secondary breaking unit
TMM	Trackless Mobile Machine
tpd	Tonnes per day
TPM	Total Productive Maintenance
tpm	Tonnes per month
tpw	Tonnes per week
WC	Water cannons
XCUT	Crosscut

LIST OF DEFINITIONS

Term	Definition / Meaning
Block caving	**A massive mining method involving the undermining of the mineral deposit, with high reliance on gravity to fragment the rocks to manageable sizes, usually from the bottom of a previously mined-out open pit, using LHDs and other loading equipment**
Blockage or Hang-up	**An obstruction of the flow of rock in a rock pass or drawpoint**
Cave availability	**It is defined as a measure of the number of drawpoints available against the total number of drawpoints**
Cave Management	**Systems in place to manage the loading schedules, equipment allocation, and reporting**
Drawbell	**Openings between the undercut and production, through which drawpoint are developed**
Draw control	**Control measures to ensure that correct areas are loaded to minimise high waste ingress, grade control, and reduce potential impacts from rockmass over and under-loading of drawpoints**
Drawpoint	**A point where caved material is loaded in block caving**
Preferential drawing	**Preference by operators to load areas of convenience**
Yield	**Tonnages recovered before a hang-up occurs**

1. INTRODUCTION

1.1 Introduction

Mining is an essential contributor and backbone to economies of resource countries and is defined as the process of extracting mineral deposits from the ground using different mining methods (Silva et al. 2017, Pretty & Odeku 2017, and Mabey et al. 2020). To this effect, the mining industry plays a crucial role through tax contributions, employment opportunities, skills development, and investment programmes for the sustainability of local economies (Brew et al., 2015).

The process of carrying out mining activities involves the application of different mining methods based on the accessibility to ore through surface and underground mining methods. The surface mining methods are used when the orebody outcrops or is economical to mine with surface mining methods, which are usually less capital-intensive compared to the underground mining methods. The underground mining methods require high capital to create access to the orebody through adits, shafts, and declines, the size of which depends on the equipment type used for rock, men and material transportation (Brazil et al., 2008).

Among the underground mining methods, block caving is one of the massive mining methods that has become increasingly popular due to its low operating cost which is approximately 10% of what other underground mining methods cost (Scales, 2018). The advantages of the block cave mining method include the capability for high production and extraction of low-grade orebodies. However, the disadvantages involve high upfront capital expenditure and lack of flexibility to combat the potential negative impacts of high dilution (Vyazmensky et al. 2009, and Li et al. 2014).

The extraction of the mineral deposit in block caving is achieved by first initiating an undercut by means of long-hole drilling and blasting fan-shaped or crinkle rings to fragment the rock and allow material to cave (Moss et al. 2006 and Scales 2018). As caving is initiated, the fragmented rocks are loaded from drawpoints, which are connected to the caved material through drawbells. On surface, the hoisted ore is then sent to the processing plant through a series of belt conveyors.

In mining, rock-breaking is the preferred means to break the in-situ rock (Phamotse & Nhleko 2019, and Gomez et al. 2021). There are three categories of rock-breaking, which are natural, primary, and secondary rock-breaking (Gomez et al., 2021). The natural category is reliant on the force of gravity to fragment the rock (Li et al., 2014). On the other hand, both the primary and secondary categories largely involve drilling and blasting activities to fragment the rock through manual or mechanical techniques (Gomez et al., 2021). The main method of fragmentation in block caving is natural rock-breaking with secondary rock-breaking being used in cases where there are large boulders in and around the drawpoint.

When loading from drawpoints, different rock sizes can be expected; with sizes ranging from fines to coarse material, as shown in Table 1.1. Fines to intermediate fragmentation sizes range from anything below 5 cm^3 to 1 m^3, whereas the large to oversize rocks could reach up to 2 m^3.

Table 1.1: Fragmentation sizes (PalaboraMiningCompany, 2015)

Fragmentation type	Size
Fines	Less than 5 cm^3
Small	5 cm^3 – 20 cm^3
Intermediate	20 cm^3 – 1 m^3
Large	1 m^3 – 2 m^3
Oversize	Greater than 2 m^3

1.1.1 Fragmentation in block caving

When drilling and blasting rocks, the aim is to reduce large-size rocks to mineable sizes that can be handled with ease during loading, conveying, hoisting, and crushing (Xingwana, 2016). Blasting yields different rock fragments, due to many factors involved such as the type of explosive used, rock properties and geology, drilling pattern, and charging practice (Xingwana, 2016). Fragmentation is crucial in block caving, it has to be planned for (Ngidi & Pretorius, 2010).

Poor fragmentation leads to the high susceptibility of hang-up formation in block caving. When hang-ups are present because of poor fragmentation, the drawpoint availability is reduced, which negatively impacts production rates (Ngidi & Pretorius, 2010 and Garcés et al., 2020).

The Block Cave Fragmentation (BCF) model at Palabora Mining Company (PMC) predicted that 75% of the rocks would be above 2 m^3 at the beginning of caving and contribute close to 80% of the total production in 2002. The model further predicted that with time, the percentage of oversized rocks in relation to the run-of-mine ore would reduce. In the study conducted at PMC by Ngidi & Pretorius (2010), it was revealed that oversized rocks contributed only 30% of total ore produced in 2002 and that a higher percentage of ore drawn from the cave was from the centre of the block and it was fine. Figure 1.1 shows the production of oversized rocks from the cave and interestingly, the number of oversized rocks as a percentage of the run of mine appeared to trend upward from the minimum in 2006.

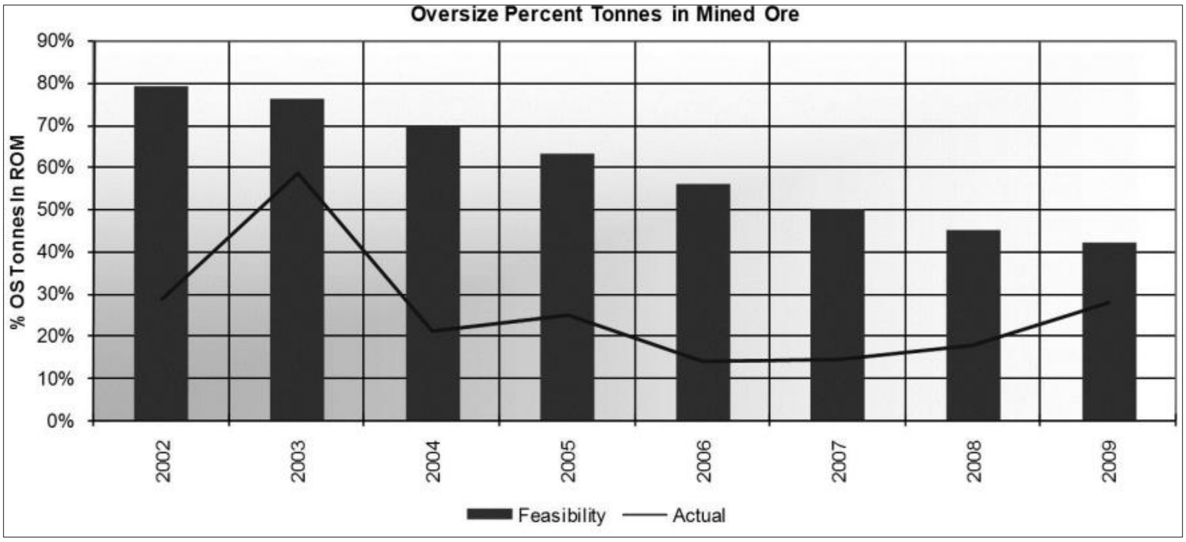

Figure 1.1: Oversize contribution to tonnes from 2002 till 2009 (Ngidi & Pretorius, 2010)

1.1.2 Definition of hang-ups and blockages

For a block cave mine, having coarser material reporting in the drawpoint leads to a high likelihood of hang-ups forming. Hang-ups are restrictions in drawpoints that occur as a result of coarse rocks preventing material flow and are a factor of poorly fragmented rock relative to the size of the drawpoint. There are different types of hang-ups ranging from partial to total restriction, and high hang-up, as shown in Figure 1.2. Hang-ups disturb the flow of material, thus resulting in the production and mining plan disturbance. In addition to hang-ups, mines can also experience drawpoint blockages due to large and oversized rocks that have dropped down to the mouth of the drawpoint thereby trapping behind correctly fragmented rocks.

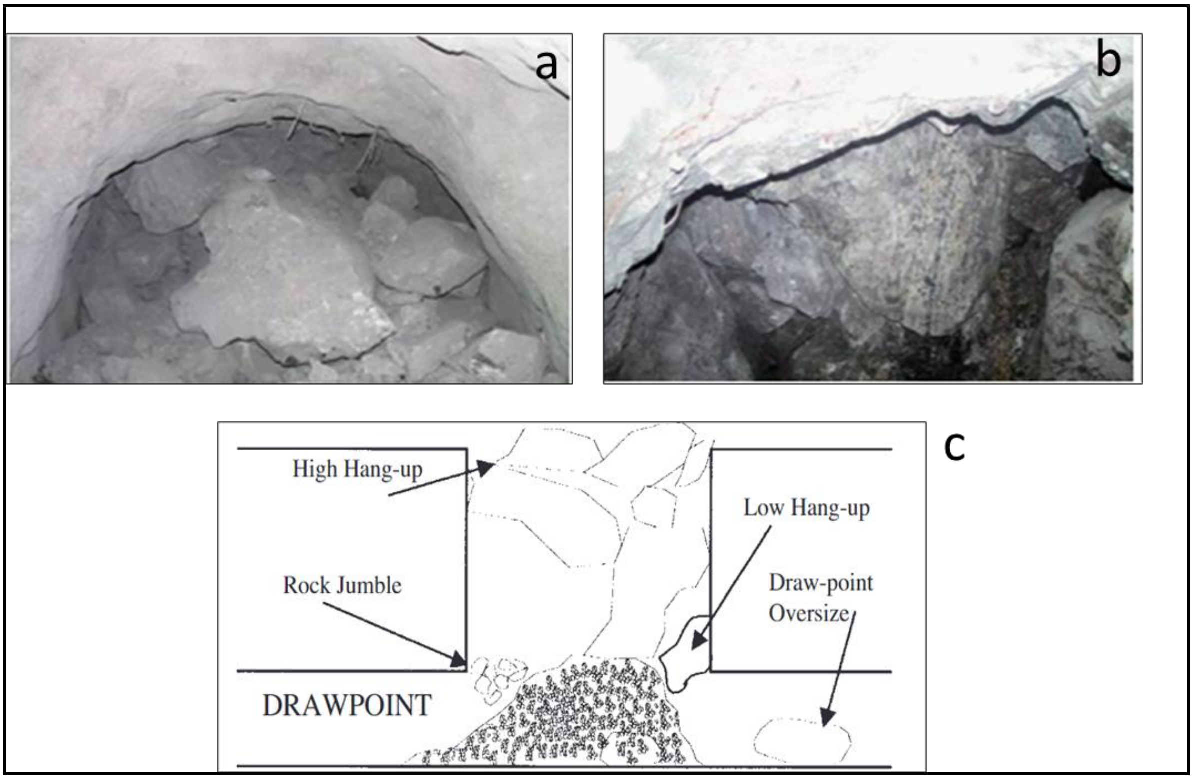

Figure 1.2: Partial hang-up (a), total blockage hang-up (b), and high hang-up (c) (PalaboraMiningCompany, 2015 and Hull, 2002)

According to Penswick (1997), the expectation during caving is that some rock sizes will be coarser at 9 m above the drawpoint floor, which will require the deployment of secondary rock-breaking equipment to reduce the fragmentation to a size range that can be loaded by an LHD, as shown in Figure 1.3.

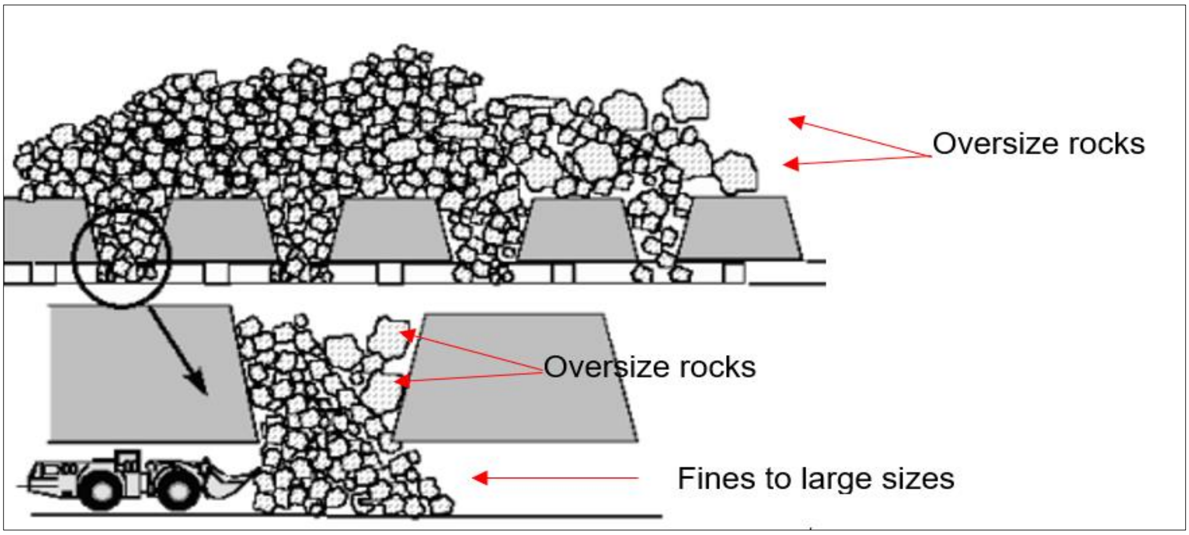

Figure 1.3: LHD hauling rock from a drawpoint (Penswick, 1997)

When hang-ups occur, the secondary rock-breaking equipment is deployed to ensure adherence to the draw control plan by opening idling draw-points due to hang-ups and blockages, which enables ease of loading through the reduction of oversize rocks *(PalaboraMiningCompany, 2015).* Figure 1.4 shows the distribution of different rock sizes that drop into drawpoints when loading. Sizes range from fines to oversize, which can be as low as 5 cm^3 for fines to greater than 2 m^3 for oversize rocks.

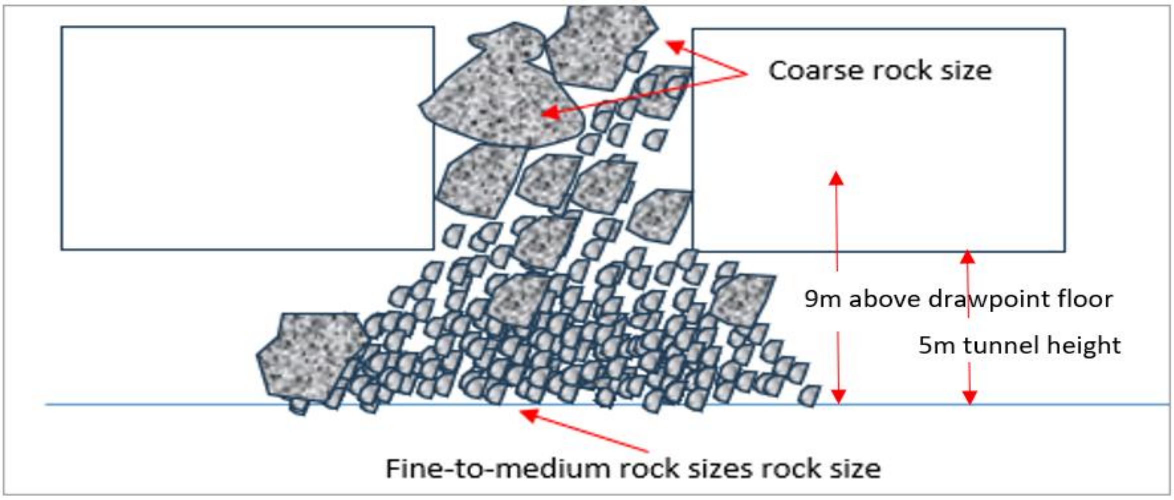

Figure 1.4: Different rock sizes produced during natural caving

1.1.3 Process of treating hang-ups

The treatment of hang-ups is sometimes a process that requires repetitive tasks (Shekhar et al., 2018). Different hang-ups, including partial, total blockage, and high hang-ups require different methods of treatment (Penswick 1997, Ngidi & Pretorius 2010, Shekhar et al. 2018, and Garcés et al. 2020). Bringing down a partial and low hang-up can be done by placing explosives on the weaker side of the hang-up, and at times, it may be brought down by the LHD operator trickling the muckpile (Shekhar et al., 2018). A partial hang-up can be brought down using a water cannon (WC) (Ngidi & Pretorius, 2010).

The total blockage and high hang-ups are different in that the LHD operator cannot recover them, nor is the placement of concussion bags possible, but other means, such as a medium reach rig (MRR) may be used to drill holes into the stable rock in the hang-ups (Penswick 1997, Ngidi & Pretorius 2010, Shekhar et al. 2018, and Garcés et al. 2020). The process of bringing down a hang-up begins first by ensuring that the drawpoint is stabilised using WC, and then, once it is confirmed that the drilling collar is stable, drilling with an MRR can commence. The hang-up treatment is complex, and at times, does not come down after the first treatment but may require the process to be repeated several times (Shekhar et al., 2018).

When a high hang-up comes down, it may also come with large boulders, which are further treated using a mobile rock breaker (MRB) (Shekhar et al., 2018). Until such time that the drawpoint is handed back to production for loading after hang-up treatment, such drawpoint will remain unavailable. The typical trackless mobile machines (TMM) for secondary rock-breaking activities are shown in Figure 1.5.

Figure 1.5: Mobile rock breaker hammering boulders (a), water cannon treating a hang-up underground (b), and a new medium reach rig at the workshop (c) (PalaboraMiningCompany, 2015)

1.1.4 Draw control in block caving

The two aspects that are critical in block caving, when it is in production, are stress management and minimisation of dilution (Heslop, 2010). Both factors influence the optimal cave operation. When drawing from drawpoints, strict adherence to the loading plan is critical to mitigate challenges related to stress buildup at the production level and early dilution entry (Nezhadshahmohammad & Pourrahimian, 2017). The scheduling of draw columns should be timed in such a way that all aspects that could potentially impact the optimal cave operation are closely monitored, particularly, loading compliance.

It is pivotal that loading is closely monitored by making use of draw control protocols, which Nezhadshahmohammad & Pourrahimian (2017) suggest that they should factor and control all the limitations to achieve the desired mining targets. Some of the limitations to production scheduling involve the presence of hang-ups and blockages that reduce the availability of drawpoints for loading. Hang-ups disturb the flow of material in the drawpoint and often come with cost implications (Castro & Cuello 2018 and Garcés et al. 2020).

Adherence to a draw control plan ensures minimal damage to pillars due to stress build-up resulting from uneven draw. To achieve an effective draw, there has to be an optimal use of secondary rock-breaking equipment to limit stress build-up at the production level and to minimise dilution (Nezhadshahmohammad & Pourrahimian, 2017).

There are three levels of mine planning, that is, short, medium, and long-term plans. According to Kloppers et al. (2015), the three levels of mine planning are integrated, which means one level influences the others and therefore any draw control objective and optimisation effort should not only consider one mine planning level but all three simultaneously. Nezhadshahmohammad & Pourrahimian (2017) suggested that the draw control in mine planning should seek to achieve the following:

- Minimisation of waste ingress;
- Setting draw rates for cave propagation thereby preventing chimneying, and controlling mudflows or mudrushes in areas where breakthrough has occurred;
- Prevention of point loading on pillars (excess stress on pillars due to columns not drawn); and

- Prevention of operator preferential draw by setting minimum and maximum draw rates per drawpoint.

Given the above, it is critical to address hang-ups and blockages on time to ensure the high availability of drawpoints. In this regard, secondary rock-breaking equipment is essential in the timely treatment of hang-ups and blockages (Ngidi & Pretorius, 2010).

1.2 The Research Purpose

The modern mining of mineral deposits is complex, it involves using different mining methods to gain access to the deposits and employing sophisticated equipment capable of achieving significant performance compared to the traditional methods. Mining exists to maximise value for its shareholders (Hall, 2009). Thus, when an investment is made to purchase new machines, they are expected to yield the required results, subject to their reliability, availability, and utilisation. The same notion applies to secondary rock-breaking equipment which should be capable of maintaining high cave availability when hang-ups and blockages occur.

The secondary rock-breaking equipment availability levels have been low at Lift 1 PMC, thus this has raised concerns about the potential impact on the mining plan. At PMC, the secondary rock-breaking equipment is managed by the Secondary Breaking Unit (SBU). The key focus of the study is on the current MRB, WC and MRR and their ability to deal with the high incidents of drawpoint hang-ups and blockages. The treatment of hang-ups is a critical factor in ensuring high cave availability. Thus, it is the purpose of this study to investigate how the deployment of the secondary rock-breaking equipment and their availability levels impact the mining plan at the PMC's Lift 1 block cave.

1.3 Research Background/Context

1.3.1 The location of PMC and background

The research was carried out at PMC, located approximately 500 km from Johannesburg and approximately 3 km from the town of Phalaborwa in the Limpopo Province in South Africa (see Figure 1.6). The main mineral at PMC is copper, mined using block cave mining method and the secondary mineral is vermiculite, mined from a shallow open pit. The other minerals recovered at PMC are copper by-products such as magnetite and nickel.

Figure 1.6: Palabora Mining Company locality plan (Southwood & Cairncross, 2017)

The PMC block cave was designed to produce 30 000 tonnes per day at an average grade of 0.68 %Cu from 20 crosscuts with a total of 332 drawpoints (Ngidi & Pretorius, 2010). During the design, it was expected that 50% of block cave output would be coarse fragmentation that required the use of secondary rock-breaking equipment to achieve daily targets (Penswick, 1997).

Currently, there are two primary blocks, namely Lift 1, which is the active block, and Lift 2, where development activities are in progress. Lift 1 commenced the undercut using the diamond shape profile initiated from the centre and extended outwardly towards the North, South, West, and East, as part of its undercutting strategy. The diamond shape was intended to provide flexibility and overcome geotechnical challenges during caving, such that drawpoints do not remain idle for extended periods but trickled for an even draw until a breakthrough.

However, the strategy led to several challenges, such as the central part of the cave maturing quicker than the Eastern and Western sectors, thus leading to high susceptible levels of hang-ups in the outer sectors and the subsequent need to deploy additional resources for recovering hang-ups and blockages. Figure 1.7 shows the production level of the Lift 1 mining block, which is divided into four sectors, each with a set of five crosscuts and one crusher each. Sector 1 covers crosscuts 1 to 5, Sector 2 covers crosscuts 6 to 10, Sector 3 covers crosscuts 11 to 15, and Sector 4, covers crosscuts 16 to 20.

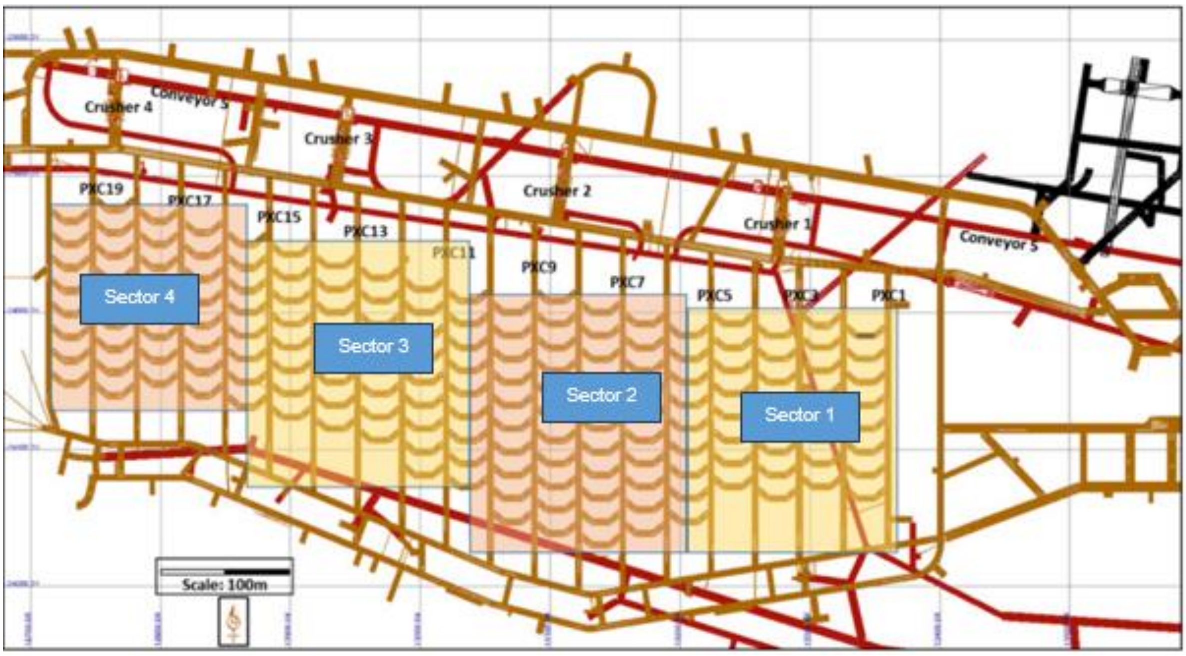

Figure 1.7: Lift 1 production footprint (PalaboraMiningCompany, 2015)

The Lift 1 mining block was designed to be mined using 17 LHDs that load from drawpoints to the crushers. The LHDs have a bucket factor of 12 tonnes and are manually operated, with an installed dispatch system for loading different sectors. Some sectors contain high grades and low dilution such as Sectors 1 and 4. However, these sectors are prone to many hang-ups. Sectors 2 and 3 have minimal hang-ups but the dilution is high, with increased fines due to the central initiation during the commencement of the undercutting.

1.3.2 The research context

Due to the undercutting strategy to initiate centrally, Sectors 1 and 4 have not fully matured, meaning that there is still a high number of oversized rocks blocking the drawpoints, thus limiting the number of available drawpoints for loading. Although the secondary rock-breaking equipment is deployed to recover hang-ups through drilling and blasting, the equipment availability levels are low, thus more drawpoints remain idle. This problem affects the extraction sequencing and loading. As a result, whenever the mine experiences hang-ups, LHDs are not allocated targets for that specific drawpoint, thus impacting the planned depletion schedule (mine plan).

1.4 Research Motivation

Secondary rock-breaking machines have exceeded their lifespan at PMC and their availability levels have constantly been dropping. The mine management's strategy was to run the equipment to failure due to the justification that new equipment would be procured under the capital budget of Lift 2, the new mining block project (PalaboraMiningCompany, 2015). It was expected that Lift 2 would be completed in 2015, but to date, the mining of the Lift 1 block is still ongoing. There is also an increase in the number of drawpoints that remain idle for more than three days, putting constraints on the LHD loading schedule and achievement of the daily production targets.

With Lift 1 nearing depletion, strict adherence to loading schedules is critical to minimise dilution and ensure maximum ore recovery. With the rise in the number of drawpoints that have hang-ups, there is a need to understand how that impacts production targets, hence this research. Hang-ups at PMC are a mix of partial, total blockage, and high hang-ups (Penswick 1997 and Ngidi & Pretorius 2010).

The study by Ngidi & Boshoff (2007) suggested that secondary rock-breaking equipment should be prioritised in the western and eastern regions of the cave, due to poor fragmentation compared to the central region with fewer incidents of hang-ups.

1.5 Problem Statement

Mining is one of the crucial activities in the mining value chain, which entails the actual extraction of the mineral deposit utilising specialised equipment such as trucks, drill rigs and loaders. Within mining, the mine planning's role is to ensure that the planned mining blocks are executed accordingly and that the product yields the anticipated value for shareholders (Hall, 2009). The execution of the mining blocks requires an integration of the short-, medium-, and long-term plans. This means that the short-term plan execution has a material effect on the long-term value delivered (Kloppers et al., 2015). In this regard, the achievement of a mining plan in the short-term is of utmost importance.

Thus, the unavailability of drawpoints due to hang-ups is a challenge that affects production rates and the mining plan (Penswick 1997, Ngidi & Boshoff 2007, Castro & Cuello 2018, and Garcés et al. 2020). PMC loses 100 tonnes per unavailable drawpoint on a daily basis. There have been instances where up to 30% of the drawpoints were unavailable in the block cave. Additionally, hang-ups cause irregular draw that pose challenges with the acceleration of the migration of fines as well as the chimneying of the cave, which is a mechanism in which uneven draw creates a path through which fines can migrate into drawpoints, thus increasing dilution (Diering et al., 2018).

According to Ngidi & Pretorius (2010), prolonged idling of drawpoint can potentially lead to writing off reserves. For example, there is a potential loss of up to 30% of the Lift 1 tonnes in Sector 4. It should also be noted that the treatment of hang-ups can temporarily increase the cave unavailability in the sense that drifts in which drawpoints are being treated for hang-ups for the time being are closed off for loading, rendering all available drawpoints in the drift unavailable. This puts an additional constraint on LHD assignments.

Table 1.2 shows a snapshot depicting the cave management record on the 27th of December 2020 (PalaboraMiningCompany, 2021). In this table, the number of days that drawpoints set idling and untreated were tracked and reported to the operations team. The allowable number of days a drawpoint can remain idle should not exceed three.

Table 1.2: Idling drawpoints status on 27 December 2020 at PMC Lift 1 block cave

Drawpoint name	Idle days before 26 Dec 2020	Drawpoint Status on 26 Dec-2020	Number of blast/attempts to bring down a hang-up	Drawpoint Status on 27 Dec-2020	Average grade (%Cu)
01W08	3	Hangup	Not attempted	Hangup	1,391
02W08	8	Hangup	4	Hangup	2,417
03W07	12	Hangup	3	Hangup	0,638
08E09	11	Hangup	7	Hangup	0,681
12E09	18	Hangup	Not attempted	Hangup	0,639
14W03	18	Misfire	Not attempted	Misfire	0,661
15E08	18	Hangup	Not attempted	Hangup	0,287
15W07	4	Hangup	1	Hangup	0,551
16E07	3	Ready	9	Misfire	0,472
16W04	10	Ready	Not attempted	Hangup	0,572
17W08	7	Hangup	Not attempted	Hangup	0,405
18E02	7	Hangup	21	Hangup	0,462
18E07	7	Hangup	21	Hangup	0,741
19E02	3	Ready	9	Hangup	0,449
19E03	7	Hangup	4	Hangup	0,499
19E05	10	Ready	2	Hangup	1,012
19E06	3	Hangup	Not attempted	Hangup	0,693
19W03	3	Ready	1	Hangup	0,446
19W04	3	Ready	1	Hangup	0,582
19W05	7	Ready	3	Hangup	0,635
19W06	3	Ready	1	Hangup	0,658

Drawpoint name	Idle days before 26 Dec 2020	Drawpoint Status on 26 Dec-2020	Number of blast/attempts to bring down a hang-up	Drawpoint Status on 27 Dec-2020	Average grade (%Cu)
19W08	18	Hangup	Not attempted	Hangup	0,601
20E08	3	Hangup	2	Hangup	0,508

Table 1.2 does not show the types of hang-ups the mine was dealing with then. However, the table shows that many drawpoints, some of which have grades above the cut-off of 0.370 %Cu, have exceeded the three-day idling limit. At PMC, the low-grade upper and lower limits are 0.420% and 0.200% respectively, whereas the high-grade upper and lower limits are 0.600% and 0.450%, respectively.

PMC mining operation has been experiencing several months where the secondary rock-breaking equipment availability levels have been below the target of 65%. The reason for the low availability levels is due to the equipment having passed their operational lives (PalaboraMiningCompany, 2015). The secondary rock-breaking equipment requirements at PMC were based on the cave management system that sought to reduce hang-ups and increase ore recovery based on an *on-demand process* rather than on crosscut allocation (Penswick 1997 and Ngidi & Boshoff 2007). Therefore, this research sought to understand the impact that secondary rock-breaking equipment has on the mining plan at the PMC block cave.

1.6 Research Objectives

The research objective can be summarised as the investigation into whether the prolonged idle of drawpoints due to hang-ups is a result of the low availability levels of the secondary rock-breaking equipment. The availability and utilisation of the secondary rock-breaking equipment have a material impact on the mining plan. The research objective can be broken down into the following sub-objectives:

- Establish the extent to which secondary rock-breaking equipment contributes to cave availability.
- Determine acceptable secondary rock-breaking equipment availability levels required to mine to plan.
- Establish the maintenance strategy can be used to improve rock-breaking equipment availability at PMC despite have exceeded their planned lives.

1.7 Research Questions

The research objective was achieved by answering the research questions posed to gain an understanding of the influence of secondary rock-breaking equipment availability and utilisation on cave availability and a mining plan. The research questions are as follows:

a) How does the current PMC cave compare with the feasibility predictions?

b) What is the relationship between cave availability and loading compliance and the mining plan at PMC?

c) What is the minimum secondary-rock breaking equipment availability required to mine to plan at PMC?

d) How has the maintenance strategy at PMC affected secondary rock-breaking equipment availability?

1.8 Assumptions

In this study, the Lift 1 block cave has broken through into the bottom of the previously mined-out open pit and therefore has matured. However, based on the block cave prediction model and the work of Ngidi & Pretorius (2010), the Lift 1 block cave is prone to the production of oversized rocks at this stage of its life contrary to the mature cave theory.

1.9 Significance of the Study

Secondary rock-breaking equipment play a significant role in the treatment of hang-ups and blockages in block caving, thus improving cave availability. However, very little literature is available that details how the availability of secondary rock-breaking equipment influences mining plans. This study then contributes to the literature on the impact of secondary rock-breaking equipment availability levels in block caving.

1.10 Structure of the Report

Chapter 1 introduces the research and states the background and motivation for undertaking this research. In addition, the problem statement, objectives, and research questions, and assumption underpinning this research are stated. The problem statement also outlines the basis for carrying out the study by taking the view of the problem faced by PMC.

Chapter 2 discusses the main concepts of the study, which include mining planning stages and their significance, draw control, and secondary rock breaking. The other concepts such as equipment availability and utilisation are discussed to understand their impact on the mining plan. Lastly, the gap in the literature is analysed, which includes the need to address why the fragmentation of the Lift 1 block cave is not in line with the cave theory. The effects of maintenance strategies on the availability levels of equipment is also discussed.

Chapter 3 outlines the method followed in executing this research. The data used was provided by the Secondary Breaking Unit (SBU) at PMC, which is the unit responsible for all the secondary rock-breaking activities at the mine. With the challenges encountered in 2020 of low secondary rock-breaking equipment availability levels, there is a need to improve it.

Chapter 4 provides the results of the data collected and analysis thereof. In this study, data is detailed in table formats and graphically to answer the research question and the objectives of the study. The correlational analysis is used to arrive at certain conclusions. Chapter 5 provides a summary of the research, including analysis discussed in Chapter 4. It also provides recommendations for future studies.

2 LITERATURE REVIEW

2.1 Introduction

This section introduces the chapter that covers past research work, which includes literature in mining and mechanisms involved in rock breaking. Firstly, the chapter introduces block caving challenges and considerations when selecting the preferred method of mining. Secondly, a detailed review of caving mechanisms and hang-ups formation is discussed, together with the different methods of recovering hang-ups in the cave, which involves different secondary rock-breaking equipment. Draw control is also discussed and the role played in minimising dilution and controlling the allocation of equipment in the treatment of hang-ups. The latter part of the review discusses the role that secondary rock-breaking equipment plays in the recovery of hang-ups and the factors involved affecting the availability of equipment.

2.2 Challenges Related to Block Cave Mining

When a mining block is planned, it must be such that it is mined in a manner that yields maximum recovery of ore, within the acceptable grade levels and with minimal dilution. This is achievable by taking into cognisant many factors involving drawpoint design and interaction between different draw columns as well as the minimisation of dilution (Heslop, 2010). The design of the drawpoint incorporates considerations of the rock mass strength, drawpoint height and brow, and spacing between the drawpoints. All drawpoints should be uniform to maintain cave propagation through draw column interaction and draw control to manage stresses and dilution (Heslop 2010 and van As & Guest 2020).

The control of draw rates and means of controlling dilution is often carried out by means of cave management systems, whereby each tonne loaded from a drawpoint is recorded, and adjustments are made on day and shift schedules (Heslop, 2010). Failure to have effective cave management systems may lead to overstating the draw rates, incorrect draw schedule and ultimately early ingress of waste. The study by Butcher (1999) supports this argument by stating that the main challenges in block cave mining are associated with the design, in particular draw horizons which presents challenges with dilution and the low recovery of ore.

Thus, it is critical before a mining method is selected that all aspects of its profitability are assessed. The assessment undergoes different stages, with an increasing level of confidence as it progresses from one stage to another. The assessment is termed a feasibility study that encompasses scoping, which is the initial stage conducted at the start of the project. This stage is crucial, in that it assesses whether to commit funding for exploration or pursue a particular mineral deposit, however, the level of accuracy is between 30 and 50%.

Once the scoping studies are concluded and the mineral deposit identified, then the pre-feasibility study ensues. In this phase, assumptions are backed with accurate data, with more approximate estimations. The level of accuracy is still not adequate to justify the feasibility of mining the deposit. The level of accuracy lies between 15 and 30%. Lastly, the full feasibility study is carried out, with acceptable accuracy of between 10 and 15% (Ruppecht, 2004).

2.2.1 Description of block caving mining method

Block caving is one of the underground massive mining methods largely applied when transitioning from open pit to underground mining (Vyazmensky et al. 2009; and Xia & Tan 2021). The method is high-capital intensive at the beginning, but the cost reduces as the operation progresses due to reduced primary drilling and blasting consumption costs. Unlike other massive mining methods, block caving ceases primary rock-breaking activities once development is completed and the cave propagates upward. Drilling and blasting activities are then only applicable during the secondary rock-breaking.

A schematic representation of a block cave mine is shown in Figure 2.1 which shows access (shaft), haulages, production and undercut drives, conveyor and crusher systems, and the loading station with skips (PalaboraMiningCompany 2015). A large orebody, orientated vertically or inclined, is mined by developing accesses by means of both the production and the undercut levels. The undercut level is then drilled and blasted to induce caving to cater for material loading at the production level (Jakubec 2016; and Xia & Tan 2021).

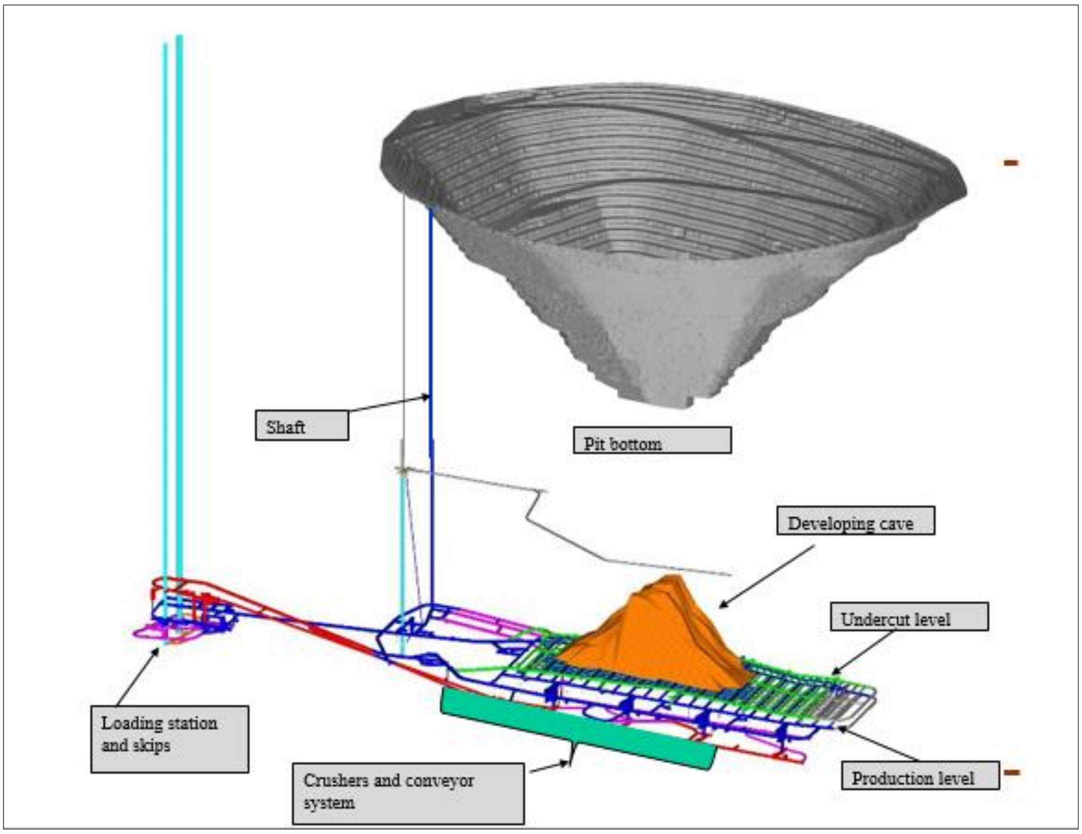

Figure 2.1: Block cave mine schematic (PalaboraMiningCompany, 2015)

Undercutting is a process of initiating caving in block caving. Caving is premised on fragmenting a part of the orebody above the undercut level. The production level underneath the undercut level is used for drawing fragmented rock through drawbells and drawpoints, from which LHDs load. The LHDs then transport ore from drawpoints to crushers for further size reduction and for ease of movement through conveyor systems, which transport ore out to the surface or some other means of storage bins and silos.

The undercut sequence is critical to ensure cave propagation, prevention of airblasts and minimisation of stresses (Galindo-Torres et al., 2018). The cave propagation and minimisation of stresses are functions of draw control while air pockets form due to the rate of draw being higher than the rate of caving.

During the process of loading, a mix of different rock sizes gravitates downward and is loaded until an obstruction (hang-up) occurs, blocking the free flow of material (Castro & Cuello, 2018). The hang-ups can be attributed to the oversized rocks or due to fine material compacting, thus preventing the free flow of material (Castro & Cuello, 2018).

The cause of hang-ups may occur at different phases of the cave. Van As & Guest (2020) attributed the cause of hang-ups to poor drawpoint design, such as an incorrectly spaced drawpoint spacing and orientation. However, at times it may not be due to the poor design but poor fragmentation during the undercutting phase as material is allowed to slowly cave under the influence of gravity. Additionally, the geotechnical challenges of the rockmass influence the fragmentation (Ngidi & Pretorius 2010, Castro & Cuello, 2018).

Loading practices can also influence the success or failure of caving, and the potential risks associated with mud pushes and airblasts (Vallejos et al., 2017; and Flores & Catalan, 2019). The comparison between the advantages and disadvantages of block caving is outlined in Table 2.1.

Table 2.1: Advantages and disadvantages of block cave mining method

	Advantages	Disadvantages
Safety and people	• Minimal blasting (Gomez et al., 2021)	• Mud push and air blasts (Flores & Catalan, 2019) • Prone to mud pushes (Vallejos et al., 2017)
Cost	• Low operating cost (Castro et al., 2017)	• High initial capital cost (Mutwiwa & Fondo, 2015)
Production output	• High production rates (Castro et al., 2017); • Massive and efficient (Xia & Tan, 2021)	• Inability to be mined concurrently with another block (Flores & Catalan, 2019) • Requires strict adherence to ensure that material breakthrough does not interact with the level above

2.2.2 Application of block caving at PMC

PMC commenced its block caving in 2001, and in 2004, a failure in Sector 2 occurred within two structures, resulting in the failure and closure of one production drive (Crosscut 11) (Ngidi & Boshoff 2007). Since the occurrence of the failure, the number of active drawpoints has reduced, thus prompting the expansion project to develop the second lift. The final approval was granted in 2014 and development commenced in December 2011.

The transitioning of the PMC pit to an underground block cave mine presented an opportunity to extend the life of mine, however, this was met with several challenges relating to the pit slope failure and secondary rock breaking issues. The block cave was developed in competent rock, the first in the world. The challenge of developing a block cave in competent rock was a lack of information to accurately predict the caving mechanism and potential slope failure when the cave interacts with the pit (Moss et al. 2006 and Ngidi & Pretorius 2010). Many scholars have studied the PMC pit slope failure to understand the cave and pit interaction mechanism (Moss et al 2006, Sainsbury et al. 2016, and van As & Guest 2020).

2.3 Caving Mechanism

Most authors agree that success in block caving depends largely on ensuring even draw rates and the most common considerations for the caving mechanisms are cave initiation and propagation (Butcher 1999, Moss et al. 2006, Heslop 2010, Chitombo 2010, and van As & Guest 2020).

2.3.1 Cave Initiation

Cave initiation starts with undercutting a hydraulic radius which is a ratio of the undercut area over its perimeter to determine a caving span (Laubscher 1994, Butcher 1999, and Moss et al. 2006). According to Laubscher (1994), the hydraulic radius is then plotted against the Mining Rock Mass Rating (MRMR) to determine the cavability of the block. At PMC, the hydraulic radius was achieved at 45 (Moss et al., 2006). The success of the block cave depends largely on the quality of the undercut and strict adherence to ensure that the undercut rate does not exceed the caving rate to mitigate stress-induced damage to the block cave infrastructure (Butcher, 1999).

The design parameters such as the drawpoint size, spacing, undercut method, stress orientation, and stability of the draw columns are also important in the cave initiation and propagation (Laubscher 1994 and Butcher, 1999).

2.3.2 Cave propagation

Cave propagation is the process by which rock fracturing stresses propagate upwards from the undercut as the draw of caved material ensues. Various factors such as the undercut rate, geotechnical classification of the mining block, type of orebody, and draw control system influence how the cave propagates (Moss et al. 2006 and Garcés et al. 2020). If the design is incorrectly done, the cave would take longer to advance upwards risking the cessation of cave propagation. Figure 2.2 illustrates the cave propagation process. In frame (a) cave is being initiated through undercut and fragmentation is expected to be regular due to blasting. In frame (b), caving propagates upward from the undercut and fragmentation is expected to be rough due to natural caving. In frame (c), caving interacts with the surface, causing subsidence and fragmentation is expected to be regular due to the gestation period of fractured rock within caved material. In frame (d), the entire block is caved and the caved material is been depleted. The fragmentation at this stage is expected to be relatively finer and cave production can be unconstraint.

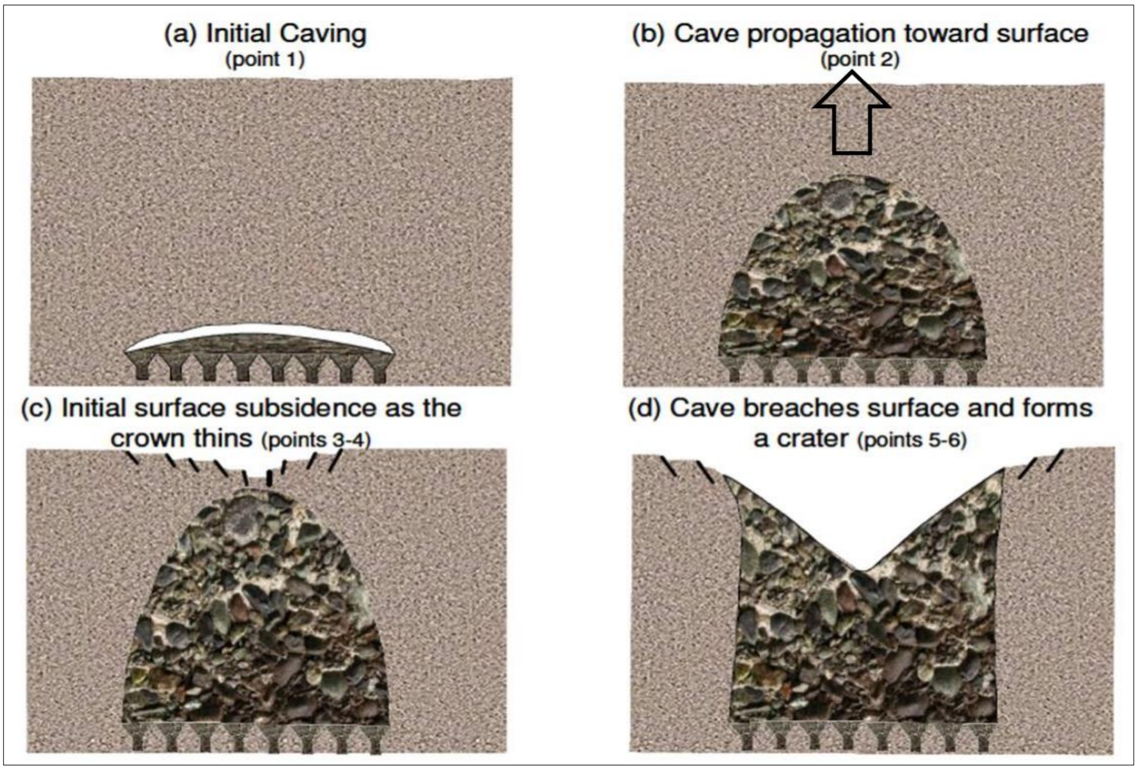

Figure 2.2: Block caving propagation (Jakubec, 2016)

Many block cave mines prefer the crinkle-cut undercut design where blast holes are drilled to produce an undercut shape depicted in Figure 2.3 and Figure 2.4 (Chitombo, 2010). Caving is initiated by drilling and blasting both the inclined and horizontal rings, thus forming an apex between the inclined holes that will be used as the protection pillar for production drives on the production level.

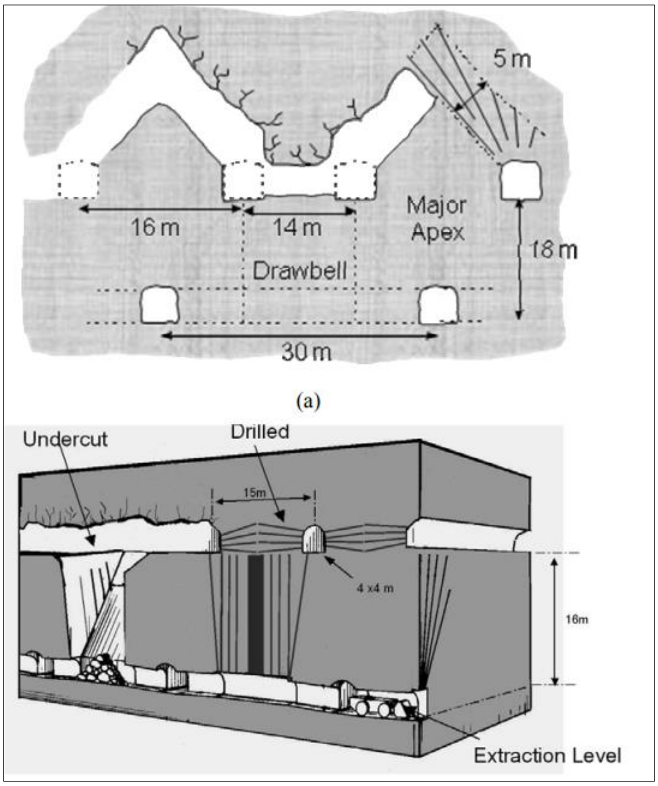

Figure 2.3: Undercut crinkle-cut design (Chitombo, 2010)

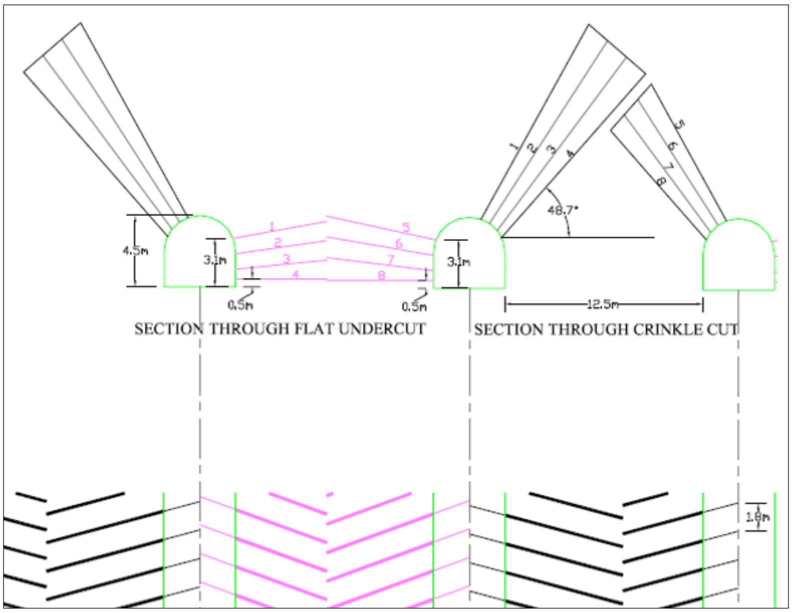

Figure 2.4: Undercut crinkle-cut design (PalaboraMiningCompany, 2015)

2.3.3 Draw mechanisms

Laubscher (1994) noted that block caving is a low-cost mining method, provided that it is designed to cave under different conditions. Furthermore, Laubscher (1994) highlighted that the draw should be designed such that material flows freely out of the drawpoints for uninterrupted loading of LHDs. According to Heydarnori et al. (2020), the draw mechanism in block caving results from gravity and induced stresses that cause caving.

During cave propagation, different rock sizes, ranging from fine to coarse, interact within the same column and are sometimes shared between the neighbouring draw columns, as shown in Figure 2.5. Thus, the drawing strategy employed will define and control the type of material exiting the draw column, whether too fine or coarse.

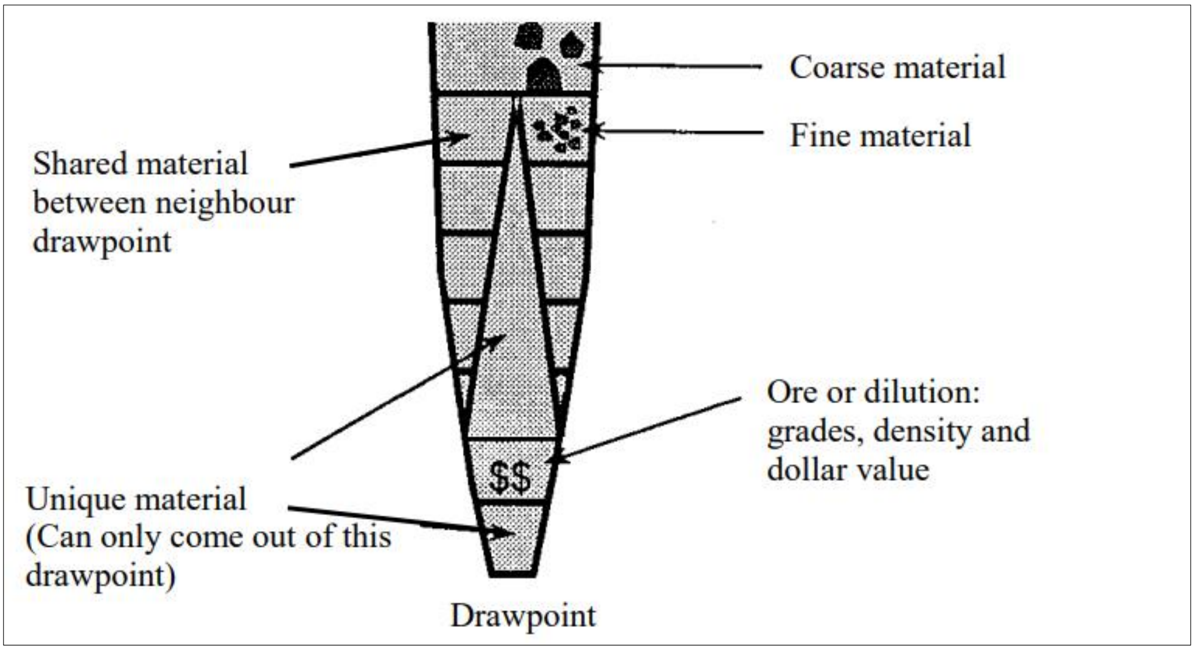

Figure 2.5: Draw mechanisms within a draw column (Diering (2000) in Heslop, 2010)

The finer material permeates quicker than the coarse material, and depending on the loading practice, the mixing at the mouth of the drawpoint might lead to a drawpoint blockage and the resulting hang-up formation. It is thus the role of the production department to ensure that an effective draw control is maintained and that the scheduling of secondary rock-breaking activities is carried out effectively as part of cave management systems (Ngidi & Boshoff, 2007). Not only is a cave management system effective in the management of hang-ups, but Heslop (2010) suggested that it influences the value of the block cave, which is determined by ensuring a specific average grade through blending from different drawpoints.

2.4 Potential Causes of Hang-ups

Hang-ups are formed due to poor fragmentation, resulting in large boulders formation. Other causes include material type, internal structures like shear planes and intrusions and compaction of fines (Stacey & Erasmus, 2005). According to Castro & Cuello (2018), hang-ups lead to low production rates and fines lead to high production rates. According to Oosthuizen & Esterhuizen (1997), weaker rockmass will result in minimal hang-ups while competent rockmass results in coarser fragmentation and high incidents of hang-ups.

The drawpoint design is also a factor in hang-ups. According to Castro et al. (2014), the wider the drawpoint, the more flow is likely to be achieved but the higher the vertical stress. On the other hand, a smaller drawpoint width restricts material flow. If hang-ups are not treated, stress builds up and later transferred to neighbouring drawpoints and the production drift (Wade, 2007).

2.5 The Role of Draw Control in Cave Management

In many mines the issues surrounding grade and dilution control are of utmost importance, as these factors affect the mine's profitability (Henning & Mitri 2007 and Heslop 2010). Similarly, in block caving, grade control and draw rates are critical factors that inform the draw control (Nezhadshahmohammad & Pourrahimian, 2017). Draw control not only regulates draw rates but also seeks to achieve planned grades and minimise stress build-up.

The other consideration for draw control is wet and very fine drawpoints which pose a risk of a mudrush. In areas where there are weaker geological structures and low grades, draw control should ensure that loading schedules are such that there is minimal material loss and profit is maximised while safeguarding against risks associated with water or mud ingress, dilution, airblast, and stress distribution or build up (Ngidi & Boshoff 2007, Castro et al. 2012, and Córdova et al. 2021).

Draw control should minimise preferential loading especially where the tip orientation or location is unfavourable. Operators generally prefer to load in areas with ease of access that require minimal effort. By enforcing strict draw control measures, material and LHD locations can be tracked to monitor performance and enforce compliance.

Shekhar et al. (2018) suggested that draw control strategies should be adaptive to ensure compliance with a mining plan based on continuous drawpoint monitoring systems. The monitoring systems must be aligned to secondary rock-breaking strategies such that idling drawpoints and hang-ups are given adequate attention and a fair amount of repair time to minimise production interruptions and delays.

2.6 Rock Breaking in Block Caving

2.6.1 Overview of rock-breaking

Rock breaking primarily involves drilling and blasting activities, where a boulder is drilled, charged with explosives, and blasted into manageable fragmentation sizes (Kansake & Suglo 2015 and Fourie et al. 2017). Both drilling and blasting activities are pivotal in secondary rock-breaking activities, particularly, where there are medium and high hang-ups (Ngidi & Pretorius, 2010). In the treatment of hang-ups, there is no well-established mining cycle, but it is dependent on the type and classification of the hang-ups. For the mines using drilling and blasting activities as rock-breaking mechanisms, the aim is to fragment the boulders into smaller and more manageable sizes for ease of loading and crushing.

The effectiveness of drilling and blasting depends on controllable and uncontrollable factors. Controllable factors are those factors that one has control over, which include hole length, diameter, and inclination. These, according to Kansake & Suglo (2015), are performance factors that can be manipulated, such as alterations to the hole length and inclination. The uncontrollable factors include geology, and rock density among others.

Rock-breaking can be divided into three categories, namely primary, secondary, and natural rock-breaking. Primary rock-breaking is the fragmentation of the in-situ rock with explosives and the natural rock-breaking involves the use of gravity to fracture and break down the in-situ rock. The secondary rock-breaking involves the use of explosives or point impact loads to fragment rocks that are too large for loading and hauling, owing to poor fragmentation (Gomez et al., 2021). The major distinction between the primary and secondary rock-breaking, is that the secondary rock-breaking is done when there is a need to clear blockages or if the fragmentation from the previous blast is coarse to the extent that it cannot be loaded. Whereas with the primary rock-breaking, the drilling and blasting is part of the mining life cycle. The secondary rock-breaking is mainly applied in boulder size reduction at the tips and in drawpoints or when treating hang-ups in drawpoints that have been standing idling without any loading (Penswick 1997 and Ngidi & Boshoff 2007). An example of rock-breaking equipment used for drilling holes for secondary blasting purposes is the MRR.

According to Oosthuizen & Esterhuizen (1997), non-blasting secondary rock-breaking can be conducted mechanically or manually, depending on the mine's appetite for technology. The two types of equipment used in non-blasting secondary rock-breaking are fixed and mobile rock breakers (MRB). The fixed rock breakers are installed next at the tip to break down boulders into fragments that can pass through grizzlies. The MRBs are used largely in the treatment of hang-ups and blockages at the drawpoints. In addition, water cannons (WC) can be used to bring down high hang-ups in drawpoints using high-pressurised water.

2.6.2 Secondary rock-breaking equipment

As aforementioned that secondary rock-breaking is required when the fragmented rock is too large to be loaded and where there is a presence of large boulders or hang-ups in the drawpoint. Both instances cause low draw rates and production delays due to the unavailability of drawpoints to load from (Castro et al., 2016; and

Gomez et al., 2021). Previously, hang-ups and large blockages in the drawpoints were treated using manual methods owing to the nature of mining and the technology in that era. Although mechanised equipment has been implemented in secondary rock-breaking activities for the treatment of hang-ups, this is still a risky undertaking (Penswick 1997 and Shekhar et al. 2018).

Each of the different types of hang-ups requires different methods of treatment and the usage of different equipment, which includes the following:

- Hang-ups caused by material compaction: This type of hang-up is treated using a hang-up rig that places explosives in the form of concussion bags or bombs directly on the weaker area around the compacted material (Penswick, 1997).
- Hang-ups caused by blockage of material: This type of hang-up is treated by drilling and blasting utilising MRRs to free up rocks blocking the drawpoint.

The critical determinant of which method to employ when recovering hang-ups depends on the type of hang-up presented and the type of equipment used (Castro et al., 2016).

Hang-ups are undesirable and have negative impacts at PMC in that, firstly, hang-ups cause a reduction in the availability of drawpoints, which may also lead to excess stress build-up. Additionally, poor fragmentation and hang-ups may lead to early dilution entry, thus leading to some reserves being written off. The PMC block cave setup is such that 48% of extraction should come from Sector 4 which is prone to high hang-ups (Ngidi & Pretorius, 2010).

2.7 Mining Equipment Applicable in Secondary Rock-breaking

As mentioned, secondary rock-breaking forms part of cave management underpinned by good draw control. That is, the maintenance of good draw control depends on prompt response to hang-ups and blockages. In a mine prone to frequent hang-ups and low cave availability, optimisation of the secondary rock-breaking activity is pivotal. For this reason, the planning and allocation of mechanised equipment becomes critical in achieving a mining plan. It is therefore imperative to incorporate equipment planning and scheduling in mine planning, although much effort to increase the availability and utilisation of equipment is still required (Kansake & Suglo, 2015).

Having the correct number of pieces of equipment is critical, however, the equipment must match the production requirements to avoid excessive blasting that is unnecessary. PMC carried out the secondary rock-breaking activities using four MRRs and MRBs, each allocated to service one of the four sectors. In addition, five water cannons were procured to wash down drawpoints or stabilise them before drilling (Ngidi & Pretorius, 2010).

The secondary rock-breaking equipment availabilities between 2006 and 2017 at PMC are shown in Figure 2.6. The availabilities of all three equipment types were higher between 2006 and 2013 than between 2014 and 2017. By the end of June 2017, the equipment availabilities were below 50%.

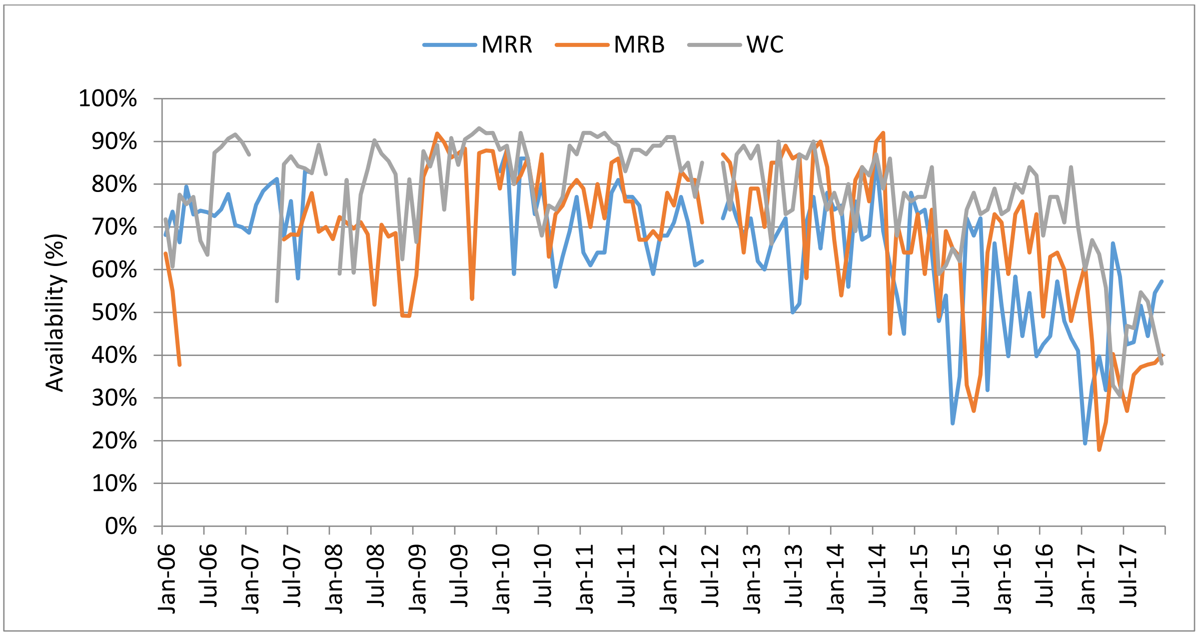

Figure 2.6: SBU availability from 2006 and 2017 (PalaboraMiningCompany, 2021)

PMC conducted a study to assess whether the slope failure material contained viable grades of copper and it was concluded that the grades therein justify the extension of the life of Lift 1 (Diering et al., 2018). This put a strain on the continuation of the use of rock-breaking equipment whose availability was waning due to their age.

Low availability levels affect the mining plan. The effective use of equipment should be incorporated into the mine planning by determining specific periods when equipment is required for maintenance or replacement (Nurock & Porteous, 2008). Failure to incorporate equipment planning into a mining plan can lead to failure to achieve the planned mine value (Kloppers et al., 2015).

2.8 Overall Equipment Effectiveness in Secondary Rock-breaking

The effective application of mining equipment for their intended use is measured through overall equipment effectiveness (OEE), which has three main components, namely, availability, performance, and quality (Aman et al., 2017). The OEE measures the equipment's performance, which indicates the expected and actual output of the equipment. According to Hedman et al. (2016), OEE is a percentage measure of the time that equipment is truly productive in the overall productive time. The OEE takes into account Total Productive Maintenance (TPM) which focuses on the equipment's productivity measurement. Furthermore, the OEE can be a vital tool for benchmarking improvements made after equipment efficiency interventions (Eswaramurthi & Mohanram, 2013).

2.8.1 Factors influencing the availability of mining equipment

Availability is a critical component of OEE. Kansake & Suglo (2015) suggested that equipment availability and its improvement typify the mines' production output. Not only does availability play a crucial role in increasing production capacity, but it is also essential for equipment planning (Silva et al., 2016). The significance of equipment availability has raised interest from many authors, with some seeking to understand its influence on the equipment lifecycle and its relationship to production performance (PricewaterhouseCoopers 2012; Silva et al. 2016, and Brodny et al. 2017).

Kansake & Suglo (2015) concluded that there is a strong correlation between improvements in equipment availability and production output, with an R-squared value of 0.98. To this effect, optimisation efforts relating to equipment availability should be closely monitored. Improving equipment availability requires strict adherence to preventive maintenance, which involves scheduled maintenance and prompt response to all breakdowns.

Preventive maintenance strategies not only aid in improving equipment availability but also the life of equipment and reduction in maintenance costs. The lack of maintenance on critical equipment has financial implications for an organisation (Nurock & Porteous, 2008).

The maintenance of equipment is necessitated by the anticipation of failure and reduced effectiveness, thus putting measures to mitigate against premature failures (Mehmeti et al. 2018 and Gackowiec 2019). The term maintenance relates to efforts to ensure that the equipment is kept in an operable state. The maintenance strategies revolve around identifying problem areas through routine inspections and the execution of different actions to either repair, replace or refurbish components (Gackowiec, 2019).

Figure 2.7 shows proactive and reactive maintenance strategies. The former is used synonymously with preventive maintenance to ensure that equipment is maintained before failure or breakdowns are experienced. The preventive maintenance at PMC involves pitstops, prompt attendance to breakdowns, and frequent maintenance schedules. The reactive maintenance strategies revolve around responding after the equipment failure has occurred (Onawoga & Akinyemi, 2010; and Gackowiec 2019).

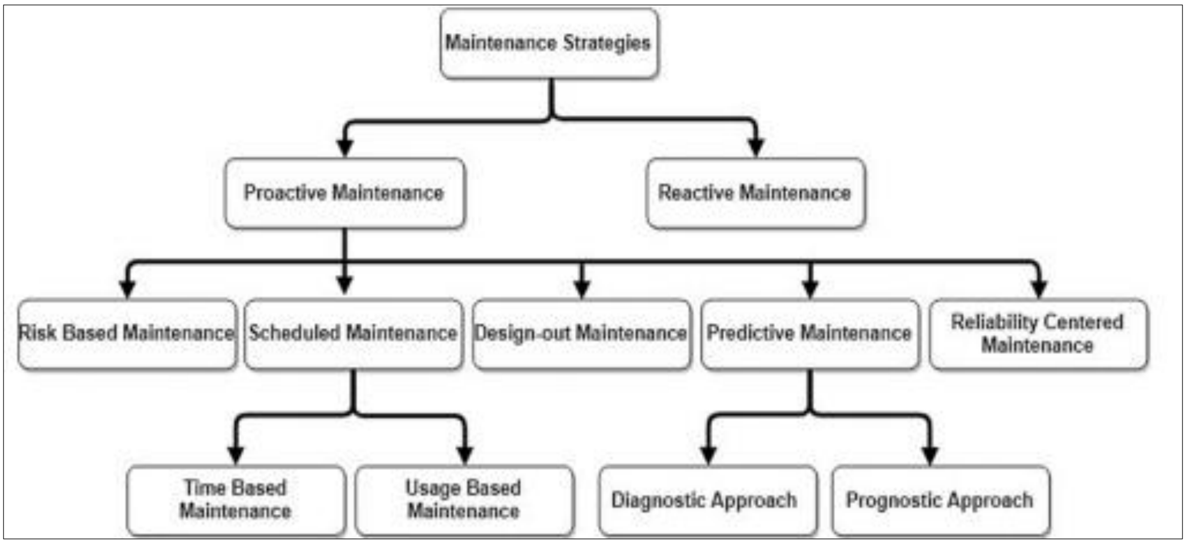

Figure 2.7: Maintenance strategies (Gackowiec, 2019).

2.8.2 Factors influencing the performance of mining equipment

The operational factors affecting the performance of mining equipment include supervision, usage and age of equipment, skill and experience of operators, maintenance strategy, work assignment and technology. The environmental factors affecting the performance of mining equipment include excess heat, cold, and other climatic conditions. The design factors affecting the performance of mining equipment include layout, grades and workload (Chandra et al. 2023 and Luozzo et al. 2023).

The application differs from equipment to equipment depending on the intended purpose; for LHDs, the measure would focus on tonnes, for utility vehicles, the measure would focus on expected loads of weight, and for vans, the focus would either be on the number of loads or persons transported. Thus, when the available time is reduced due to increased cycle time and other delays, the performance of the equipment will be reduced (Eswaramurthi & Mohanram, 2013). According to De Ron & Rooda (2006), when an organisation measures performance, it does so to have a holistic view in decision-making on improvement efforts.

2.8.3 Factors influencing the quality of mining equipment

The quality factors express the percentage of products or materials that meet the expected specifications, which involves focusing on the total number of good products subtracting the number of defects and reworks produced (De Ron & Rooda 2006, Eswaramurthi & Mohanram 2013, and Banerjee 2019). In block caving, this would involve the quality of planned production versus what is actually achieved.

2.9 Chapter Summary

This chapter provided a literature review of the block caving mining method and caving mechanism involving cave initiation, cave propagation, undercutting and draw mechanism. Furthermore, hang-up formation was also discussed. Hang-ups disturb the flow of material, thus requiring secondary rock-breaking for treatment thereof.

The chapter also discussed the draw control and the significant role it plays in cave management to reduce dilution and minimise the impact of induced stresses. Lastly, the effect of Overall Equipment Effectiveness (OEE) was discussed, including its three components namely, availability, performance and quality. How these concepts were applied in achieving the aim and objective of this research is discussed in the next chapter.

3 METHODOLOGY

3.1 Introduction

In block caving, secondary rock-breaking equipment is deployed to treat drawpoints with hanging up and bring them back in production to realise a mining plan. In this chapter, the research design, methodology, and data analysis approaches used in this research are discussed. This chapter also helps to bring about the understanding on how the findings and results presented in Chapter 4 were derived.

3.2 Research Setting

The research study was carried out in the Secondary Breaking Unit (SBU) at Palabora Mining Company (PMC). The mine uses the block cave mining method to mine copper-bearing minerals, such as carbonatite and foskoriet, from the Palabora Igneous Complex (PIC). The SBU is a support unit in the mining department and it oversees a fleet of secondary rock-breaking, fuelling, and lubrication equipment. Various departments and units collect data such as tonnage, grade, drilling and blasting cost, equipment availability and utilisation and store it on the company's central database. The data used in this research was a mix of field data and data extracted from the mine's database.

3.3 Research Methodology

Research is normally conducted if there is a need to solve a particular problem. The research questions that this study sought to answer are stated in Chapter 1. Research is also used to gain new knowledge or find ways of resolving the problem differently.

Protocols, designs, frameworks, and methods are formulated on the correct approach to follow. Research can also be conducted to test theories, develop procedures for data collection and analysis and evaluate the way an answer or solution was derived (Chege & Otieno, 2020). The three main methodologies used in carrying out research include qualitative, quantitative and mixed method (Troy, 2021).

3.3.1 Qualitative research methodology

Qualitative research entails discovering new knowledge and bringing up new discoveries based on the opinions and beliefs of the subjects. Oun & Bach (2014) refer to qualitative research as epistemology, which is the relationship between the researcher and the subject being studied. Thus the subject will provide his/her own opinion about a particular topic, which may or may not be factual, as this is based on opinion rather than fact. Contrary to qualitative research, quantitative research is based on numerical data, which is factual and not dependent on the researcher's and subject's interpretations.

Qualitative methodology involves gathering data based on interviews, observations and focus groups and depends on the expression of others rather than numerical data (Oun & Bach 2014, and Troy 2021). Jackson et al. (2007) discovered that the main distinction between qualitative and quantitative is that qualitative is central to understanding "human beings", whereas quantitative is more on numerical data and that each researcher must investigate a problem objectively and be diligent in the approaches to use.

3.3.2 Quantitative research methodology

Quantitative research methodology aims to test a hypothesis, answer a set of questions or test the previous work conducted by other researchers based on numerical data and is measurable (Troy, 2021). Different tools used for quantitative research methodology include surveys, case studies, and empirical studies to arrive at a conclusion. The collected data is then analysed using correlational, distribution, regression analysis, or analysis of variance amongst other tools (Troy, 2021).

3.3.3 Mixed method research methodology

The mixed method applies both the qualitative and quantitative research methodologies and can be used if the study requires the collection and analysis of both numerical and text or opinion datasets (Troy, 2021). This method offers advantages presented by both the qualitative and quantitative research methodologies, however, the limitation relates to challenges with the research design and the correct procedure to apply.

3.3.4 Selected research methodology

In this research, the quantitative research methodology was followed due to the nature of the research that required the collection of numerical data. In this respect, the correlation analysis was used to gain the understanding of the impact of various variables, particularly machine availability on the mining plan. Inferences were made using Microsoft EXCEL about the impact of secondary rock-breaking equipment on the mining plan.

3.4 Research Data and Analysis Methods

The process of carrying out research involves either the use of primary or secondary research designs. The two approaches differ in that primary research involves first-hand data collection and secondary research involves obtaining data from existing sources such as journals and other electronic or physical publications in databases. Secondary data research is from published data, whereas primary is original and seen as authentic in nature (Bouchrika, 2022; and Nicolas, 2021).

In this research, secondary data was obtained from the mine's central database. The aim was to analyse data related to secondary rock-breaking equipment availability levels. The data obtained related to daily equipment performance records and cave status mapping. This was complemented by planned observations underground. The data collected is the same data used by mine management for planning purposes and daily reporting.

In this respect, the secondary data obtained was collected by two Production Department units, namely, the Cave Operations Unit and Secondary Breaking Unit (SBU) and reconciled centrally by the Production Department. The Cave Operations Unit conducts all the production-related activities, such as loading, conveying and roadway maintenance, whereas the SBU conducts all secondary rock-breaking activities. There is, however, certain data not obtainable from the central database such as explosives cost and the quantities used, which are stored separately. Thus, such, data is obtained from section heads and is verified and reconciled by the Production Department and Management teams. The same data is reconciled and used in daily, weekly, monthly, and annual production reports.

The obtained data covered a period of 52 weeks, from January 2021 to December 2021. This period offered a full year of data on a weekly basis. The justification for the study period was also based on acquiring and forming a base post COVID-19.

3.4.1 Data analysis tool used

The correlation analysis was used because it was important to understand how variables associated with machine availability relate to each other. The correlation analysis is used when the researcher wants to determine how best two variables are associated and the strength between those variables and seeks to establish whether a change in one variable indicates a change in the other variable (Asuero et al. 2006 and Schober et al. 2018).

Correlation can be causal or non-causal. In the case of the causal correlation, an example could be an increase in tonnages as a result of an increase in more draw columns being available for mining. In the case of the non-causal correlation, an example could be an increase in tonnages as fuel price increases, which are not directly linked or related. Thus, the correlation measures the degree to which two variables relate and addresses the direction which seeks to determine proportionality between variables (Schober et al., 2018).

Two main tests for correlation used are the Pearson and Spearman correlation. If the Pearson correlation test is to be used, there should not be outliers or unequal variances in the dataset, the dataset must be normally distributed, and both the variables must be cardinal and linear (Dastmard, 2013; and Schober et al., 2018). On the other hand, the Spearman correlation is used in the ordinal dataset. The correlation coefficients of both Spearman and Pearson vary from -1 to +1 (Schober et al., 2018).

In this study, the Pearson correlation was used because the data was continuous and both the variables were cardinal and linear, thus satisfying the Pearson correlation requirements (Dastmard, 2013). To attempt to establish cause and effect, the coefficient of determination or the R-squared (R^2) was used. The R^2 is used to measure the degree of variability and the extent to the cause of one variable in the other (Turney, 2022). The R^2 ranges from 0 to 1 and 0 indicates a limited degree of variability and that the cause and effect most likely do not exist. The value of 1 represents a perfect linear relationship with a high likelihood of cause and effect.

In this research, the variable values were plotted on a scatter plot, and correlation coefficients were calculated. The interpretation and analysis of the correlation coefficients, particularly for the R-squared values were based on Table 3.1.

Table 3.1: Correlation coefficient values and interpretation (Schober et al., 2018)

Correlation coefficient	Interpretation
0.00- 0.10	Negligible correlation
0.10 - 0.39	Weak correlation
0.40 - 0.69	Moderate correlation
0.70 - 0.89	Strong correlation
0.90 -1.00	Very strong correlation

3.5 Fleet Population

The focus of this study was on MRBs, WCs, and MRRs. At the time this research was conducted, there were two MRBs in operation, namely, U1006 and U1007; there were five WCs, namely, U6000, U6001, U60002, U6003, and U6004 with one being on a long-term breakdown (more than six months); and there were six MRRs, namely, U3001, U3002, U3005, U3007, U3008, and U3009 with only three MRRs in operation and three were on a long-term breakdown.

3.6 Reliability and Validation of Data

Sürücü & Maslakçi (2020) stated that reliability refers to the consistency of data and validity refers to the degree of how well the measuring instrument carries out the intended functions. Thus, for this study, the data used was obtained from PMC and can be verified by any other researcher carrying out a similar study. The validity of the data lies in the fact that it is the same data used for mine planning purposes at PMC.

The main instruments used for both correlation coefficient and coefficient of determination are based on Microsoft EXCEL ® templates. The validity of the data presented was tested by using a dataset outside the assessment period, that is from January 2022 to April 2023.

3.7 Problems Encountered During the Study

While conducting this study the following challenges were encountered:

- Access to some data was a challenge, as some section heads stored data on their desktops, with access to data being at their approval.

- Subsequent to the COVID-19 restrictions, some data storage and analysis teams were assigned other tasks. This limited the ease of access, which meant multiple individuals were requested to supply data at their convenient time; and

- Some section heads were secretive about the data, as they feared that the data might be used against them.

3.8 Chapter Summary

This chapter highlighted the methodology followed in collecting and analysing data to achieve this research's objectives. The data was obtained from day-to-day central data storage over 52 weeks, from January 2021 to December 2021.

The main data analysis technique used was correlation analysis with the interpretation based on the results of the correlation coefficient and coefficient of determination. The results will be presented and analysed in the next chapter based on the methodology discussed in this chapter. The analysis is most focused on the secondary rock-breaking equipment.

4 RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents the data obtained largely from the PMC central database and some from various managers covering a period of 52 weeks from January 2021 to December 2021. Firstly, this chapter covers the overview of PMC block cave management, followed by discussions on hang-ups, the influence of cave availability on the mining plan, equipment availability levels, and lastly the effects of maintenance on rock-breaking equipment availability.

4.2 Overview of Cave Management

This section presents data and results to answer the research question of *how the current PMC cave compares with the feasibility predictions.* Cave management plays a significant role in the overall management of all data relating to the cave, which includes the shift schedules, data collection, reporting, reconciliation, and acting as key data control centre and support service (Ngidi & Boshoff, 2007). While cave management may entail the reporting and the reconciliation of data that includes secondary equipment availability, it is equally critical for equipment to be used effectively. Supervisors in the SBU are responsible for the day-to-day allocation of the secondary rock-breaking equipment, including prioritisation of rehabilitation of crosscuts (production drifts).

Table 4.1 shows the typical daily report of the activities of secondary rock-breaking equipment. Typical tasks include cleaning, blasting, rehabilitation work, and deployment of WCs, MRBs, and MRRs.

Table 4.1: Example of a shift crosscut task allocation status

NIGHT SHIFT

Dispatcher Haulage: **OLISHA**
Dispatcher SBU: **LUCIAH**

	M/S	Reason for Lost Opportunity
RB	12	
WC	12	
MRR	12	

MINING PROCESS STATUS, RATE & COMPLIANCE

CROSSCUT	1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	17	18	19	20
Handover	TER CANON			REHAB								CLEANING					MRR		
23H00-23H30				REHAB															
23H30-00H00				REHAB															
00H00-00H30				REHAB															
00H30-01H00	TER CANON			REHAB															
01H00-01H30	TER CANON			REHAB								CLEANING					MRR		
01H30-02H00	TER CANON			REHAB								WATER CANON					MRR		
02H00-02H30				REHAB								WATER CANON					MRR		
02H30-03H00				REHAB								MRR							
03H00-03H30				REHAB							WATER CAN	MRR							
03H30-04H00				REHAB							WATER CAN	MRR							
04H00-04H30	MRR			WATER CANON															
04H30-05H00	MRR			WATER CANON								BLASTED							
05H00-05H30	MRR			REHAB													BLASTED		
05H30-06H00	BLASTED			REHAB															
06H00-06H30				REHAB															CLEANING
06H30-07H00				REHAB															CLEANING
Handover				REHAB	CLEANING						MRR								WATER CAN

REASONS FOR DEVIATING FROM PROCESS

4.2.1 Drawpoint loading cycle

A daily drawpoint loading plan with the grade, tonnes, and geotechnical classification of draw columns is produced by the Mine Planning Department. The statuses of drawpoints are taken into consideration before assigning loading plans. Any drawpoint assigned for loading but unavailable due to a hang-up or blockage must be treated within three days to prevent overdrawing of adjacent drawpoints and prevent early dilution entry.

4.2.2 Mapping the actual drawpoint status of the cave

To achieve the main objective of this research, it was necessary to conduct a holistic PMC block cave drawpoint status mapping. The aim of mapping the actual statuses of the drawpoints was two-fold. First, it was to establish a correct representation of the entire cave to use as a base for the study. Secondly, the mapping was used as a working tool to present a holistic overview of the cave, which can be used daily to represent the true cave status that supervisors can monitor. Cave mapping is a tool that can be used to address equipment utilisation by minimising errors in equipment allocation, thus ensuring that effective face time is achieved.

The mapping of the block cave in January 2021 showed that only 182 drawpoints were ready for loading at any specific time as shown in Figure 4.1. The Lift 1 block cave layout is a herringbone originally with 166 drawbells and 332 drawpoints. There are between 8 and 21 drawpoints per production drift (crosscut). Currently, there are 257 active drawpoints and 75 are closed permanently. The 75 include those in crosscut 11 where seven million tonnes of ore were lost (Ngidi & Boshoff, 2007).

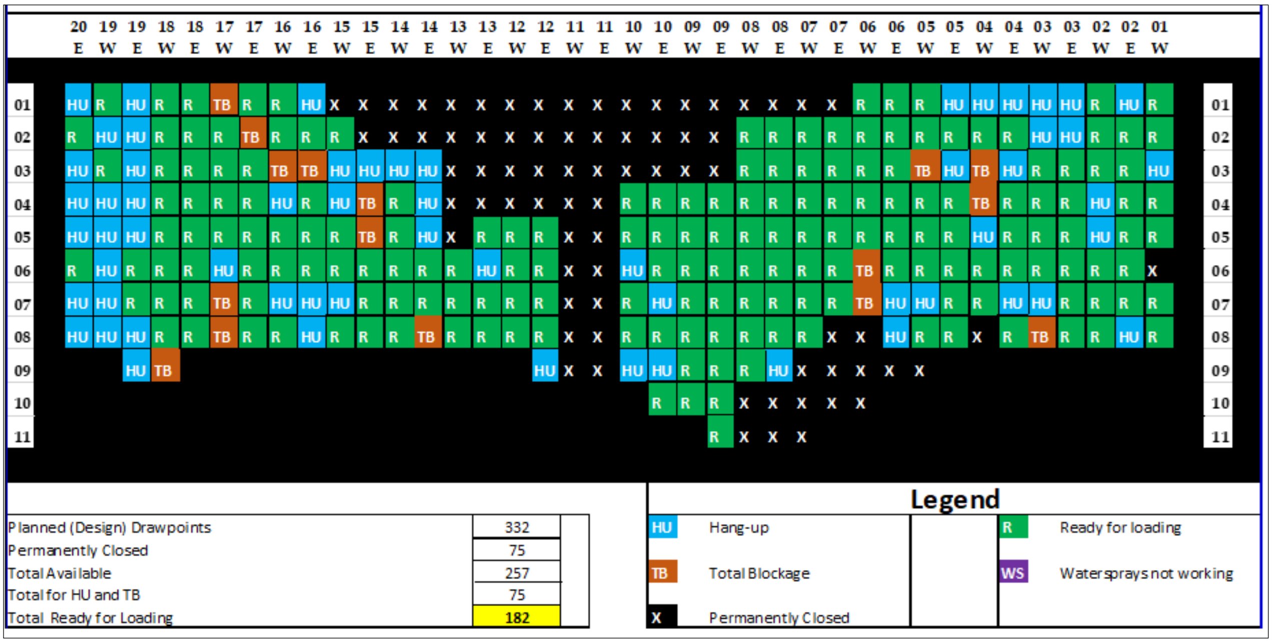

Figure 4.1: Cave status base mapping (aspects affecting cave availability)

Having 257 active drawpoints does not mean all are available for loading; some are under rehabilitation; some are hung up or blocked and others are not scheduled based on the draw control rule. When more than 50% of the drawpoints in the crosscut are unavailable, the practice at PMC is to hand over the entire crosscut to the SBU, or if major rehabilitation work is required, then the entire crosscut is assigned accordingly.

When a hang-up occurs, the systematic approach requires that a drawpoint is first cleaned and prepared for WC using LHDs. Once the drawpoint is cleaned, the WC is deployed, followed by drilling with MRR and blasting. Table 4.2 shows that it takes approximately one and a half hours for the WC to wash a drawpoint and one hour for the MRR to drill or place a concussion bag. The re-entry period after blasting is 30 minutes, whereas rehabilitation can take more than a week.

Figure 4.2 shows the drawpoint allocation process applied at PMC. The first step in the allocation of a drawpoint for loading is to establish whether a drawpoint is ready for loading or otherwise. From that assessment, two outcomes are possible; the first relates to an available drawpoint ready for loading. In this instance, the LHD is assigned to load, and the reconciliation report is generated to analyse and report on the loading compliance.

The loading compliance focuses on what was planned and the actual draw, which includes the actual drawpoints loaded, actual buckets loaded from each drawpoint, and the grade. In an instance where the drawpoint is unavailable for loading, the reasons behind the unavailability must be established. The two commonly reported reasons are hang-ups and damage. In the case of hang-ups, the first step is to clean around the area where the WC will be deployed. The WC will then move in an attempt to wash any loose fines and unstable rocks. This process can be repeated several times. If the hang-up does come down, the drawpoint is declared ready for loading. But, if the hang-up does not come down, the WC will stabilise it to enable MRR to drill or place a concussion bag and then blast. In some instances, the hang-up comes down but with oversized rocks. In this case, the MRB is deployed to break the oversized rocks into loadable sizes.

Table 4.2 Example of the secondary rock breaking activities and duration

Date	**1-Jun**				**2-Jun**				**3-Jun**			
	Time Allocation (hrs)				**Time Allocation (hrs)**				**Time Allocation (hrs)**			
XCUT Name	Cleaning, Rehab, or MRB	WC	MRR	Blasting	Cleaning, Rehab, or MRB	WC	MRR	Blasting	Cleaning, Rehab, or MRB	WC	MRR	Blasting
XCUT 1	0	1,5	1	0,5	1 Cleaning	2	2	0,5	0,5 Cleaning	1	1	0,5
XCUT 2	0	0	1,5	0,5	0	0	0	0	0	0	0	0
XCUT 3	0	2	2,5	0,5	0	0	0	0	1 Cleaning	0	0	0
XCUT 4	1 Cleaning	1	2	0,5	0	0,5	0	0	0	0	0	0
XCUT 5	0	0	0	0	1 Cleaning	1	1,5	0,5	1 Cleaning	1	1	0,5
XCUT 6	0	0	0	0	0	0	0	0	1 Cleaning	1	0	0
XCUT 7	0	0	0	0	0	1	0	0	0	0	0	0
XCUT 8	0	0	0	0	0	0	0	0	0	0	0	0
XCUT 9	0	0	0	0	0	0	0	0	0	0	0	0
XCUT 10	0	1	0	0	0	0	1	0,5	0	0	0	0
XCUT 11	0	0	0	0	0	0	0	0	0	0	0	0
XCUT 12	24 Rehab	0	0	0	24 Rehab	0	0	0	24 Rehab	0	0	0
XCUT 13	0	1	1	0,5	1 Cleaning	2	0	0	1 Cleaning	1	0	0
XCUT 14	0	0	0	0	2 Cleaning	2	0	0	0	0	0	0
XCUT 15	0	0	0	0	0	0	0	0	0	0	0	0
XCUT 16	0	0	0	0	0	0	0	0	1 Cleaning	1	1	0,5
XCUT 17	0	0	0	0	0	0	0	0	1 Cleaning	1	3	1
XCUT 18	0	0	0	0	0	0	0	0	0	2	2	0,5
XCUT 19	1 Cleaning	1	2	0,5	0	2	2,5	0,5		1,5	1,5	0,5
XCUT 20	1 Cleaning	1,5	1	0,5	1 Cleaning	0,5	0	0,5	1 Cleaning	1	1,5	0,5
Total	**24**	**9**	**11**	**3,5**	**24**	**11**	**7**	**2,5**	**24**	**10,5**	**11**	**4**

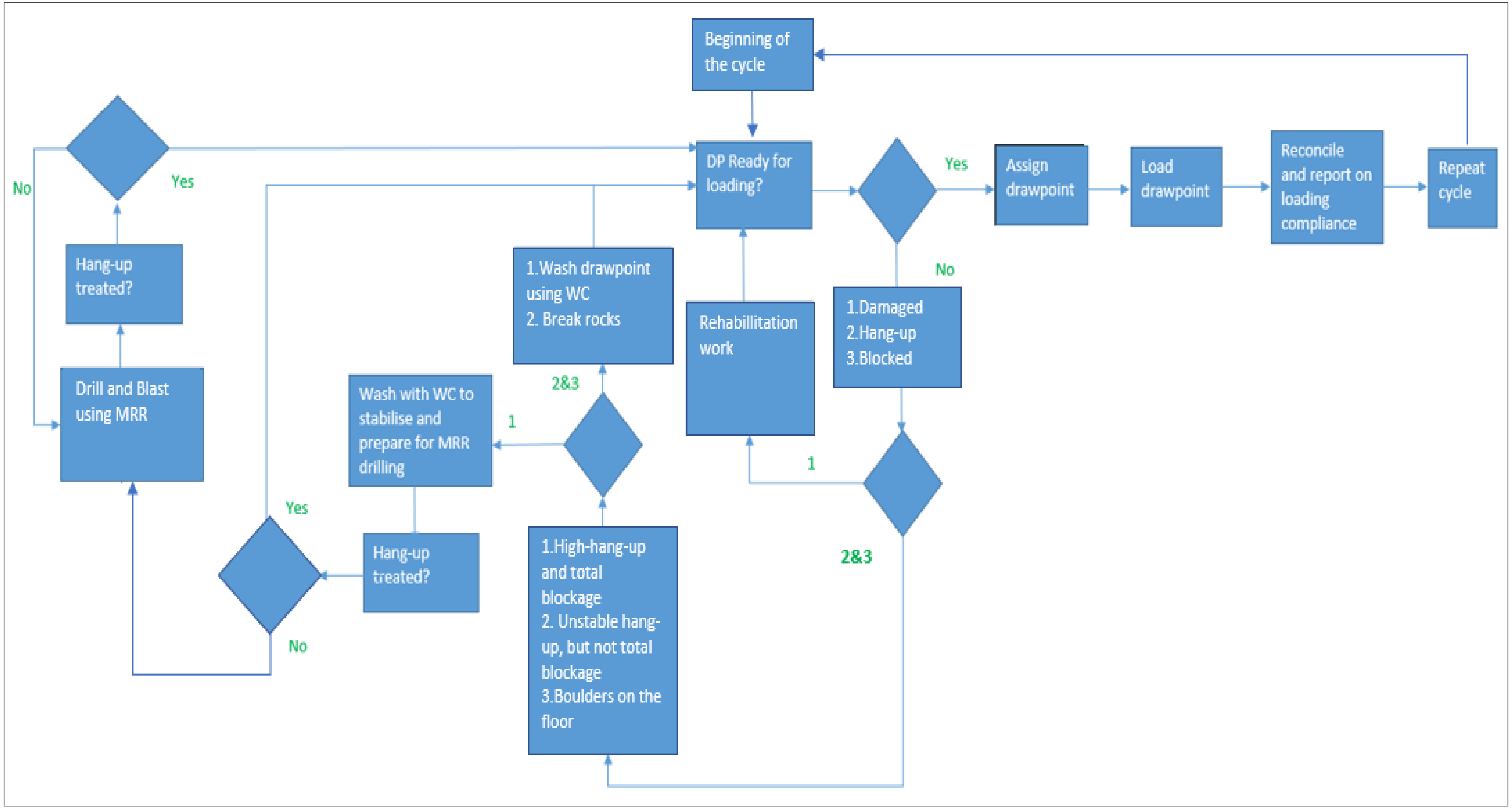

Figure 4.2: Drawpoint allocation process at PMC

In the case where drawpoints are damaged, the repair work will commence and that includes all the civil work to prepare drawpoints and crosscuts, including roadway maintenance, brow, and crosscut support, as well as sidewall and bull nose support. Figure 4.3 shows the status of drawpoints in 2021 at PMC.

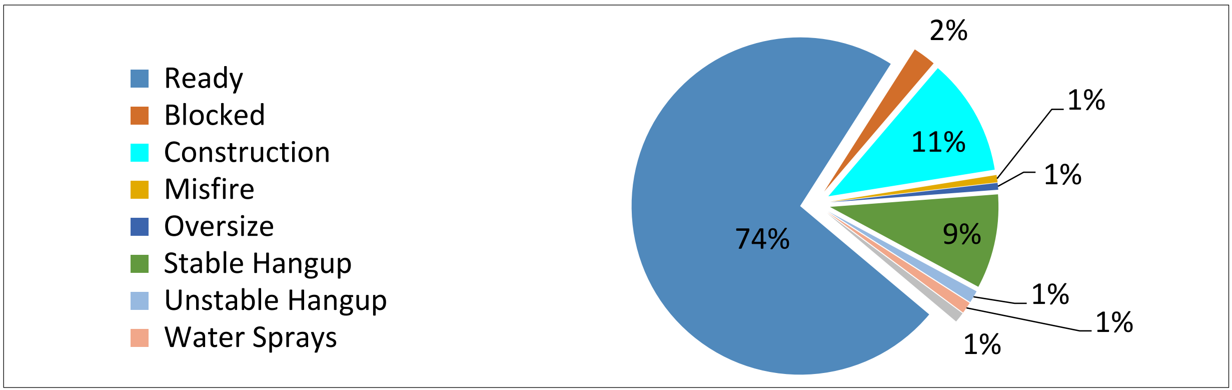

Figure 4.3: The status of drawpoints from January 2021 to December 2021

In Figure 4.3, 74% of drawpoints were available for mining in 2021, while 9% and 11% respectively were unavailable due to construction (rehabilitation) and stable hang-ups (hang-ups that have been stabilised and ready for drilling). The 2% of drawpoints were unavailable due to blockages, which may not necessarily be hang-ups, but obstructions.

4.2.3 The hang-up split between MRR and WC

The split between hang-ups treated with MRRs and WCs is presented in Table 4.3 and Figure 4.4. There were, on average, 469 and 215 hang-ups treated weekly by WCs and MRRs respectively in 2021. In total, 35 541 hang-ups were treated in 2021. The yield in Table 4.3 is tonnes drawn from a drawpoint before hanging up. On average, the weekly yield of drawpoints in 2021 was 900 tonnes.

It was predicted that the Lift 1 block cave would have between 60 and 70 hang-ups per day after 2003. However, the data in Table 4.3 indicates a daily average of 97 hang-ups (683 weekly) in 2021. This is contrary to a maturing cave theory.

Table 4.3: Hang-ups treatment split from January 2021 to December 2021

Week No	Actual Tonnes	The total number of hang-ups recovered	Hang-ups recovered by WC	Hang-ups recovered by MRR	Yield
WK1	20 350	730	410	320	64
WK2	75 658	699	179	520	145
WK3	59 294	829	259	570	104
WK4	51 482	549	429	120	429
WK5	60 516	787	427	360	168
WK6	78 930	561	251	310	255
WK7	92 917	309	29	280	332
WK8	130 742	649	299	350	374
WK9	74 956	615	470	145	517
WK10	80 007	721	541	180	444
WK11	142 872	697	497	200	714
WK12	53 855	663	463	200	269
WK13	105 878	799	521	278	381
WK14	147 581	774	523	251	588
WK15	134 095	489	212	277	484
WK16	93 941	679	554	125	752
WK17	111 541	759	688	71	1 571
WK18	121 851	734	591	143	852
WK19	148 283	779	713	66	2 247
WK20	100 045	710	670	40	2 501
WK21	133 957	589	225	364	368
WK22	162 474	769	287	482	337
WK23	107 978	683	573	110	982
WK24	107 775	769	644	125	862
WK25	161 726	650	443	207	781
WK26	156 805	709	615	94	1 668
WK27	141 755	696	266	430	330
WK28	156 641	763	763	0	-
WK29	161 620	839	802	37	4 368
WK30	128 596	359	359	0	-
WK31	92 616	769	157	612	151
WK32	97 633	774	660	114	856
WK33	151 004	786	656	130	1 162
WK34	181 423	822	778	44	4 123
WK35	170 829	829	494	335	510
WK36	167 710	754	333	421	398

Week No	Actual Tonnes	The total number of hang-ups recovered	Hang-ups recovered by WC	Hang-ups recovered by MRR	Yield
WK37	16 125	561	234	327	49
WK38	-	529	456	73	-
WK39	111 360	709	633	76	1 465
WK40	114 592	719	603	116	988
WK41	169 847	732	540	192	885
WK42	101 269	543	228	315	321
WK43	-	486	468	18	-
WK44	4 055	589	492	97	42
WK45	99 474	749	467	282	353
WK46	152 704	707	236	471	324
WK47	144 833	759	714	45	3 219
WK48	152 266	758	522	236	645
WK49	113 571	507	253	254	447
WK50	103 408	619	375	244	424
WK51	70 939	761	736	25	2 838
WK52	88 080	721	643	78	1 129
Total	5 607 859	35 541	24 381	11 160	43 216

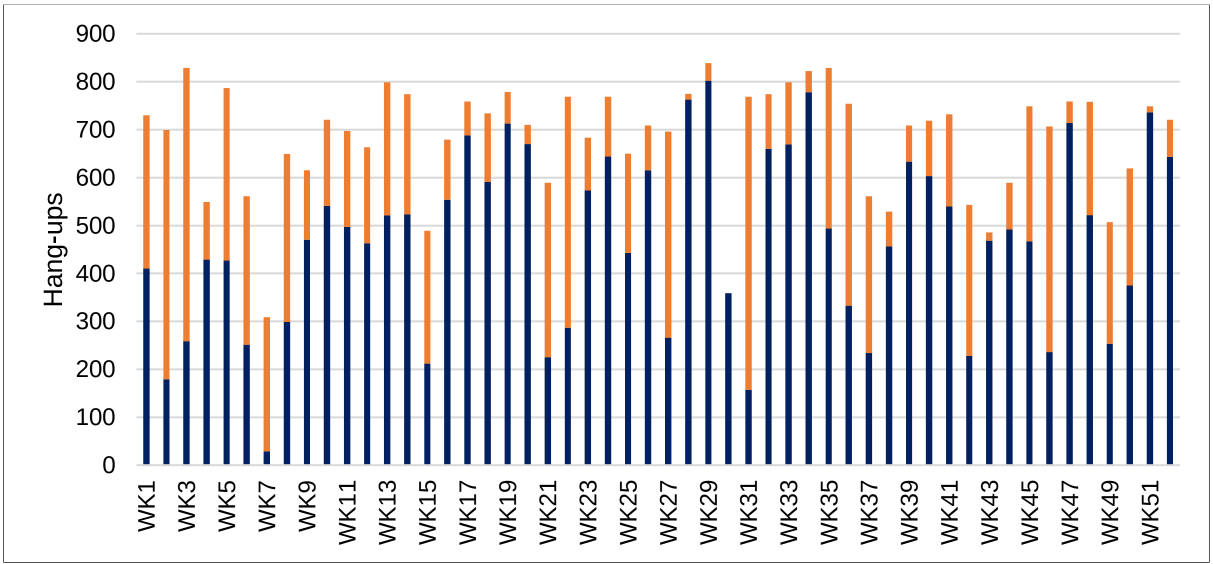

Figure 4.4: WC and MRR hang-ups split from January 2021 to December 2021

4.2.4 The number of hang-ups per sector

Table 4.4 presents the summary of the mined tonnes, hang-ups treated with MRR, and yield. Ngidi & Pretorius (2010) predicted that Sector 4 would contribute 36% of the overall production post the year 2009 and that this would continue beyond 2021. However, the results presented in Table 4.4 and Figure 4.5, show that Sector 4 only contributed 29% in 2021, and Sector 1 was the most productive sector. This can be attributed to a high number of hang-ups in Sector 4 compared to other sectors. Interestingly, Sectors 1 and 4 had a higher number of hang-ups (see Table 4.4 and Figure 4.6) and low yield (see Table 4.4 and Figure 4.7) compared to Sectors 2 and 3. It should be appreciated that low yield per drawpoint puts an enormous constraint on draw control and compliance with a mining plan, given that more tonnes come from Sectors 1 and 4.

Table 4.4: Mined tonnes, hang-ups, and yield from January 2021 to December 2021

	Mined Tonnes		**Hang-ups**		**Yield**
Unit	t	%Sector Split	t/hang-up	%Sector Split	t/hang-up
Sector 1	1 730 265	31%	3 847	34%	450
Sector 2	1 105 341	20%	825	8%	1 340
Sector 3	1 111 277	20%	1 552	14%	716
Sector 4	1 660 976	29%	4 936	44%	337

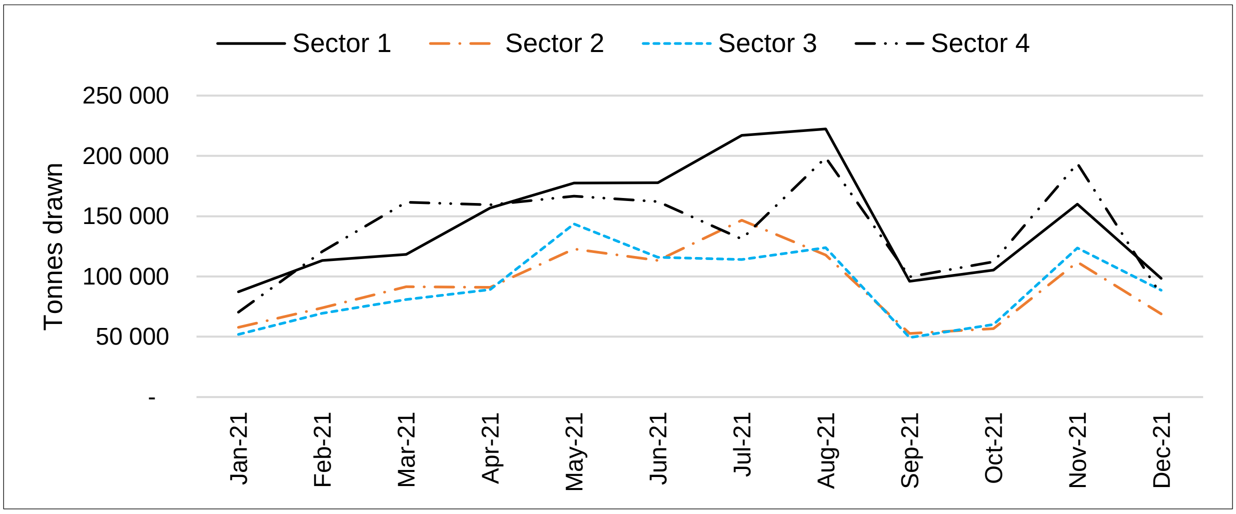

Figure 4.5: Tonnes mined per sector from January 2021 to December 2021

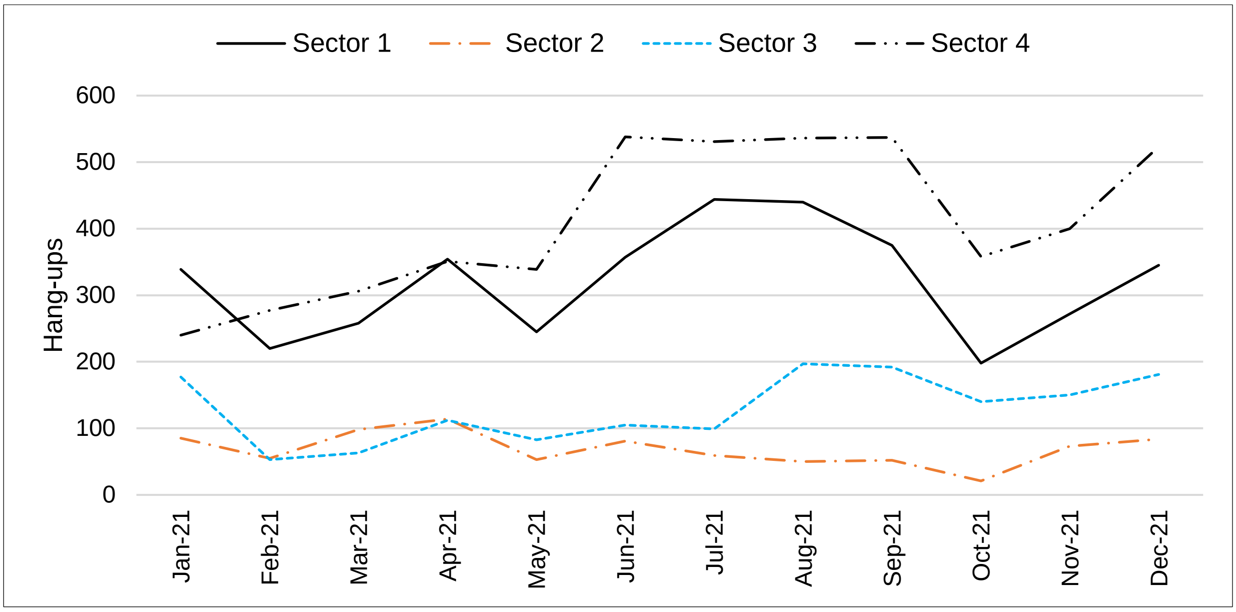

Figure 4.6: Hangups treated per sector from January 2021 to December 2021

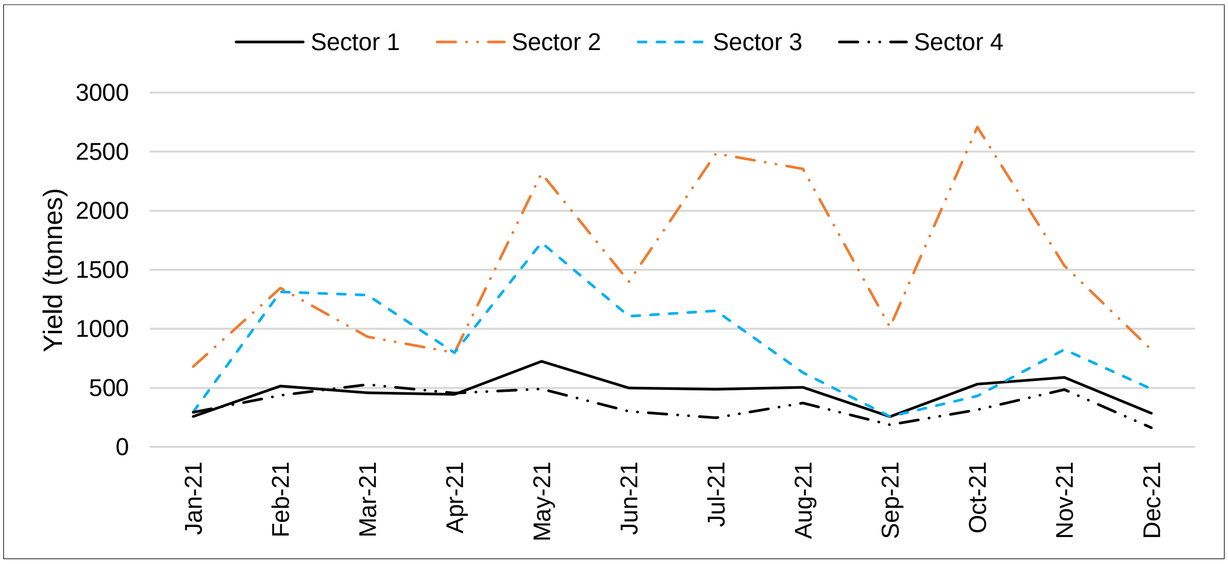

Figure 4.7: Drawpoint yield from January 2021 to December 2021

In general, bar the collapse of crosscut 11 and the open pit slope failure, it can be said that the Lift 1 block cave is behaving as predicted except that it has exceeded its planned life. In this context, it is conceivable that plans to handle hang-ups and oversized rocks would firmly be in place, inclusive of rock-breaking equipment availability and utilisation.

4.3 Cost implications associated with hang-ups

Drawpoints with hang-ups not only present production challenges, but also increase operational cost, as shown in Figure 4.8. The figure presents the correlational analysis of the explosives cost and the number of hang-ups present, which shows that as the number of hang-ups increases, the explosives cost increases. The explosives cost is not only associated with MRR drilling and blasting, but all activities that include the placement of concussion bags and creating cone bombs placed on weaker areas inside the drawpoint.

The correlation coefficient between the explosives cost and hang-ups is 0.9368, and the coefficient of determination or R-squared value is 0.8776. This relationship explains the causality between the two variables in that as the number of hang-ups increased, so did the explosives cost. Thus, 88% of the increase in explosives cost can be explained by the increase in the number of hang-ups in drawpoints.

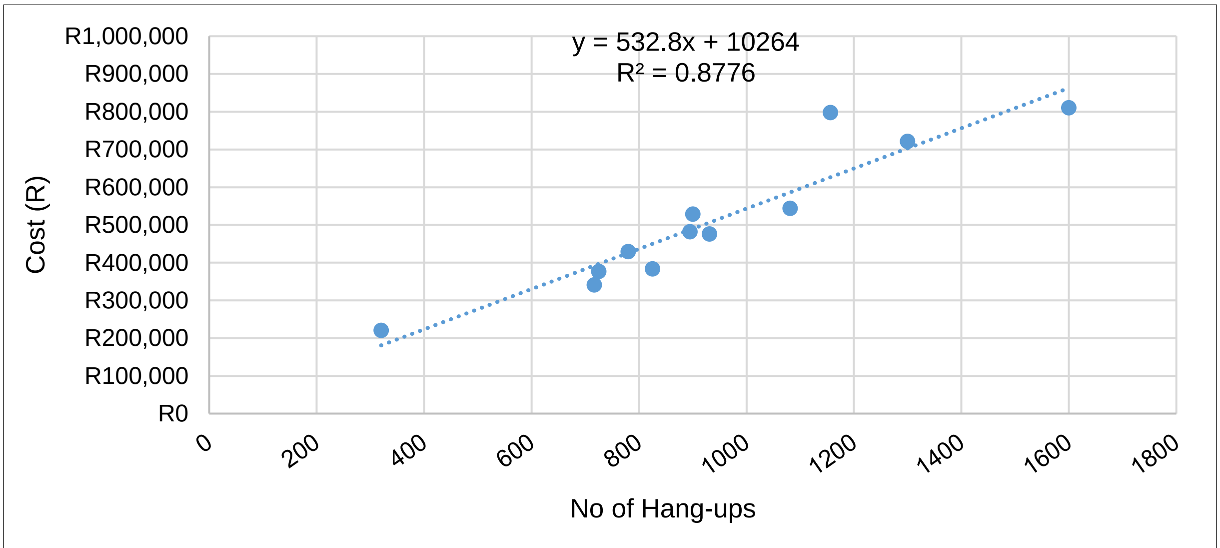

Figure 4.8: Explosives cost and hang-ups from January 2021 to December 2021

It should be noted that sometimes drawpoints may be blasted more than once to clear the hang-up. Some drawpoints can idle for more than three days, and not because they are not being treated, but sometimes as a hang-up is being treated, it changes from a high to a low hang-up. When a drawpoint is blasted multiple times, the explosive cost will still be assigned to the same drawpoint. Therefore, the number of blasts per drawpoint and even the size of the explosive charge (the bigger the charge, the bigger the cost) explains the R-squared of 0.8776.

4.4 Mining Plan Compliance

This section sought to answer the research question of *what the relationship between cave availability and loading compliance and the mining plan is at PMC.* A mining plan definition for this study is based on PMC's cave management protocol, which involves in-situ mined tonnes and copper grade, but excludes moisture content, recoveries, pricing, and exchange rates. Thus, the actual (mined) copper content will be used as a proxy for the mining plan, which factors only two variables, namely mined tonnes and grade.

The cave availability is the ratio of the number of available drawpoints for loading against the total number of active drawpoints. These are drawpoints that can be immediately assigned to LHDs for loading. The planned weekly cave availability in 2021 was 78%. The draw rate per drawpoint was 100 tonnes per day, with the cycle time for some drawpoints being shorter due to their proximity to crushers while for some it was longer. This draw rate translated into roughly nine bucket loads per drawpoint per day. That is three bucket loads per shift in a three-shift configuration.

The secondary rock-breaking activities are such that at most one crosscut per sector is given over to the SBU to treat hang-ups. For example, when the WC is deployed in one sector, the other activities will be assigned to another sector, thus minimising having all secondary rock-breaking activities focused on one sector but ensuring an even split to maintain an adequate supply of ore and draw control. Therefore, the planned 22% weekly cave unavailability was due to drawpoints assigned for repairs and treatment of hang-ups and blockages. This means that on every shift there are four crosscuts, each with an average of 16 drawpoints which are unavailable.

However, the actual weekly cave availability in 2021 was 71% and the loading plan compliance, a measure of how well a loading plan is executed, was 64% as shown in Table 4.5. The table shows different columns that include loading compliance, cave availability, mined tonnes, grade, and copper content. Each variable and how it was calculated is explained below:

- The first column relates to the week's numbers.
- The second and third columns relate to planned and actual mined tonnes respectively. The weekly plan is 175 000 tonnes in the second column, translating into 25 000 tonnes daily. The average weekly actual was 112 157 tonnes, with a low of 4 055 tonnes and a high of 181 423 tonnes. The 52-week performance shows that the actual tonnes mined were 38% below the plan in 2021.
- The fourth and fifth columns relate to in-situ planned and actual copper grade (%Cu) obtained respectively. This is in-situ projected grades and does not include the recovered grade but is solely based on in-situ values. The planned copper grade was 0.485% per week, and the weekly average actual copper grade achieved was 0.45%. The 52-week performance shows that the grade performance was 6.97% below plan in 2021.
- The sixth and seventh columns relate to planned and actual copper (Cu) content respectively. The copper content is obtained by multiplying grade and mined tonnes.

The weekly average actual copper content achieved in 2021 was 35.67% less than planned.

- The eighth column relates to the deviation from the mining plan, which measures the absolute difference between the plan and actual copper content, expressed as a percentage. The average weekly deviation from the mining plan was 39% in 2021.
- The ninth column relates to loading compliance, which measures the difference between the assigned and the actual loads per drawpoint expressed as a percentage. That is whether correct drawpoints were loaded correctly according to the plan. For example, in week 1, the loading compliance was 30%, which means that 30% of the 20 350 tonnes mined were from the correct drawpoints and 70% was loaded from the wrong drawpoints. This measure also focuses on the quality of the material loaded, which is based on draw control and in-situ grade constrains to ensure an even draw.
- The tenth column relates to cave availability and is explained above.

Table 4.5: Mining plan data from January 2021 to December 2021

Week No	Plan Tonnes (t)	Act. Tonnes (t)	Plan Grade (%Cu)	Act Grade (%Cu)	Plan Cu content (t)	Act Cu content (t)	Deviation to Plan %	Load comp (%)	Cave Avail (%)
WK1	175 000	20 350	0,485%	0.236%	849	48	94%	30%	68%
WK2	175 000	75 658	0,485%	0,413%	849	312	63%	50%	63%
WK3	175 000	59 294	0,485%	0,509%	849	302	64%	59%	77%
WK4	175 000	51 482	0,485%	0,512%	849	264	69%	48%	78%
WK5	175 000	60 516	0,485%	0,529%	849	320	62%	53%	80%
WK6	175 000	78 930	0,485%	0,412%	849	325	62%	49%	60%
WK7	175 000	92 917	0,485%	0,436%	849	405	52%	62%	69%
WK8	175 000	130 742	0,485%	0,542%	849	709	16%	68%	80%
WK9	175 000	74 956	0,485%	0,482%	849	361	57%	53%	84%
WK10	175 000	80 007	0,485%	0,500%	849	400	53%	51%	60%
WK11	175 000	142 872	0,485%	0,505%	849	721	15%	79%	79%
WK12	175 000	53 855	0,485%	0,424%	849	228	73%	49%	60%
WK13	175 000	105 878	0,485%	0,483%	849	512	40%	77%	66%
WK14	175 000	147 581	0,485%	0,466%	849	687	19%	64%	82%

Week No	Plan Tonnes (t)	Act. Tonnes (t)	Plan Grade (%Cu)	Act Grade (%Cu)	Plan Cu content (t)	Act Cu content (t)	Deviation to Plan %	Load comp (%)	Cave Avail (%)
WK15	175 000	134 095	0,485%	0,443%	849	593	30%	65%	77%
WK16	175 000	93 941	0,485%	0,442%	849	415	51%	57%	60%
WK17	175 000	111 541	0,485%	0,492%	849	548	35%	72%	71%
WK18	175 000	121 851	0,485%	0,493%	849	601	29%	72%	75%
WK19	175 000	148 283	0,485%	0,501%	849	743	12%	84%	75%
WK20	175 000	100 045	0,485%	0,482%	849	483	43%	69%	65%
WK21	175 000	133 957	0,485%	0,483%	849	647	24%	80%	79%
WK22	175 000	162 474	0,485%	0,525%	849	853	0%	90%	81%
WK23	175 000	107 978	0,485%	0,513%	849	554	35%	70%	89%
WK24	175 000	107 775	0,485%	0,492%	849	531	37%	68%	79%
WK25	175 000	161 726	0,485%	0,485%	849	784	8%	84%	82%
WK26	175 000	156 805	0,485%	0,451%	849	707	17%	63%	78%
WK27	175 000	141 755	0,485%	0,452%	849	640	25%	74%	69%
WK28	175 000	156 641	0,485%	0,511%	849	801	6%	60%	80%
WK29	175 000	161 620	0,485%	0,484%	849	782	8%	85%	76%
WK30	175 000	128 596	0,485%	0,405%	849	520	39%	65%	79%
WK31	175 000	92 616	0,485%	0,487%	849	451	47%	67%	75%
WK32	175 000	97 633	0,485%	0,482%	849	471	45%	56%	75%
WK33	175 000	151 004	0,485%	0,475%	849	717	16%	86%	79%
WK34	175 000	181 423	0,485%	0,535%	849	970	14%	93%	88%
WK35	175 000	170 829	0,485%	0,513%	849	877	3%	88%	81%
WK36	175 000	167 710	0,485%	0,512%	849	859	1%	90%	80%
WK37	175 000	16 125	0,485%	0,000%	849	82	90%	26%	33%
WK38	175 000	-	0,485%	0,000%	849	-	100%	0%	0%
WK39	175 000	111 360	0,485%	0,465%	849	518	39%	71%	75%
WK40	175 000	114 592	0,485%	0,474%	849	543	36%	69%	80%
WK41	175 000	169 847	0,485%	0,523%	849	888	5%	85%	88%
WK42	175 000	101 269	0,485%	0,501%	849	508	40%	73%	73%
WK43	175 000	-	0,485%		849	-	100%	0%	0%
WK44	175 000	4 055	0,485%	0,405%	849	16	98%	20%	0%
WK45	175 000	99 474	0,485%	0,473%	849	471	45%	66%	80%
WK46	175 000	152 704	0,485%	0,480%	849	733	14%	79%	77%
WK47	175 000	144 833	0,485%	0,521%	849	755	11%	73%	81%
WK48	175 000	152 266	0,485%	0,531%	849	809	5%	79%	88%
WK49	175 000	113 571	0,485%	0,475%	849	539	37%	69%	78%
WK50	175 000	103 408	0,485%	0,450%	849	466	45%	59%	78%
WK51	175 000	70 939	0,485%	0,543%	849	385	55%	52%	92%
WK52	175 000	88 080	0,485%	0,515%	849	454	47%	65%	82%
Weekly Average	175 000	112 157	0.48%	0,46%	849	546.16	39%	64%	71%

The total actual copper content over the 52 weeks in Table 4.5 was 27 308 tonnes, 38% below the planned 44 148 tonnes. The 38% deviation from the mining plan was because of the non-achievement of mined tonnes and grade. For instance, tonnes are managed by ensuring that loading drawpoints are available, which relates to cave availability. On the other hand, the grade is controlled by ensuring that quality tonnes are drawn from the correct areas, which relates to loading compliance.

4.4.1 Mining plan and cave availability

Logically, the cave availability should have a direct relationship with the mining plan and in turn the mining plan will have inverse relationship with the deviation from the mining plan. That is, if the deviation from the mining plan is high, the achievement of the mining plan will be low. Figure 4.9 shows a plot of the deviation from the mining plan and cave availability. The equations for cave availability and deviation from a mining plan are shown in Equations 4.1 and 4.2.

$$C_{Av} = \left(\frac{\mathrm{x-p}}{k}\right) \times 100 \quad \text{...}\textit{(Equation 4.1)}$$

C_{Av} = Cave availability (%)

x = Available drawpoints ready for loading

p = Unavailable drawpoints due to hang-ups, drawpoint maintenance, and misfires

k = Active drawpoints, which is the difference between the design and permanently closed drawpoints.

$$Dtp = \left(\frac{\mathrm{Cca-Ccp}}{Ccp}\right) \mathrm{x}\ 100 \quad \text{...}\textit{(Equation 4.2)}$$

Dtp = Deviation to mining plan (%), measures the difference between the actual and plan copper content. As aforementioned, the copper content is a proxy for the mining plan.

Cca = Actual copper content, which is a product of actual tonnes mined and grade.

Ccp = Plan copper content, which is a product of plan tonnes mined and grade.

The deviation from the mining plan and cave availability in Figure 4.9 had a correlation coefficient of -0.713 and coefficient of determination of 0.45 which implies that 45% of the deviation from the mining plan can be explained by cave availability. This means that the cave availability correlates strongly with the mining plan but have a moderate causality. Therefore, the notion that if there is a high percentage of drawpoints available for loading, compliance with a mining plan will automatically be high is misplaced.

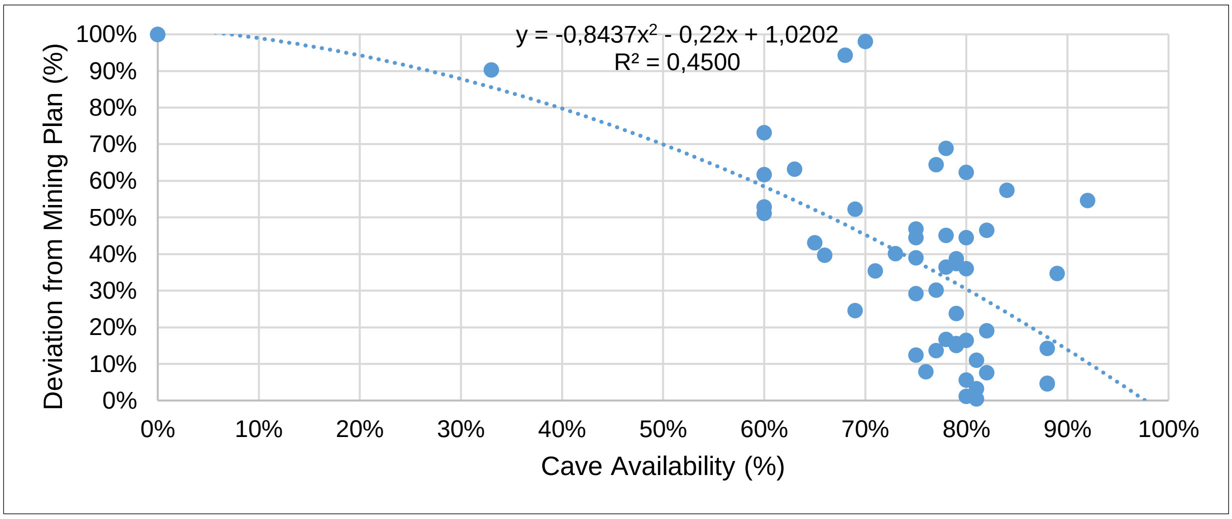

Figure 4.9: Cave availability and deviation from the mining plan from January 2021 to December 2021

4.4.2 Mining plan and loading compliance

Logically, the loading compliance should have an inverse relationship with the deviation from the mining plan. When plotted, this relationship is shown in Figure 4.10 where the correlational analysis is displayed. The correlational analysis between loading compliance and the deviation from the mining plan had a correlation coefficient of -0.908 and a coefficient of determination (R-squared) of 0.8376, which implies that 84% of the deviation from the mining plan can be explained by loading compliance. Due to the strength of the negative relationship between loading compliance and deviation from the mining plan, this relationship can be used to predict the impact that a change in loading compliance has on the deviation from the mining plan. In this regard, quadratic regression equations (Equation 4.3 and 4.4) were derived.

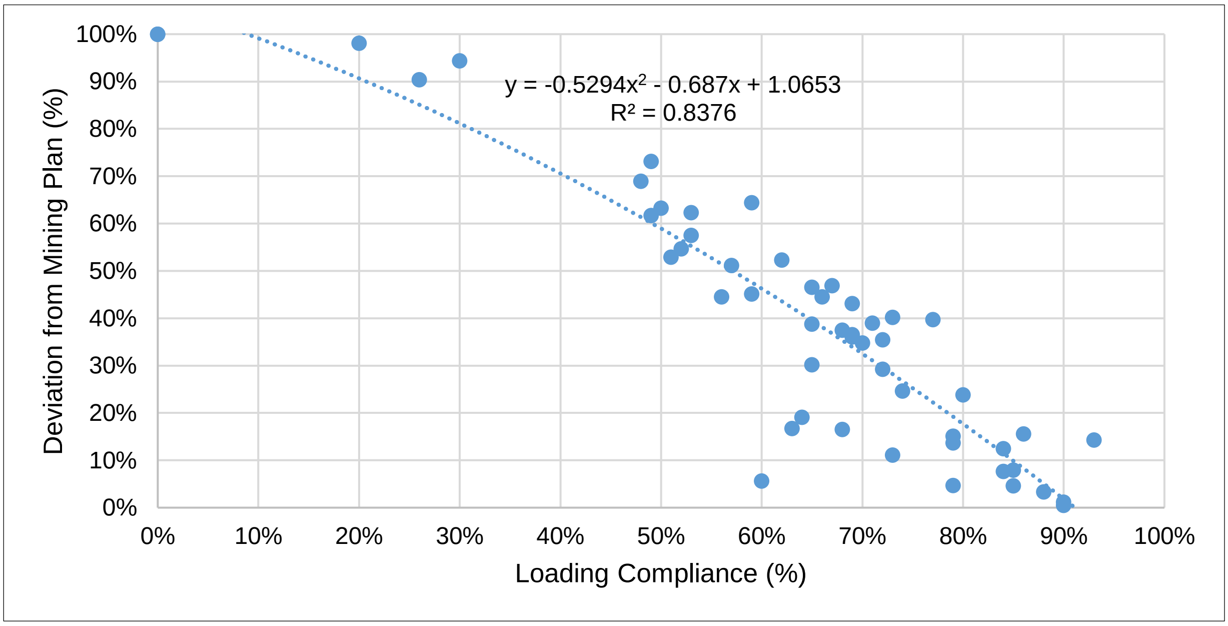

Figure 4.10: Loading compliance and deviation from the mining plan from January 2021 to December 2021

$Y = ax^2 + bx + 1$ .... *(Equation 4.3)*

$Y = -0{,}5294x^2 - 0.687x + 1$ .... *(Equation 4.4)*

$Y = Dependent\ variable\ (deviation\ to\ plan)$

$x = Independent\ variable\ (Loading\ compliance)$

$a = Quadratic\ coefficient\ , which\ is - 0.5294$

$b = Linear\ coefficient, which\ is - 0.687$

$c = Constant\ with\ a\ value\ of\ 1$

It can thus be hypothesised that loading compliance affects the deviation from the mining plan at PMC. It should be noted that in this study, the actual copper content is used as a proxy for the mining plan. However, cave availability has a strong correlation but moderate causality with a mining plan at PMC, thus it can be ignored.

4.4.3 Validation of the deviation to mining plan equation

To test the validity of Equation 4.4, data was collected outside the assessment period. The collected data extends for four months, from January 2022 to April 2022 to validate whether the equation can be used to predict deviation from the mining plan. The result of the validation is shown in Table 4.6. The correlation coefficient between the calculated deviation from the mining plan based on the loading compliance and the deviation from the mining plan reported by PMC is 0.97 with an average difference of 0.29%. This means that Equation 4.4 can reliably be used to predict the deviation from the mining plan at PMC and by implication, the impact of loading compliance on the mining plan.

Table 4.6: Equation validation from January 2022 to April 2022

a	b	c		
-0.5294	-0.687	1		
Week No:	**Loading Compliance**	**Estimated Deviation**	**Observed deviation**	**Diff**
Wk1	81%	10%	11%	-1%
Wk2	74%	20%	18%	2%
Wk3	85%	3%	4%	-1%
Wk4	63%	36%	35%	1%
Wk5	94%	11%	13%	-2%
Wk6	87%	0%	0%	0%
Wk7	88%	1%	0%	1%
Wk8	93%	10%	9%	1%
Wk9	72%	23%	22%	1%
Wk10	75%	19%	21%	-2%
Wk11	82%	8%	11%	-3%
Wk12	70%	26%	21%	5%
Wk13	76%	17%	21%	-4%

Wk14	76%	17%	13%	4%
Wk15	74%	20%	19%	1%
Wk16	77%	16%	15%	1%
Wk 17	73%	22%	21%	1%
Average	79%	15%	15%	0.29%

The challenge going forward in Lift 1 of compliance with the mining plan is the deterioration of the average grade per crosscut. Table 4.7 shows the estimated average grade per crosscut. The red colour indicates grades below 0.30% Cu, yellow and orange indicate grades between 0.30% Cu and 0.45% Cu, and green indicates grade above 0.45% Cu. It can be observed in Table 4.7 that in general, Sector 4 has the best average grade per crosscut and yet is the sector with the highest incidents of drawpoints hang-ups and the lowest drawpoint yield.

Table 4.7: Average per grade crosscut at the PMC's Lift 1 block cave

		2021	**2022**	**2023**	**2024**
XCUT1	Sector 1	0,411	0,360	0,192	0,056
XCUT2		0,477	0,414	0,235	0,082
XCUT3		0,514	0,445	0,264	0,114
XCUT4		0,392	0,319	0,146	0,021
XCUT5		0,332	0,250	0,111	0,041
XCUT6	Sector 2	0,291	0,239	0,087	0,004
XCUT7		0,187	0,110	0,032	0,008
XCUT8		0,275	0,206	0,083	0,005
XCUT9		0,297	0,272	0,182	0,077
XCUT10		0,310	0,278	0,197	0,088
XCUT11	Sector 3	0,000	0,000	0,000	0,000
XCUT12		0,287	0,257	0,200	0,137
XCUT13		0,207	0,183	0,089	0,006
XCUT14		0,297	0,276	0,116	0,030
XCUT15		0,341	0,300	0,193	0,085
XCUT16	Sector 4	0,471	0,474	0,463	0,089
XCUT17		0,570	0,612	0,649	0,199
XCUT18		0,576	0,631	0,667	0,210
XCUT19		0,545	0,590	0,615	0,213
XCUT20		0,488	0,518	0,533	0,082
		0,363	0,337	0,253	0,077

4.4.4 Discussion on mining plan compliance

Section 4.3 sought to highlight the influence of cave availability and loading compliance on the mining plan using the deviation from the mining plan to conduct a correlational analysis. The study indicated that cave availability has minimal effect on the deviation from the mining plan and by implication the mining plan. On the other hand, the loading compliance and the deviation from the mining plan have a very high negative correlation coefficient and coefficient of determination. It is from this relationship that Equation 4.4 was derived. Equation 4.4 can be used to estimate the deviation from the mining plan (hence the mining plan) based on the measured loading compliance. Equation 4.4 was validated by using data from January 2022 to April 2022 and the average percentage difference between the deviation provided by PMC and the calculated deviation using Equation 4.4 was 0.29% over the aforementioned period. Therefore the validity is high.

4.5 The Minimum Secondary Rock-breaking Equipment Availability

This section sought to answer the question of *what the minimum secondary rock-breaking equipment availability required to mine to plan at PMC is.* Secondary rock-breaking equipment is used to treat drawpoints with hang-ups or blockages. The equipment type selection and applicable method is informed by the different type of hang-ups or blockages. At PMC, two main secondary rock-breaking equipment types used to treat hang-ups are MRR and WC. The split between the number of hang-ups treated by each equipment type over 52 weeks in 2021 is presented in Figure 4.11. In total, there were 35 541 hang-ups in 2021. In Figure 4.11, the WC treated 24 381 (69%) and the MRR treated 11 160 (31%) hang-ups. The MRB is used to break oversized rocks blocking access to drawpoints.

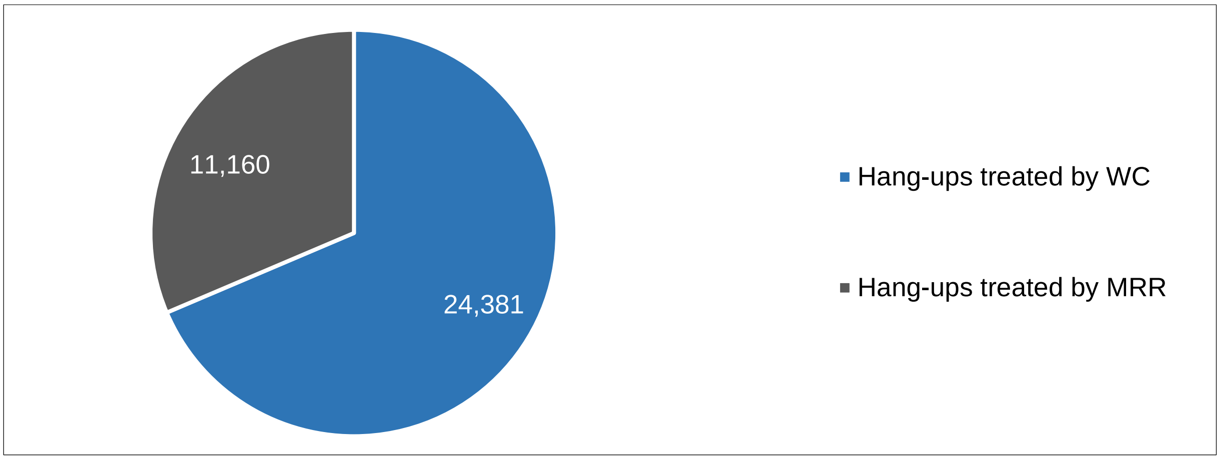

Figure 4.11: Hang-up split between MRR and WC January 2021 to December 2021

When the equipment is available, it must be utilised to good effect. The availability and utilisation are two variables that are critical in maximising equipment efficiency. The availability and utilisation equations are shown as Equations 4.5 and 4.6 respectively.

$$Availability\ (\%) = \left(\frac{\text{Actual Running Time}}{Total\ Planned\ Production\ Time}\right) \times\ 100 \ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 4.5)}$$

$$Utilisation\ (\%) = \left(\frac{Utilised\ Time - (Delays + Standby\ Time)}{Total\ Available\ Time}\right) \times\ 100 \ldots\ldots\ldots\ldots\ldots \text{(Equation 4.6)}$$

Equation 4.5 is the equation for availability calculation used in this study. The actual running time is the time the equipment is available and ready to do work. This is obtained by deducting planned and unplanned downtime from the total time. The planned and unplanned downtime includes all the time the equipment was down due to breakdown failures or planned maintenance.

Different equipment availability levels are presented in Table 4.8 which shows the weekly average of 27%, 27%, and 71% for the MRB, MRR, and WC, respectively in 2021. The overall secondary rock-breaking equipment availability was 45% in 2021.

Equation 4.6 is the equation for utilisation calculation used in this study. The utilisation is the portion of the available time used to carry out a planned task. The utilised time is obtained by deducting the downtime, that is, delay time and equipment standby time from the available time. The delay and standby downtimes include operator breaks, line-up, travelling, fatigue, refuelling, awaiting dispatch orders, and lunch.

Based on Equation 4.6, the equipment average MRB, MRR, and WC utilisation in 2021 in Table 4.8 was 20%, 17%, and 58%, respectively. The overall secondary rock-breaking equipment utilisation was 33% in 2021.

Table 4.8: Equipment availability and utilisation from January 2021 to December 2021

Week No.	Deviation to Plan %	MRB Avail %	MRB Utilis%	MRR Avail %	MRR Utilis%	WC Avail %	WC Utilis%	SBU Avail %	SBU Utilis %
WK1	94%	19%	13%	12%	15%	45%	70%	41%	28%
WK2	63%	26%	22%	26%	15%	92%	65%	48%	34%
WK3	64%	23%	19%	16%	10%	60%	81%	47%	33%
WK4	69%	19%	18%	19%	15%	40%	68%	38%	28%
WK5	62%	35%	26%	22%	18%	47%	60%	45%	30%
WK6	62%	23%	20%	10%	10%	75%	62%	39%	27%
WK7	52%	23%	20%	19%	15%	72%	58%	38%	26%
WK8	16%	21%	19%	26%	20%	79%	54%	42%	32%
WK9	57%	30%	25%	18%	6%	78%	30%	42%	23%
WK10	53%	31%	20%	21%	10%	62%	80%	48%	31%
WK11	15%	35%	22%	37%	15%	88%	81%	51%	36%
WK12	73%	31%	30%	15%	10%	42%	88%	47%	31%
WK13	40%	33%	26%	26%	10%	93%	50%	51%	32%
WK14	19%	31%	20%	32%	22%	84%	71%	52%	39%
WK15	30%	30%	20%	30%	12%	78%	72%	41%	34%
WK16	51%	35%	3%	22%	10%	69%	64%	43%	27%
WK17	35%	45%	40%	24%	6%	70%	48%	46%	29%
WK18	29%	29%	19%	30%	24%	62%	51%	40%	33%
WK19	12%	29%	18%	39%	10%	79%	40%	35%	25%
WK20	43%	31%	26%	23%	20%	70%	60%	41%	30%
WK21	24%	26%	20%	36%	16%	86%	82%	51%	41%
WK22	0%	29%	16%	41%	30%	90%	74%	53%	45%
WK23	35%	33%	30%	18%	11%	75%	45%	52%	36%
WK24	37%	41%	12%	22%	6%	74%	70%	52%	29%
WK25	8%	28%	34%	48%	20%	87%	63%	49%	42%
WK26	17%	20%	14%	47%	22%	86%	71%	46%	41%
WK27	25%	22%	16%	31%	25%	83%	64%	47%	42%
WK28	6%	28%	25%	42%	30%	86%	56%	45%	42%
WK29	8%	25%	20%	55%	33%	82%	65%	51%	48%
WK30	39%	25%	20%	36%	20%	72%	0%	46%	40%
WK31	47%	14%	2%	23%	11%	56%	45%	31%	34%
WK32	45%	36%	35%	21%	11%	66%	74%	47%	31%

Week No.	Deviation to Plan %	MRB Avail %	MRB Utilis%	MRR Avail %	MRR Utilis%	WC Avail %	WC Utilis%	SBU Avail %	SBU Utilis %
WK33	16%	18%	13%	45%	25%	77%	60%	43%	38%
WK34	14%	32%	27%	64%	16%	89%	60%	54%	43%
WK35	3%	21%	16%	55%	30%	82%	65%	50%	47%
WK36	1%	26%	22%	49%	25%	84%	55%	49%	40%
WK37	90%	17%	10%	11%	15%	72%	62%	37%	29%
WK38	100%	17%	15%	0%	0%	0%	0%	51%	9%
WK39	39%	30%	23%	25%	10%	80%	60%	45%	30%
WK40	36%	45%	42%	32%	15%	74%	71%	47%	31%
WK41	5%	26%	20%	30%	35%	76%	55%	52%	36%
WK42	40%	25%	21%	19%	36%	71%	26%	48%	32%
WK43	100%	32%	31%	0%	0%	0%	0%	38%	19%
WK44	98%	14%	6%	0%	12%	44%	40%	35%	20%
WK45	45%	26%	10%	18%	10%	75%	65%	40%	28%
WK46	14%	32%	16%	45%	30%	85%	77%	54%	37%
WK47	11%	25%	10%	30%	25%	85%	50%	47%	34%
WK48	5%	29%	23%	42%	16%	90%	60%	47%	32%
WK49	36%	31%	19%	26%	20%	82%	70%	46%	39%
WK50	45%	26%	12%	24%	19%	74%	65%	48%	32%
WK51	55%	19%	6%	0%	12%	55%	70%	43%	35%
WK52	47%	24%	22%	16%	15%	56%	65%	43%	29%
Ave.	39%	27%	20%	27%	17%	71%	58%	45%	33%

Each of the equipment types were analysed for impact on the mining plan using the deviation from the mining plan for correlation analysis. First, MRR, followed by MRB, and lastly WC.

4.5.1 The impact of MRR availability on mining plan

This subsection presents a correlational analysis conducted between MRR availability and the deviation from the mining plan based on data presented in Table 4.8. The correlation coefficient was -0.856 and the coefficient of determination was 0.6834, as shown in Figure 4.12. This suggests that 68% of the change in the deviation from the mining plan is due to MRR availability. This means that the MRR availability correlates strongly with the mining plan but have a moderate causality.

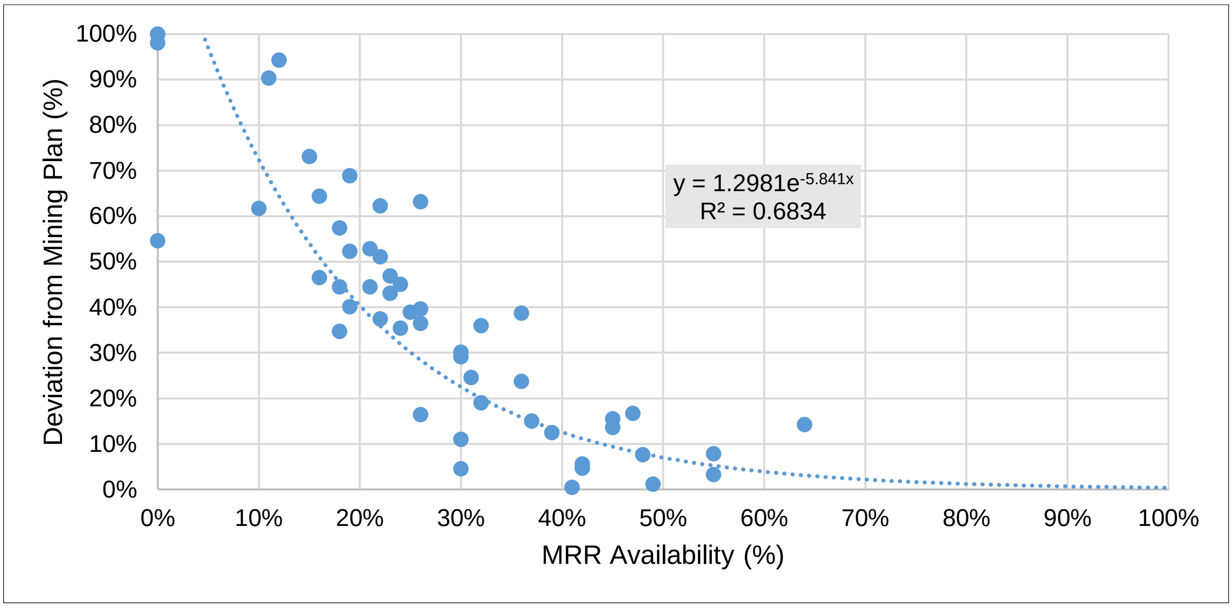

Figure 4.12: MRR availability deviation from the mining plan from January 2021 to December 2021

4.5.2 The impact of WC equipment availability on mining plan

This subsection presents a correlational analysis conducted between WC availability and the deviation from the mining plan based on data presented in Table 4.8. The correlation coefficient was -0.776 and the coefficient of determination was 0.621, as shown in Figure 4.13. This suggests that 62% of the change in the deviation from the mining plan is due to WC availability. This means that the WC availability correlates strongly with the mining plan but have a moderate causality.

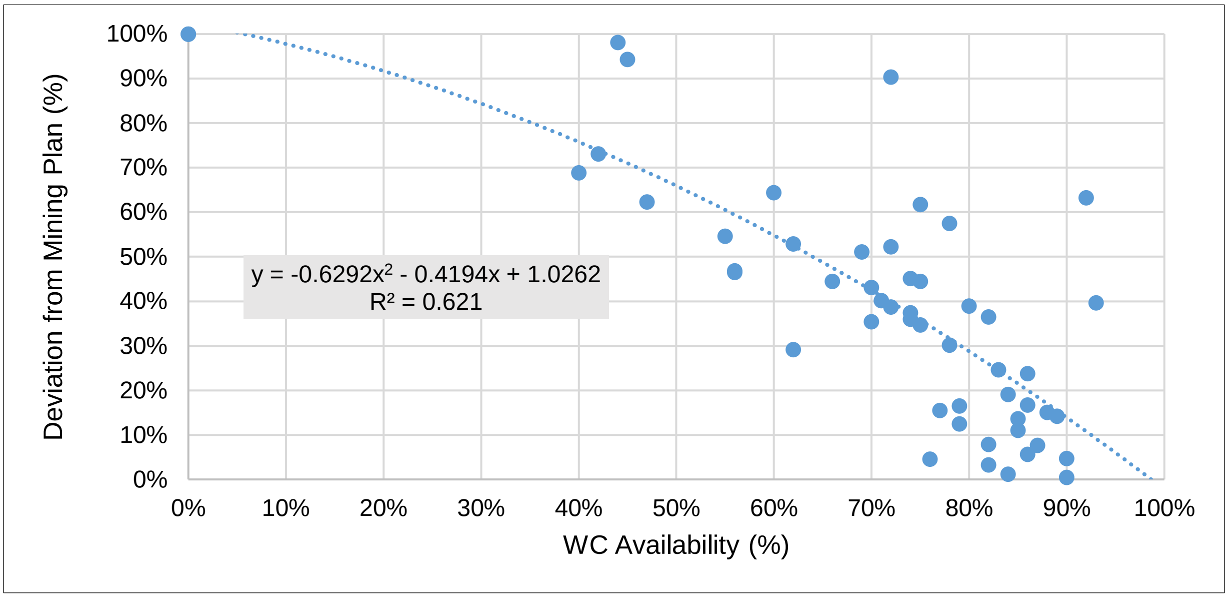

Figure 4.13: WC availability and deviation from the mining plan from January 2021 to December 2021

Usually, the use of WC does not bring immediate success. Some drawpoints are treated more than once before coming down. Thus, an additional measure entails focusing on the WC success rate, which is calculated by looking at the number of attempts that were successful against the overall number of attempts, expressed as a percentage in Equation 4.7.

$$Success\ rate\ (\%) = \left(\frac{Successful\ Attempts}{Total\ Number\ of\ Attempts}\right) \times\ 100 \qquad \textit{(Equation 4.7)}$$

Figure 4.14 shows the success rates of WC deployments against the number of hang-ups treated by WC. The average success rate of WC in 2021 was 68%. The success of WC is largely dependent on the skill of the operator. It should be noted that the WC is the first equipment type to be deployed in the case of a hang-up ahead of the MRR and with 68% average success rate, it means WC are crucial in ensuring acceptable cave availability and compliance to a mining plan.

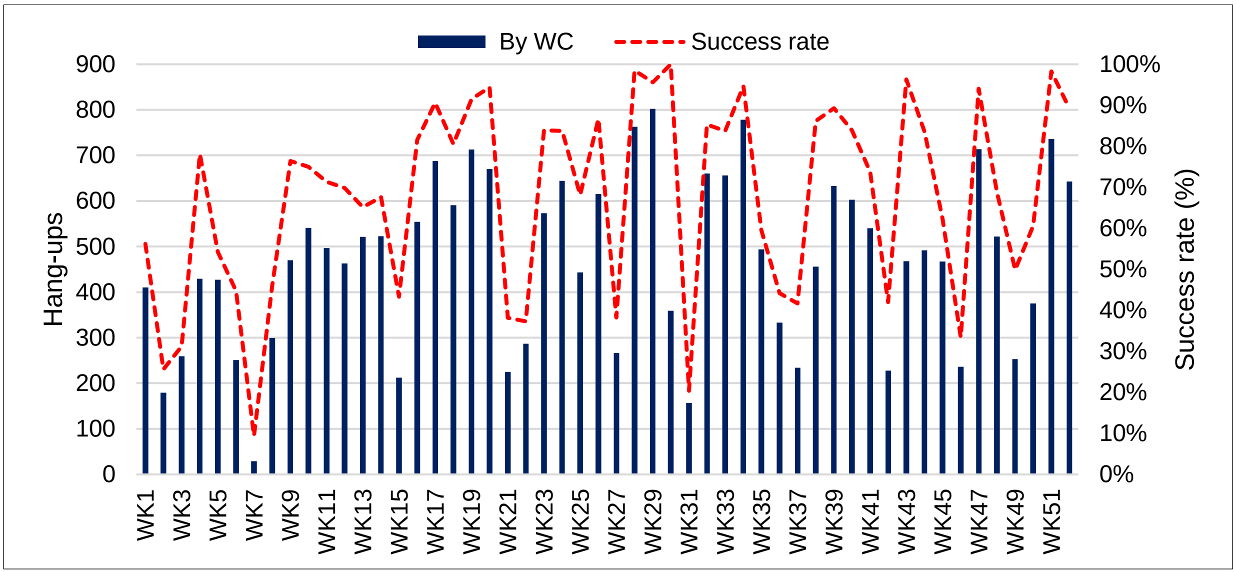

Figure 4.14: The number of hang-ups treated with WCs and their success rate in bringing down the hang-ups from January 2021 to December 2021

4.5.3 The impact of MRB equipment availability on mining plan

The study by Ngidi & Pretorius (2010) noted significant improvement in the number of oversized rocks broken per day due to MRBs. Figure 4.15 presents the number of oversized rocks broken from 2004 to 2021. At peak in 2011, 230 116 oversized rocks were broken and the number has been trending downwards since then reaching a low of 4 944 in 2018. In 2021, the total number of oversized rocks broken was 8 630, equating to the daily average of 24 rocks broken.

In addition, correlational analysis was conducted between MRB availability and the deviation from the mining plan based on data presented in Table 4.8. The correlation coefficient was -0.234 and the coefficient of determination was 0.084, as shown in Figure 4.16. This suggests that 8.4% of the change in the deviation from the mining plan is due to MRB availability. This means that the MRB availability has a weak correlation with the mining plan and a weak causality.

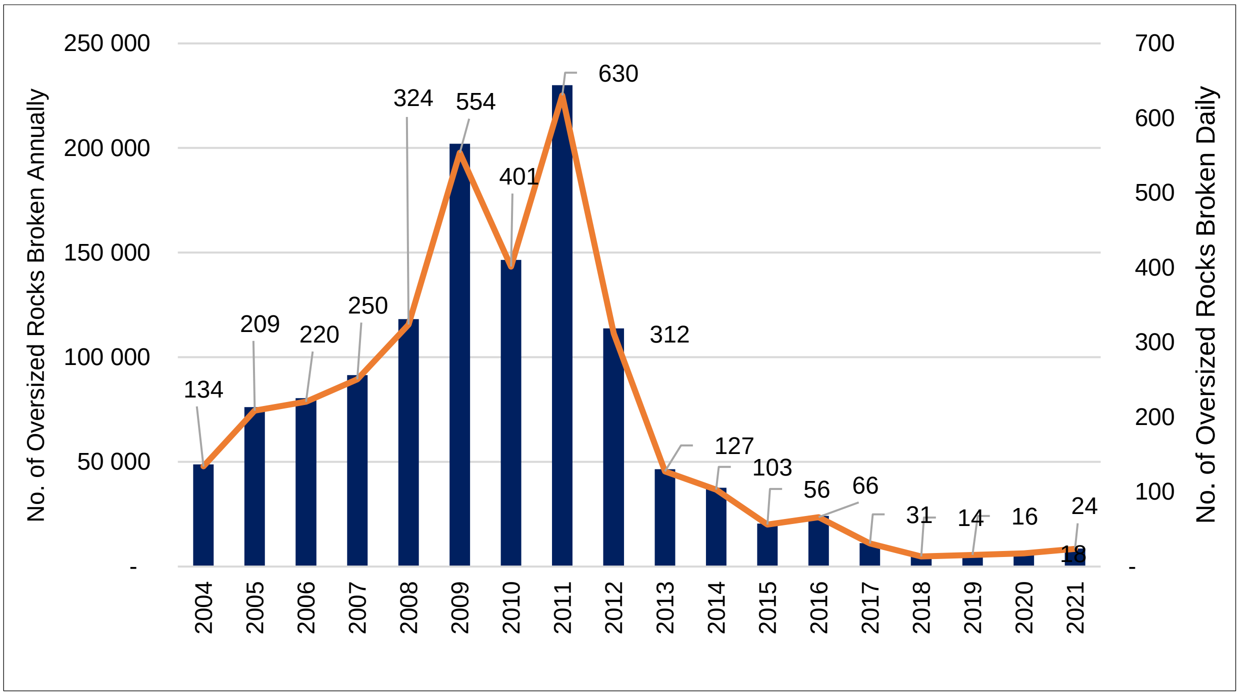

Figure 4.15: Oversize rocks broken by MRB from 2004 to 2021

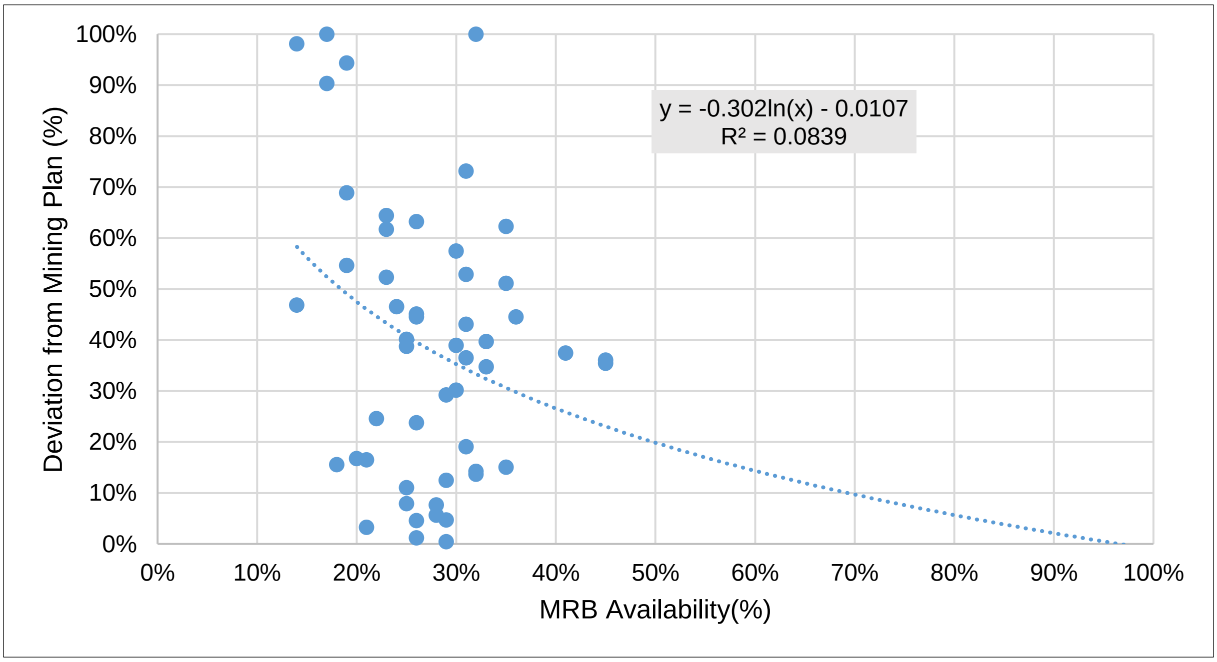

Figure 4.16: MRB availability and deviation from the mining plan from January 2021 to December 2021

4.5.4 The overall rock-breaking equipment availability impact on mining plan

This subsection presents a correlational analysis conducted between rock-breaking equipment availability and the deviation from the mining plan based on data presented in Table 4.8. The correlation coefficient was -0.467 and the coefficient of determination was 0.2184, as shown in Figure 4.17. This suggests that 22% of the change in the deviation from the mining plan is due to rock-breaking equipment availability. This means that the rock-breaking equipment availability has a moderate correlation with the mining plan and a weak causality.

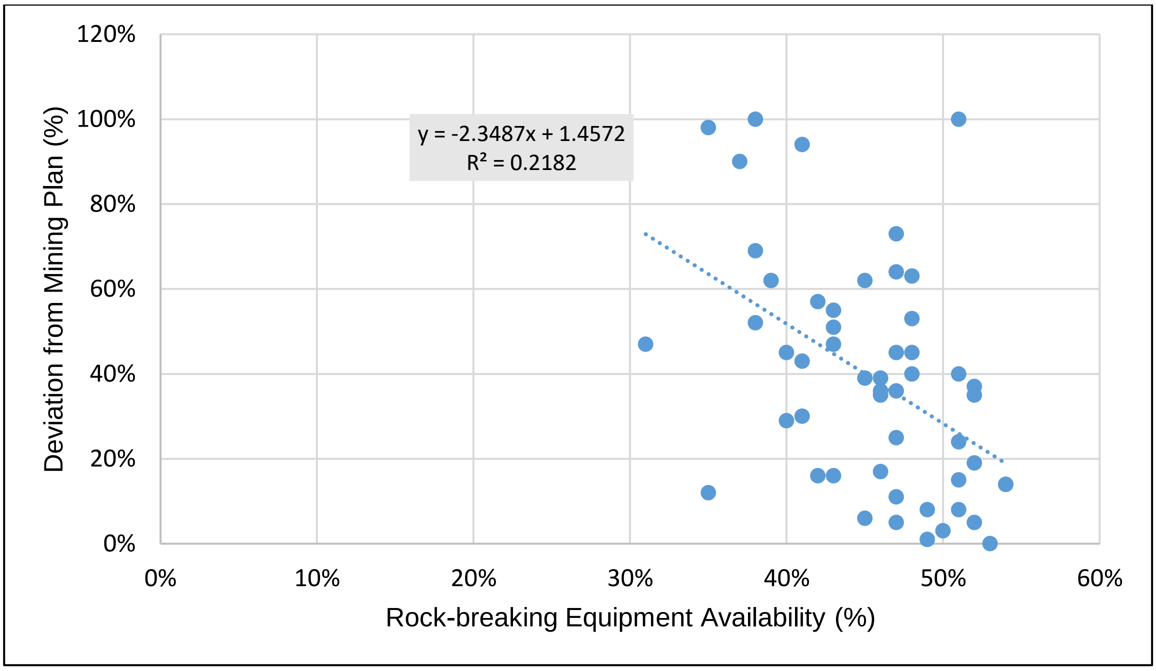

Figure 4.17: Rock-breaking equipment availability and deviation from the mining plan from January 2021 to December 2021

Having conducted correlational analysis between the availability of various rock-breaking equipment types and the deviation from the mining plan, the correlation in general is not strong enough to be able to determine the acceptable minimum availability for rock-breaking equipment at PMC.

4.5.5 The impact of rock-breaking equipment availability on cave availability

It was necessary to conduct a correlational analysis between rock-breaking equipment availability and cave availability based on data presented in Tables 4.5 and 4.8. The correlation coefficient was 0.32 and the coefficient of determination was 0.574, as shown in Figure 4.18. This suggests that 57% of the change in the cave availability is due to rock-breaking equipment availability. This means that the rock-breaking equipment availability has a weak correlation with cave availability and a moderate causality.

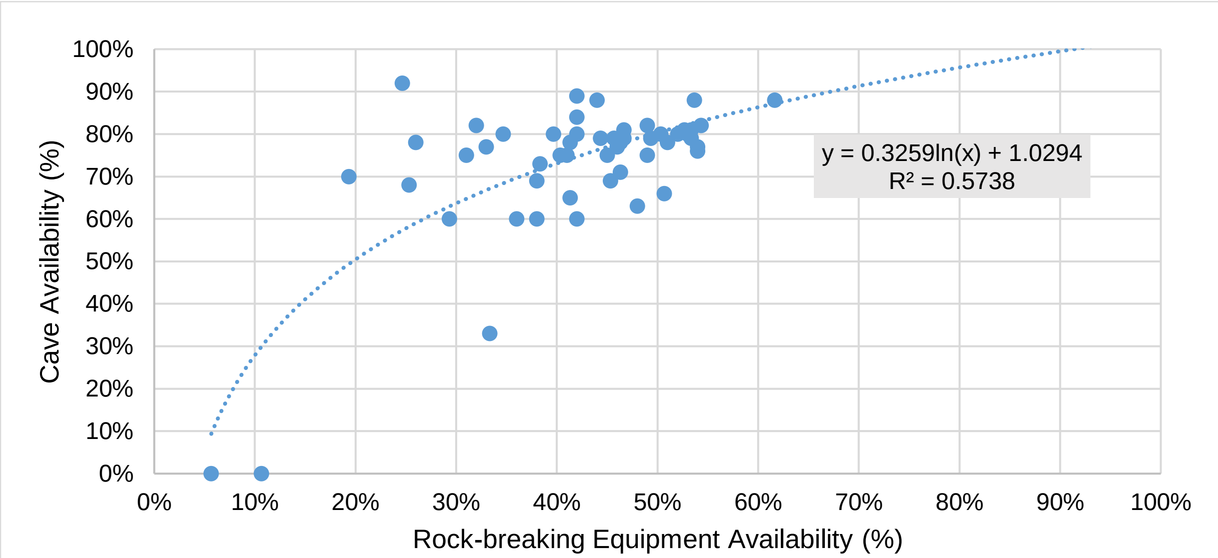

Figure 4.18: Rock-breaking equipment availability and cave availability from January 2021 to December 2021

4.5.6 The impact of rock-breaking equipment availability on loading compliance

It was also necessary to conduct a correlational analysis between rock-breaking equipment availability and loading compliance based on data presented in Tables 4.5 and 4.8. The correlation coefficient was 0.419 and the coefficient of determination was 0.7534, as shown in Figure 4.19. This suggests that 75% of the change in the loading compliance is due to rock-breaking equipment availability. This means that the rock-breaking equipment availability has moderate correlation with loading compliance and strong causality.

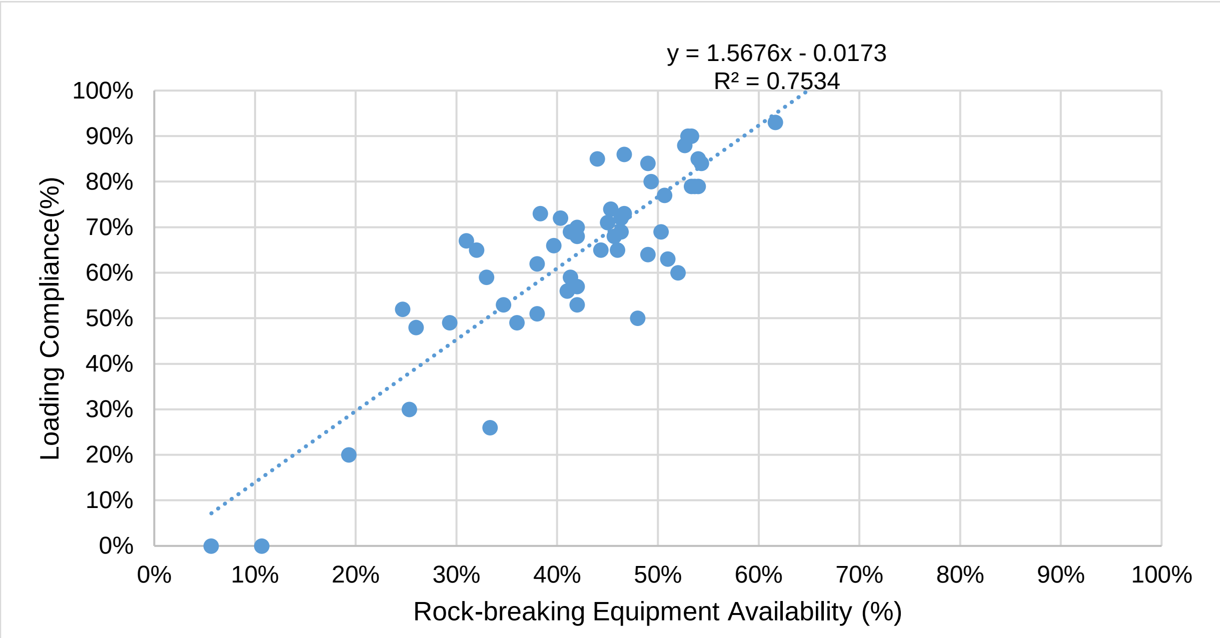

Figure 4.19: Rock-breaking equipment availability and loading compliance from January 2021 to December 2021

4.5.7 Discussion on acceptable rock-breaking equipment availability

Section 4.4 presented correlational analysis between MRR, WC and MRB availabilities and mining plan in 2021, using the deviation to the mining plan as a variable. The results were largely inconclusive in terms of answering the research question of what the minimum secondary rock-breaking equipment availability to mine to plan at PMC is. It then became necessary to look at period longer than a year. In this case, Table 4.9 presents data on loading compliance and rock-breaking equipment availability from 2015 to 2021.

Table 4.9: Rock-breaking equipment availability and loading compliance from 2015 to 2021

Year	Loading Compliance	MRR Avail%	MRB Avail%	WC Avail%	SBU Equipment Avail%
2015	81%	32%	55%	81%	56%
2016	84%	43%	49%	84%	59%
2017	84%	59%	37%	84%	60%
2018	-	-	-	-	-
2019	76%	63%	63%	76%	68%
2020	74%	65%	65%	74%	68%
2021	64%	27%	27%	71%	42%
Mean	77%	48%	49%	78%	59%

In Table 4.9, the 2018 data is missing due to the fire incident on the main feed conveyor underground which affected mining operations and therefore it was omitted in the calculation of averages. In this regard, the correlation coefficient between rock-breaking equipment availability and loading compliance from 2015 to 2021 was 0.9468 and the coefficient of determination was 0.9005, as shown in Figure 4.20. This suggests that over long term, a 90% of the change in the loading compliance is due to rock-breaking equipment availability. This means that historically the rock-breaking equipment availability has a very strong correlation with loading compliance and very strong causality.

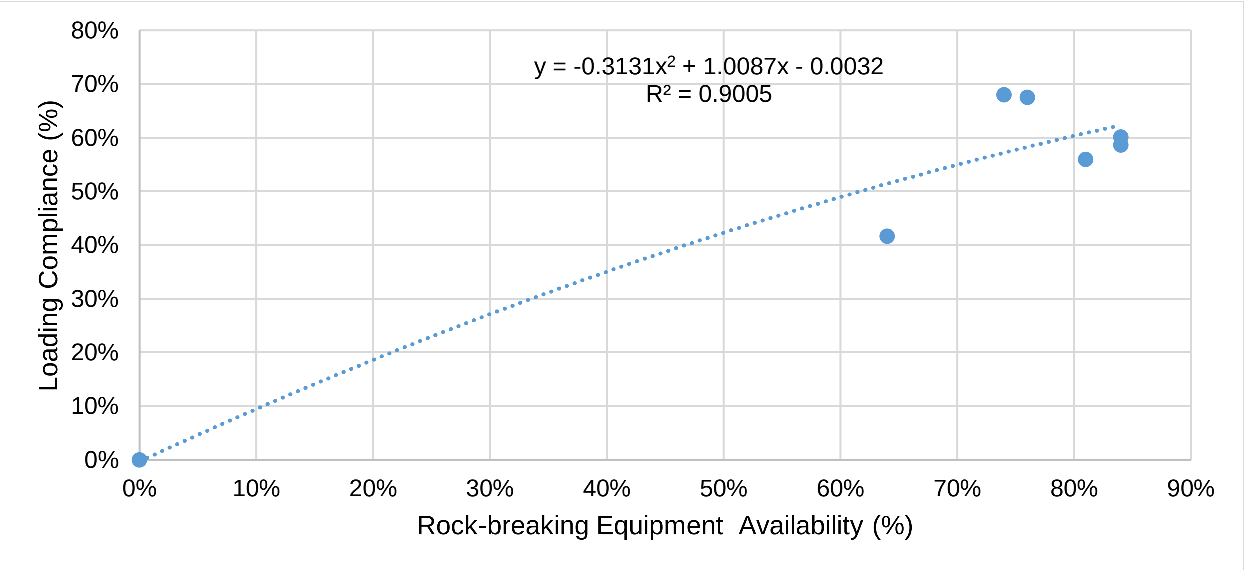

Figure 4.20: Rock-breaking equipment availability and loading compliance from 2015 to 2021

That would suggest that the 59% rock-breaking equipment availability is acceptable to maintain the loading compliance of 77%. Given that a very strong correlation and strong causality between the loading compliance and the mining plan was established in Section 4.4.2, it can be cautiously concluded that the minimum secondary rock-breaking equipment availability required to mine to plan at PMC is approximately 60%. This is, however, below the 65% percent target but above the 2021 level of 42%.

4.6 The Effect of Maintenance Strategy on Equipment Availability

This section sought to answer the question of *how the maintenance strategy at PMC has affected secondary rock-breaking equipment availability.* It was established in Section 4.4 that the overall rock-breaking equipment availability was 42% in 2021. In Section 4.4 factors contributing to availability levels and issues pertaining to the effectiveness of the maintenance strategy were not discussed but the focus was on finding whether a correlation existed between rock-breaking equipment and the mining plan, cave availability and loading compliance. In this section, the downtime contributing factors are discussed.

4.6.1 MRR equipment downtime contributing factors

Table 4.10 presents downtime data obtained from PMC. In Table 4.10:

- Downtime category relates to the type of downtime;
- Events is the number of times a downtime was reported;
- Duration is the combined downtime of all MRR in hours per category;
- Contribution is the proportion of each downtime category in relation to the overall downtime time in 2021; and

- Cumulative contribution is the cumulative percentage of the downtime for all categories, starting with the highest contributor to the lowest.

Table 4.10: MRR downtime categories from January 2021 to December 2021

Downtime category	Events (number)	Duration (hour)	Contribution (%)	Cumulative Contribution (%)
Machine rebuild	7	27 495	62%	62%
Electrical fault	87	5 261	12%	74%
Maintenance over-run	259	3 640	8%	82%
Engine cut out	55	2 321	5%	88%
Brake system failure	24	1 956	4%	92%
Boom functions fail	108	1 774	4%	96%
Hydraulic oil leak	300	875	2%	98%
Remote control failure	76	431	1%	99%
Tyre change	12	231	1%	100%
Fire suppress system	5	200	0%	100%

Table 4.10 presents data pertaining to major MRR downtime categories in 2021. The total number of events in 2021 was 933 with the hydraulic oil leak category being the highest with 300 events. However, a category with highest duration was machine rebuild with a total of 27 495 hours. Three MRRs at a time were not operational in 2021 due to machine rebuild.

The top three downtime categories, namely machine rebuild, electrical fault, and maintenance over-run contributed 82% of the total downtime in 2021. It should be noted that MRRs has exceeded their operational lives, as such, the maintenance strategy is to keep them running for as long as possible until the migration to Lift 2 mining block.

Figure 4.21 shows a plot of downtime categories against duration and the number of events. Although the machine rebuilds contributed 62% of the overall downtime, there were only seven events owing to the nature of the breakdown compared to hydraulic oil leaks. The turnaround time in downtimes such as hydraulic oil leaks and tyre changes are shorter than downtimes such as machine rebuild and electrical fault because they are easy to diagnose and repair.

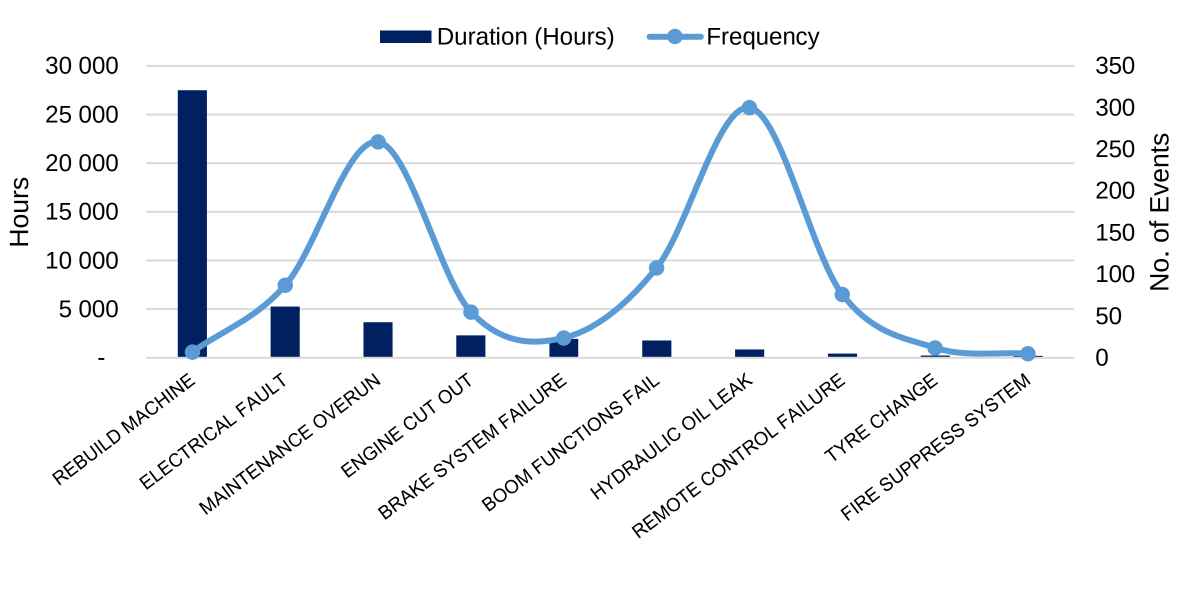

Figure 4.21: MRR top ten downtime categories from January 2021 to December 2021

Thus, in identifying the major contributors to the downtime of the MRRs, the Pareto chart was plotted, as shown in Figure 4.22. The Pareto-chart is useful when deciding on which factors to prioritise that can yield maximum gains. The three factors requiring prioritisation in maintenance with a combine contribution of 82 % of the downtime are machine rebuild, electrical fault, and maintenance over-run. Based on Figure 4.22, by putting resource to reduce the impact of these three breakdown categories, the MRR equipment availability could significantly improve.

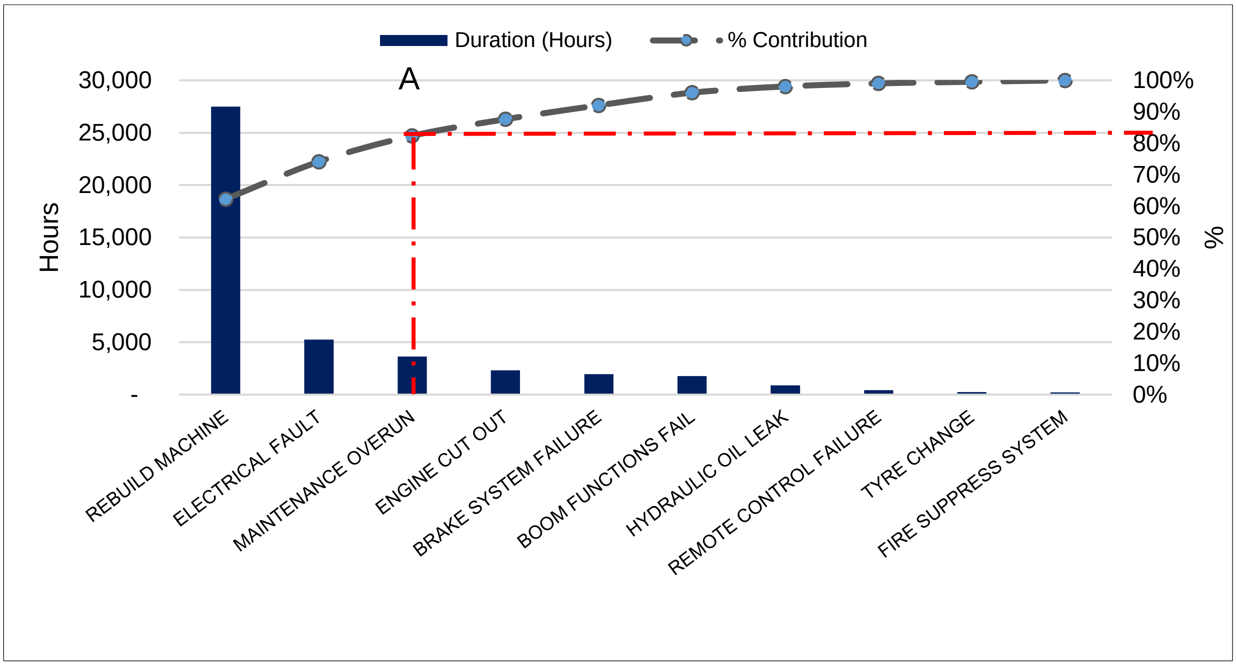

Figure 4.22: MRR downtime Pareto chart from January 2021 to December 2021

4.6.2 MRB equipment downtime contributing factors

Section 4.4 reported the MRB equipment availability of 27%, which is attributed to the 21 511 downtime hours, as shown in Table 4.11. There are ten categories of downtimes recorded for MRBs and the top five categories were hammer and boom failure, maintenance over-run, steering failure, transmission failure, and percussion hydraulic system, with contributions of 27%, 20%, 18%, 14%, and 6%, respectively. The results in Table 4.11 are graphically shown in Figure 4.23.

Table 4.11: MRB downtime categories from January 2021 to December 2021

Downtime category	Events (number)	Duration (hour)	Contribution (%)	Cumulative Contribution (%)
Hammer and boom failure	122	5 881	27%	27%
Maintenance overrun	70	4 219	20%	47%
Steering failure	259	3 838	18%	65%
Transmission failure	88	3 109	14%	79%
Percuss hydraulic system	135	1 257	6%	85%
Drive line failure	72	1 132	5%	90%
Hydraulic oil leak	150	1 101	5%	95%
Aircon fail	275	394	2%	97%
Bolting tool hydraulic	120	375	2%	99%
No operator	78	206	1%	100%

In Figure 4.23, category of downtimes is plotted against duration the number of events. The downtime with the highest events in 2021 was aircon failure (275) with the combined duration of 394 hours. However, hammer and boom failure occurred less than aircon failure, but its combined downtime was 5881 hours.

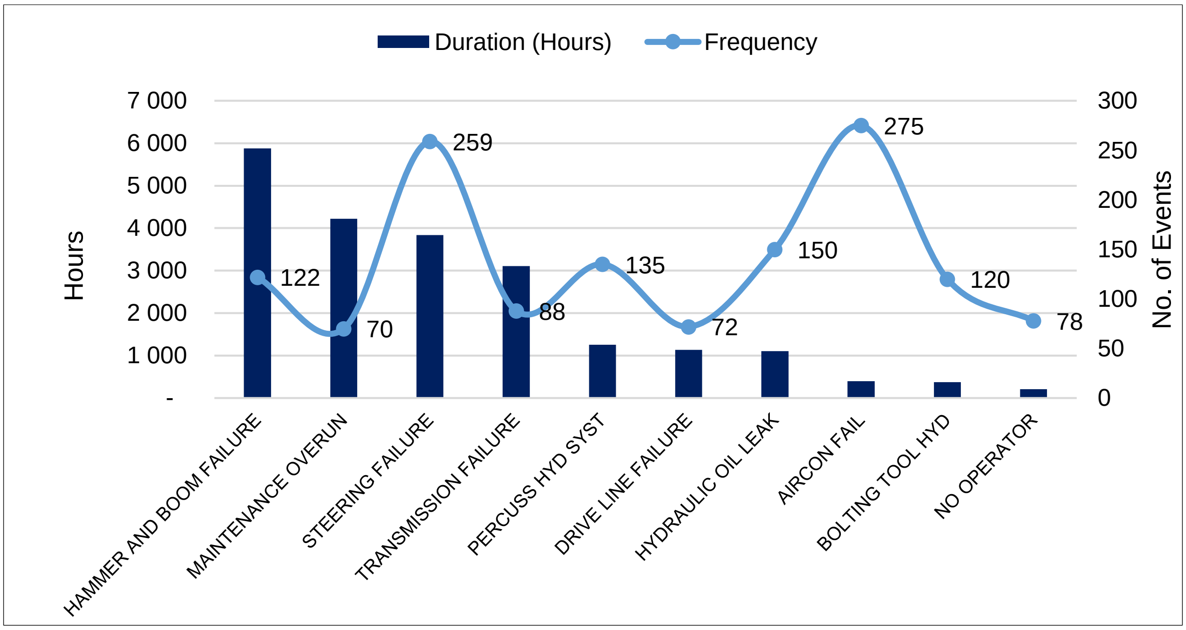

Figure 4.23. MRB top ten downtime categories from January 2021 to December 2021

The Pareto chart was used to highlight focus areas for improvement. The 79% of the downtime was caused by top four categories of downtime, which are indicative of areas for resource allocation and improvement. In terms of the Pareto principle, the focus should be on hammer and boom failure, maintenance over-run, steering failure, and transmission failure, as shown in Figure 4.24.

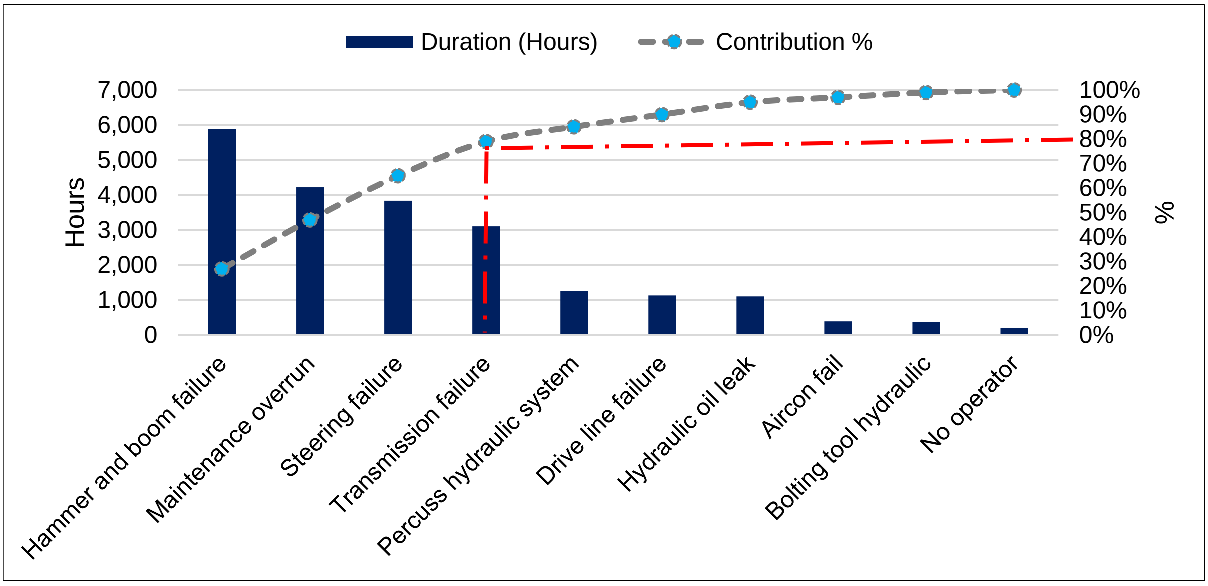

Figure 4.24: MRB downtime Pareto chart from January 2021 to December 2021

4.6.3 WC equipment downtime contributing factors

Table 4.12 presents data on downtime categories for the WC. There were 15 events of the maintenance over-run which had a collective duration of 2800 hours or an equivalent of eight days per event in 2021. The other downtime categories of grave concern in terms of time were electrical fault and remote-control failure. Overall, the collective WC downtime in 2021 was 8358 hours, with a total of 870 recorded events.

Table 4.12: WC downtime categories from January 2021 to December 2021

Downtime category	Events (number)	Duration (hour)	Contribution (%)	Cumulative Contribution (%)
Maintenance over-run	15	2 800	34%	34%
Electrical fault	240	1 210	14%	48%
Remote control failure	80	1 000	12%	60%
Mud in tank	125	850	10%	70%
Boom functions fail	70	640	8%	78%
Fire suppress system	41	500	6%	84%

Downtime category	Events (number)	Duration (hour)	Contribution (%)	Cumulative Contribution (%)
Gear failure to engage	45	489	6%	90%
Blocked nozzle	121	370	4%	94%
Hydraulic oil leak	77	349	4%	98%
Brake failure	77	150	2%	100%

Figure 4.25 is a graphical representation of Table 4.12, which depicts the downtime factors and their duration and the number of events. It can be seen in Figure 4.25 that electrical fault had total of 240 reported events, the highest compared to 15 of maintenance over-run.

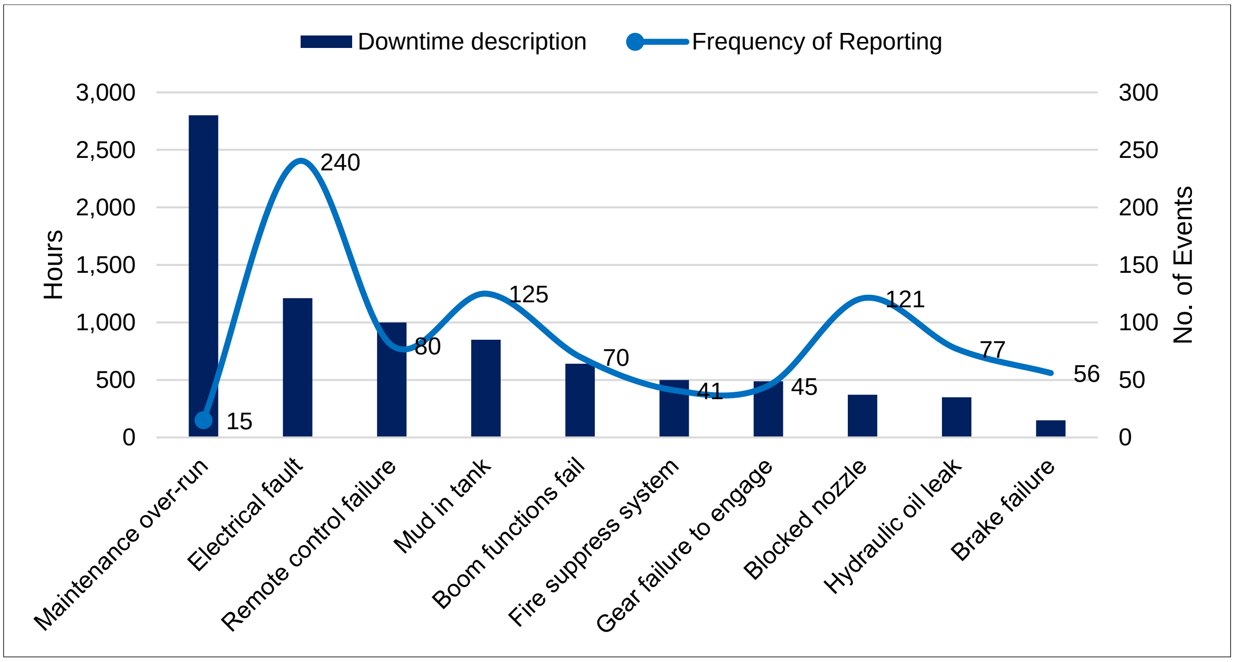

Figure 4.25: WC top ten downtime categories from January 2021 to December 2021

Figure 4.26 shows the Pareto chart for the WCs' downtime categories. In Figure 4.26, maintenance over-run, electrical fault, remote control failure, mud in tank, and boom functions fail accounted for 78% of the downtime and should therefore be prioritised to improve WC availability.

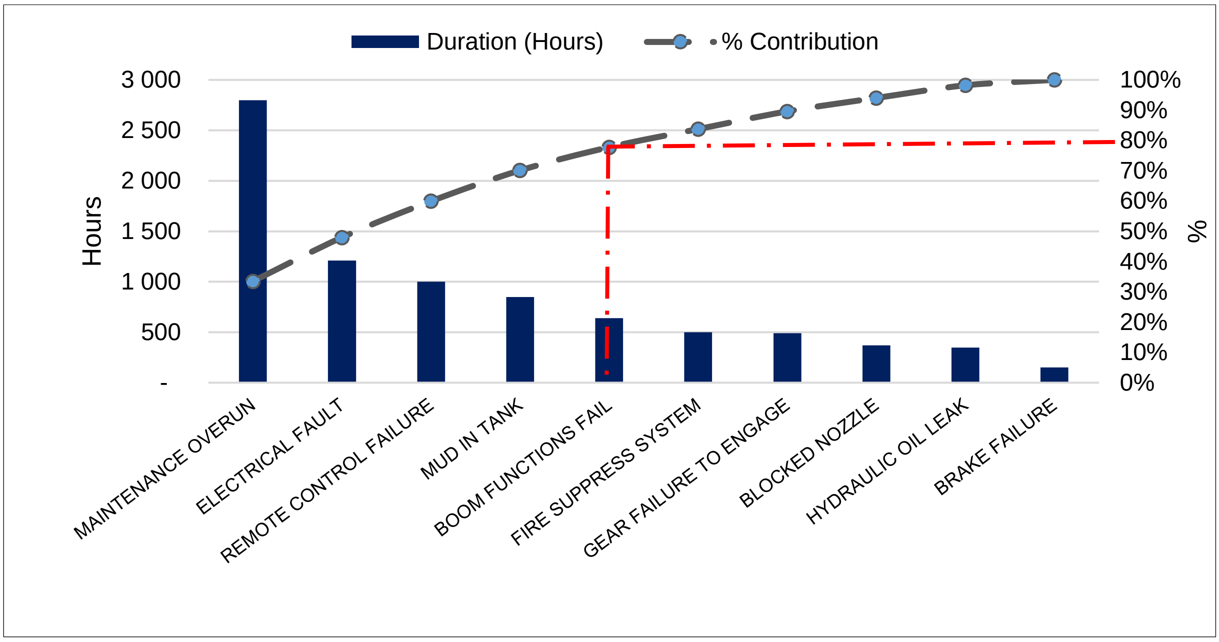

Figure 4.26: WC downtime Pareto chart from January 2021 to December 2021

4.6.4 Discussion on rock-breaking equipment maintenance

The categories that contributed 78% of the combined downtime for MRRs were machine rebuild, electrical fault, and maintenance over-run. Those that contributed 79% to the combined MRB downtime were hammer and boom failure, maintenance overrun, steering failure, and transmission failure. Those that contributed 78% to the WC downtime were maintenance over-run, electrical fault, remote control failure, mud in tank, and boom functions fail. The rational, based on Pareto principle, is that the aforementioned downtime categories per rock-breaking equipment type should be the focus areas for maintenance in the effort to increase the respective equipment availabilities.

Notwithstanding, the biggest downtime category for MRRs is machine rebuild with seven events and combined duration of 27 495 hours. As noted above, at any point in time in 2021, there were three MRRs out of six that were on long term rebuild downtime. The biggest MRB downtime was hammer and boom failure with 122 events and combined duration of 5881 hours. The biggest WC downtime was maintenance over-run with 15 events and combined duration of 2800 hours.

Perhaps the low hanging fruit in the effort to improve rock-breaking equipment availability is to eliminate the maintenance over-run. Table 4.13 shows the maintenance over-run of MRRs, MRBs and WCs. There were a total of 344 events of rock-breaking equipment maintenance over-run in 2021 with a combined duration of 10 695 hours or 44.4 days per operational equipment per year. Perhaps in this case, the Proactive Maintenance strategy, in particular, the Schedule Maintenance can be adopted with clearly defined maintenance time per equipment (see Figure 2.7).

Table 4.13: Maintenance over-run from January 2021 to December 2021

Downtime category	Events (number)	Duration (hour)	Contribution (%)
MRR Maintenance over-run	259	3 640	8%
MRB Maintenance overrun	70	4 219	20%
WC Maintenance over-run	15	2 800	34%

4.7 Chapter Summary

This chapter presented the analysis of 52-week data largely obtained from PMC central database in 2021 to achieve objectives and answer the research questions posed in Chapter 1. Firstly, the cave management systems was discussed, including the mapping of the drawpoint statuses in January 2021. In addition, the prevalence of hang-ups and blockages were discussed with the view of comparing the current PMC block cave with the feasibility predictions. It was also established that the cost of explosives has a very strong correlation with the number of hang-ups experienced and that the causality was strong.

The correlational analyses between the mining plan using the deviation to the mining plan, and cave availability and loading compliance were conducted. It was concluded that cave availability has a strong correlation with the mining plan with moderate causality while the correlation between loading compliance and the mining plan is very strong and the causality is strong. Due to this finding, Equation 4.4 was derived to predict the deviation from the mining plan due to loading compliance at PMC.

The correlation analyses between the deviation from the mining plan and the MRR, WC, MRB, and overall rock-breaking equipment respectively was conducted. The correlation ranged from strong to weak and similarly causalities ranged from strong to weak. The combinations of correlations and causalities were not acceptable to derive a useful regression equation.

Lastly, using Pareto charts, categories of downtime regarding MRR, MRB and WC that the mine should focus at to increase rock-breaking equipment availability were identified with maintenance overrun being common among the three equipment types. It was then concluded that a quick win will be to eliminate the maintenance overrun by adopting the Schedule Maintenance strategy with clearly defined maintenance time per equipment.

The next provides concludes the research by providing a summary of salient points emanating from the research and further provides recommendations on complementary research that could be undertaken.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The aim of this research was to understand the impact that secondary rock-breaking equipment has on the mining plan at the PMC block cave. The proxy for the mining plan in this research was the copper content, with planned copper content being the proxy for the mining plan and the actual (achieved) copper content being the proxy for the achieved mining plan. The absolute difference between the two proxies was deem as the deviation from the mining plan.

The objectives of this research were framed in Section 1.6 and the related research questions were posed in Section 1.7. To adequately achieved the objectives of this research and answer the research questions, the review of the literature was undertaken in Chapter 2 and the research methodology was framed in Chapter 3 as well as the research method. The literature review sought to understand the caving mechanism and related block caving problems, especially with respect to the PMC Lift 1 block cave. In general, the rockmass being caved in PMC is competent and this was among the first competent rockmass in the world to be mined with a block caving mining method. It can be appreciated that competent rockmass in block caving would result in coarse fragmentation and this is the case with the PMC block cave.

Coarse fragmentation leads to hang-ups in block cave. It is in this context that the literature on the cause and nature of hang-ups was reviewed and the control mechanisms. It was established that draw control is paramount in ensuring even draw and stress distribution in the block cave. Draw control is also related to the mining plan. However, the draw control execution can be interrupted by hang-ups and drawpoint blockages. The effective remedy to hang-ups and drawpoint blockages is the deployment of rock-breaking equipment. In the case of PMC, this would be medium reach rigs (MRR), mobile rock breakers (MRB), and water cannons (WC). It therefore would mean that the maintenance of this equipment is important in maintaining a productive block cave that mines competent rockmass as is the case at PMC.

Following the description of the research methodology and method in Chapter 3, Chapter 4 firstly sought to answer research questions posed in Chapter 1 and so doing, achieve the objectives of this research. The first research question was about *how the current PMC cave compares with the feasibility predictions* discussed mainly by Ngidi & Pretorius (2010). To answer this question, it was necessary to describe the cave management at PMC to map the drawpoint statuses in 2021 in relation to the design profile. Furthermore, the prevalence of hang-ups and drawpoint yield was discussed. In this regard, it was established that there is a very strong positive correlation between the explosives cost and the number of hang-ups with strong causality. In the end, bar the collapse of crosscut 11 and the open pit slope failure, it was concluded that the Lift 1 block cave behaves as predicted even though it has exceeded its planned life.

Secondly, Chapter 4 sought to answer the research question of *what the relationship between cave availability and loading compliance and the mining plan is at PMC.* In this case, correlational analysis between the deviation from the mining plan and both cave availability and loading compliance was conducted. The cave availability is the ratio of the number of available drawpoints for loading against the total number of active drawpoints and loading compliance is the difference between the assigned and the actual loads per drawpoint expressed as a percentage. It was concluded from the analysis that cave availability has a strong correlation with the mining plan but have a moderate causality. The correlation between the loading compliance and the mining plan was discussed and it was established that the correlation between the two was very strong and the causality was strong. Due to this finding, Equation 4.4 was derived to predict the deviation from the mining plan due to the loading compliance at PMC.

Thirdly, Chapter 4 sought to answer the research question of *what the minimum secondary rock-breaking equipment availability required to mine to plan at PMC is.* It was established that the MRR availability correlates strongly with the mining plan but have a moderate causality, the WC availability correlates strongly with the mining plan but have a moderate causality, and the MRB availability has a weak correlation with the mining plan and a weak causality. Overall, the rock-breaking equipment availability has a moderate correlation with the mining plan and a weak causality. Furthermore, it was established that the rock-breaking equipment availability has a weak correlation with cave availability and a moderate causality, and moderate correlation with loading compliance and strong causality. However, when data from 2015 to 2021 was considered, it was found that rock-breaking equipment availability has a very strong correlation with loading compliance and very strong causality. Given that the long term rock-breaking equipment availability of 59% resulted in 77% loading compliance, it was cautiously concluded that the minimum secondary rock-breaking equipment availability required to mine to plan at PMC is approximately 60%, well above the 2021 availability of 42%.

Lastly, Chapter 4 sought to answer the question of *how the maintenance strategy at PMC has affected secondary rock-breaking equipment availability*. It was established that downtime categories of machine rebuild, electrical fault, and maintenance over-run jointly contributed to 78% of the MRRs downtime duration. The combined MRB downtime that contributed 79% of the downtime duration were hammer and boom failure, maintenance overrun, steering failure, and transmission failure. The combined

WC downtime that contributed 78% of the downtime duration were maintenance over-run, electrical fault, remote control failure, mud in tank, and boom functions fail. It was concluded that a quick win will be to eliminate the maintenance overrun by adopting the Schedule Maintenance strategy with clearly defined maintenance time per equipment.

5.2 Recommendation for Further Studies

As the study was unfolding, there were various discoveries brought to light that have sparked an interest to conduct further studies. The following list contains possible research that could be carried out in the future relating to secondary rock-breaking equipment:

- The investigation of the equipment service life influence on the mining block productivity.
- Role played by operators in influencing grade recoveries and minimising dilution.
- Investigation of technologies to predict hang-ups and find proactive response measures.
- Dynamic production simulations to establish the sensitivities and or/impact to a PCBC/production schedule if hang-ups occur at different probabilities and various treatment durations (probability distributions).
- More detailed investigation as to why/when the different hang-up treatment methods are used and the personal experiences captured of the crews that uses them.
- The Impact of hang-ups on the operation in the future when available draw points decrease over time and the occurrence of oversized material increases (which will happen due to the nature of block caving operation)

- Investigate the efficiency of the crews treating the hangups (treatment success rate, techniques used, risks taken, etc.)
- Occurrence of oversized material as a product of draw control compliance/deviation.

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