School of Mining Engineering

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WHAT IS THE OPTIMAL PUSHBACK DIMENSION FOR SISHEN MINE THAT WILL COMPLEMENT ITS CURRENT MINING FLEET?

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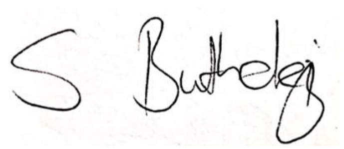
A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2025

DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

I have familiarised myself with the University of the Witwatersrand Student Academic Misconduct Policy (SAMP). I hereby declare that the work I am submitting for assessment is my original work. I affirm that I have not plagiarised, misrepresented, or colluded with any other person or source. I have properly acknowledged, cited, and referenced all the sources that I have used in my work. I also declare that where I have used artificial intelligence (AI) tools it has only been as a means of guidance. The ideas and arguments presented in my work are my original thoughts and interpretations. I acknowledge that any academic misconduct, such as plagiarism or collusion will result in serious consequences. According to the SAMP, these consequences may include a reduced grade, a fail mark, or disciplinary action. The Faculty of Engineering and the University of the Witwatersrand have my consent to investigate any potential academic misconduct in my work. This investigation may include the use of similarity and AI detection software to check the originality of my work. I undertake to abide by the decision of any such investigation.



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ABSTRACT

Sishen mine has been an operational mine for over 70 years mining the orebody by means of pushbacks. There has never been a study done on the operation to determine the optimal pushback width that will be suited with the equipment that will be used at the operation. This was never seen to be a problem in the past due to high iron ore prices and mining lower stripping ratio areas so the Life of Mine (LOM) has never indicated an ore deficit until now. This has triggered the company to be forced to interrogate the current pushback widths and to fully understand with the mining fleet that is being used at the mine what the optimal pushback width would be.

Research on pushback configurations primarily examines geometric limitations, and there are limited studies on determining the ideal pushback dimensions. The assumptions regarding production rates incorporated into a company's long-term strategies typically rely on historical data, with slight annual enhancements factored into the outer years. If historical data rates are not fully grasped, their application can result in misleading conclusions.

Earlier research determined optimal mining width, mainly by optimizing pushback width based on tonnage, ignoring specific equipment. This leaves a gap that once the pushback width has been identified, then what mining fleet should be deployed in that pushback to ensure that the pushback will be mined optimally. A lack of precise comprehension may lead mining firms to acquire machinery that does not match their pushback specifications, resulting in suboptimal fleet utilization.

This research focuses on the Sishen mine to analyse the existing mining fleet and determine feasible pushback widths, creating practical designs. Evaluating the designs with a schedule and cash flow analysis to determine the best mining width based on NPV and IRR.

Mining enterprises around the world can apply a consistent approach to identify the most effective pushback width that aligns with their machinery capabilities. This strategy of designing pushback widths for a specific mining fleet will be particularly beneficial for new mining ventures, yet it remains applicable to ongoing mining operations as well.

“Success is no accident, it is hard work, perseverance, learning, studying, sacrifice, and most of all, love what you are doing or learning to do”

Pele

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1 INTRODUCTION

Nestled within the vast expanse of the Northern Cape province in South Africa, Sishen mine is a large open-pit iron ore mining operation that employs traditional mining methods. The mining operation, which initially began its journey in the year 1953, has remarkably evolved into a mining asset of global significance. Presently, it boasts an impressive production capacity of approximately 30 million metric tonnes of iron ore each year, catering not only to the local market but also facilitating substantial export activities. Sishen stands out as the top mine in the iron and manganese-rich region of the Northern Cape, consistently holding the position as the primary private financial supporter of the Northern Cape province. The mine employs about 10,000 individuals, comprising both permanent employees as well as contractors (Kumba Iron Ore, 2023).

Mining utilises traditional methods of drilling and blasting, as well as loading and hauling, using a substantial number of large trucks and shovels. Waste rock is stripped from the 12km long pit and backfilled in-pit or tipped on-surface waste dumps. A total of 190Mt is mined annually with approximately 37Mt of Run of Mine (ROM) extracted from the pit annually. The material is mixed, broken down, sifted, and based on its refining properties, enhanced in either the Dense Medium Separation (DMS) or Jig processing facilities. The processed ore is stacked on beds and later loaded onto train trucks for global delivery to customers (Kumba Iron Ore, 2023).

Sishen mine is situated approximately 822 km north-north-east of Cape Town and 522 km to the west of Johannesburg, as shown in Figure 1-1. The mine site is approximately 1 200m above sea level and the nearest towns and cities are:

- Kathu 8km (east)
- Vryburg 200km (north-east)
- Kuruman 50km (east)
- Upington 200km (south-west)
- Postmasburg 65km (south)
- Kimberley (city) 280 km (south-east)

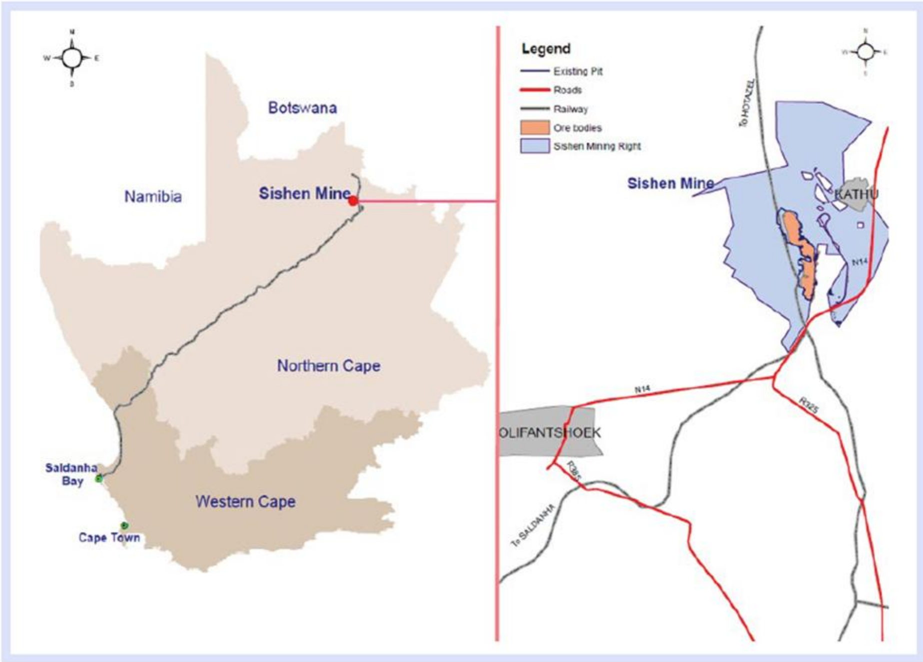

Figure 1-1: Sishen mine location *(Kumba Iron Ore, 2023)*

Kathu is the closet town to the mine where most employees reside. The Sishen Mine has access to the national road network via the N14 for all tarred road transport requirements and its own airport for private and regular commercial flights from Johannesburg (Kumba Iron Ore, 2023).

The mine is connected to the Eskom grid for power and has self-sufficiency in water resources, including both potable and processed water extracted from various boreholes (Kumba Iron Ore, 2023).

The mine boasts reliable and properly kept facilities. It is connected to Transnet's Sishen-Saldanha rail line, which spans approximately 861 km in length, for shipping ore through the Saldanha harbour. Additionally, there is a connection to the national rail line system for the transportation of ore to steel mills located in Gauteng (689km) and northern KwaZulu-Natal in South Africa (Kumba Iron Ore, 2023).

The central part of Kathu town can be found 8 km to the east of the mine. The residential areas of Sesheng and Mapoteng (approximately 2 km north of the mine entrance) house many of the mine’s labor force. The mine's location falls within the Gamagara Municipal Boundary, which forms part of the Kgalagadi Regional District (Kumba Iron Ore, 2023).

1.1 Research Background and Context

Sishen mine exploits its massive iron ore resource through open pit mining using pushbacks. Pushback designs are preferred as only a certain amount of stripping is needed to expose the required ore for a specific period. This approach facilitates the distribution of stripping across the Life of Mine (LOM), thereby reducing the upfront investment necessary to access the initial ore. Once the ore has been exposed, stripping can be included as an operational expenditure.

Sishen mine comprises 20 pushbacks with diverse mining widths. Assessing the optimal mining width is vital, particularly since pushback D (which will be detailed in the study) exemplifies the problem of certain pushback widths being too excessive. The production capability of the current mining fleet should drive the optimal pushback width. To meet the company's corporate objectives, pushbacks must be designed to complement the production capability of the mining fleet. If there is a mismatch between the width of the pushback and the production capability of the mining fleet, then there is a high probability that the company's corporate objectives will not be met.

Sishen mine’s 2023 LOM plan illustrated that by scheduling a certain pushback, which for the purpose of this study will be referred to as Pushback D, the required ore will not exposed in time. This is due to the existing mining fleet not complimenting the mining width hence increasing the stripping requirements associated with Pushback D. This comes as a result of the lack of understanding of the minimum pushback width ideal for the mining fleet to meet the company’s objectives. The delayed exposure will lead to an ore shortage starting in 2029, as the stripping process in that area requires excessive time. This highlighted that to meet the company’s objectives, either the mining fleet needs to be increased to expedite the stripping or to reduce the pushback width of Pushback D.

The company did not have an appetite to increase the mining fleet by either increasing the owner fleet or introducing mining contractors to expedite the stripping. This is mainly due to the capital expenditure associated with increasing the owner fleet as well as the operational costs associated with introducing contractors. The company wanted to understand with the current mining fleet, what pushback width would be practically suitable for Sishen Mine to meet the company's objectives.

There is no clear guide that mine planners can use to determine the optimal mining width for pushback designs that align with a specific mining fleet. This process is usually an iterative process, as multiple widths need to be designed and scheduled before finding the optimal mining width that aligns with a specific mining fleet.

Variations in geological formations across different regions complicate the process of establishing benchmarks with other mining operations, making it challenging to identify the optimal pushback width necessary for exposing a specific volume of ore, given a particular mining fleet.

1.2 Problem Statement

Sishen faces the challenge of ascertaining the optimal mining width, considering the operational capabilities of the mining fleet, the geological context, and the company's objectives.

The 2023 LOM schedule indicated that from 2029 there would be an ore deficit as the ore from Pushback D will not be exposed on time. This was misaligned with the company's objectives and other mitigation measures needed to be put in place to try to close that ore deficit.

The existing economic conditions prevent the organisation from allocating funds for the acquisition of a mining fleet or from raising its operational costs by hiring mining contractors to achieve its business goals. Therefore, the mine planning team is responsible for determining the most effective pushback width for the mine, considering the existing mining fleet to align with the corporate goals of ensuring a steady ore supply.

1.3 Justification for Research

The mining width of a pushback will determine the amount of ore and waste that will be mined in that particular pushback. The wider the pushback the more ore and waste to be mined in that pushback and the inverse is also true. The wider the pushback the more stripping is required to expose the ore but once the ore is exposed the ore will be mined for a longer period. One of the objectives of exploiting orebodies using pushbacks is to reduce the stripping time to get to the ore sooner.

The duration at which an operation can maintain stripping without facing a shortfall in ore is determined by the production capacities of its mining fleet. The production capacity of a mining fleet determines the pushback width. The greater the capacity a wider pushback and the narrower the capacity the narrower the pushback that can be mined by the mining fleet.

Open-pit operations need to understand the production capabilities of their equipment and use that rate to determine the optimal mining widths of their pushbacks. Sishen mine currently has not defined the optimal mining width based on its mining fleet to meet the business expectations.

1.4 Research Aims and Objectives

This study aims to achieve the following:

- Firstly, to define and understand the production capabilities of the mining fleet that is currently deployed at Sishen mine. Historical performance of the mining fleet will be used to determine production capabilities.
- Once the current Sishen mine equipment capabilities has been identified, then the study aims to identify the optimal mining width that will be best suited to compliment the current mining fleet. The pushback D will be redesigned into different mining widths for this analysis.
- A bench productivity model will be built in order to know the mining rate that should be scheduled per mining width to guide the scheduling process.

- The schedule results will then be run through a financial model to determine the Net Present Value (NPV) of each design to determine which mining width is the most economical.

1.5 Sources of Data

The Sishen mine database is used to obtain the production equipment's past performance which is used to determine the production capability. The 2024 geological and geotechnical block models and optimisation pit shells is used to guide the pushback designs. A factor is used to adjust Anglo-American's approved 2024 financial assumptions to be used to calculate the cash flow for each of the design sets.

1.6 Research Limitations

The research will have the following limitations:

- The research will only be based on the current Sishen mining fleet and will be limited to only the pushback D area.
- The research assumes the production rates for the equipment whereas in other operation the equipment could have higher or lower production rates.
- The Sishen Standard Operating Procedure (SOP) will be used in for the study which may not necessarily apply to other mines.

1.7 Structure of the Research Report

This research report consists of seven chapters. Chapter 1 is the introduction and covers the background of the research topic, the problem statement, the justification for the research, and the research objectives.

Chapter 2 reviews the existing literature regarding the principle of pushback designs and principles that govern the minimum mining width that is required for a certain mining fleet. The chapter examines three geometric constraints that are associated with pushback designs and finally looks at key controversies that are associated with pushback designs as well as other research that has been done to calculate the ideal pushback width.

Chapter 3 provides a detailed explanation of the methodology that will be systematically implemented in the research. This methodology is composed of six interrelated sections, and each of these sections is concisely outlined, with every individual section receiving its own distinct chapter for in-depth discussion.

Chapter 4 the three proposed mining widths to separate the Pushback D are introduced, emphasizing the rationale behind their selection for the study. The chapter provides visual representations of three design sets and their respective volumes. This chapter then summarizes the volume difference between the three design sets and the overall stripping ratio of each of the design sets.

Chapter 5 looks at the current mining fleet that is used at Sishen mine and examines the historical production performance for each of the equipment. In this chapter, based on previous equipment performance a systematic bench productivity model is built to understand the various production rates that can be achieved based on a particular dimension. This productivity model aims to guide the production rate that should be used to schedule the various design sets per bench based on the dimensions of the bench.

Chapter 6 indicates the schedule results of each of the design sets based on the productivity model. This chapter looks at which of the design sets when scheduled will complement the current mining fleet to meet the company’s expectations. This chapter also looks at the financial impact of each of the design sets by building a financial model to assess the feasibility of each of the design sets. The design sets are then rated to determine which of the design sets is the most economical option for Sishen mine.

Chapter 7 summaries the findings and the conclusion of the study by looking at the various design sets and identifying the advantages and disadvantages of each of the design sets for Sishen mine and recommends the optimal mining width that Sishen mine should base its pushback designs based on the current mining fleet.

2 LITERATURE REVIEW

Developing a strategic approach for long-term production in open pit mining significantly enhances the financial stability of the mine. Long-term planning serves as a crucial framework that effectively guides individuals and organisations in successfully achieving their short-term and mid-term goals and objectives. To conduct a comprehensive long-term production planning, the area of the mine is systematically partitioned into several progressively developing pits or nests. Following this division, these pits are carefully analysed with respect to a range of technical considerations regarding specific parameters, which results in their conversion into structured pushbacks (Kakha & Monjezi, 2017).

In the push back design methodology, multiple layers of pits are created and subsequently evaluated as potential push backs, taking into account the essential minimum width criteria for push backs. The creation of these nested pits results from the analysis of a specific economic factor, such as the price of commodities, costs associated with mining or processing, or the stripping ratio. The key feature of these push backs is that the innermost layer possesses the greatest value per ton, followed by the second innermost layer, which holds the next highest value, and this pattern continues outward (Gholamnejad & Osanloo, 2007).

In the next step, production strategies are formulated for each pushback, enabling the mine to fulfil its comparative production plan. Essentially, the primary aim of the design behind pushbacks is to provide a comprehensive framework of long-term strategies that dictate the systematic extraction of mineral blocks over time, ultimately striving to achieve the highest possible net value at the present moment (Kakha & Monjezi, 2017).

A significant volume of non-valuable material must be removed, known as stripping, as shown in Figure 2-1 it depletes the fundamental principles of open pit mining to uncover the orebody in open pit mine. The ore that is mined is either sent to designated stockpiles, sent directly to the process plant, or even to the waste dump depending on the economics of that ore. The waste is sent to designated areas usually referred to as waste dumps or dumped back into the pit in a process called backfilling (Hustruild, et al., 2006).

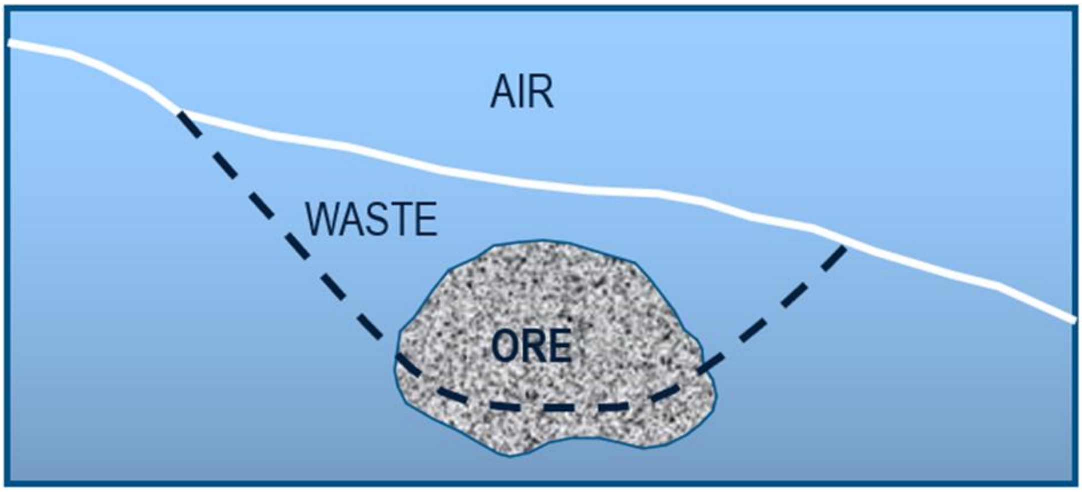

Figure 2-1: Open-pit mining concepts *(GEOVIA, 2017)*

In surface mining, the process of strategic mine planning entails the development of a detailed plan that covers the entire lifespan of a mining operation. This planning phase includes the formulation of pit outlines, the design of pit layouts, and the establishment of mining schedules at a strategic level. These offer an economic perspective and crucial engineering direction for medium and short-range production plans. One of the inputs to strategic planning is to design cutbacks, which are also referred to as pushbacks, stages, or periods (Bai, et al., 2018).

In the context of mine planning, establishing a long-term production strategy is essential, as it directly impacts the project's economic viability. Long-term plans serve as a framework for organizing medium and short-term production schedules. Due to the extensive number of blocks within the final pit boundary, it is possible to segment the pit into several smaller sections, often referred to as push backs, cutbacks, or phases. The design of these push backs incorporates access to haul roads and serves as a reference point throughout the annual scheduling process. Consequently, the design of pushback significantly influences the annual cash flows produced by a mining operation (Gholamnejad & Osanloo, 2007).

2.1 Pushback Designs

Pushbacks refer to a sequence of distinct stages that can be exploited in the operation of an open pit mine, as depicted in Figure 2-2 (which showcases the principles behind pushback configurations). The area surrounding the ore deposit is generally depicted as a three-dimensional rectangular grid, with each individual unit referred to as a block. Information regarding the spatial coordinates of each block is linked to specific attributes of the mineral deposit's geology (such as the concentration of valuable resources, levels of contaminants, density and type of rock), geotechnical classification, and potential profit. In open-pit mining, a series of smaller pits or pushbacks is excavated in a methodical sequence. The primary objective of this sequence is to enhance the net present value (NPV) of the mine during its entire production period, which underpins the development of production plans (Nacel-Penard & Morales, 2021).

Open pit mining operations proceed systematically from the uppermost bench down to the lowest level of the excavation, leaving no alternative methods for extraction. Figure 2-2 illustrated a final pit design boundary in red and the orebody in green with the topography in blue. If this design was to be mined as it is without separating the design into smaller pushbacks, then a huge capital investment upfront would be required to fund the stripping and this methodology usually has the lowest NPV and is referred to as the "worse-case" during the pit optimisation process (Maepa, 2021).

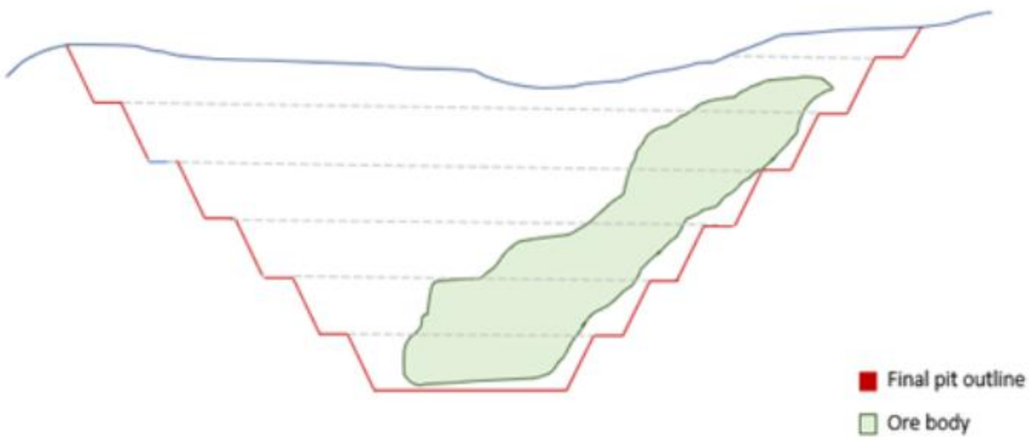

Figure 2-2: Final pit design with no pushbacks *(Maepa, 2021)*

One may be inclined to believe that excessive waste extraction poses no significant issue, as it ultimately leads to the discovery of substantial ore deposits, resulting in considerable financial gain. The concept of time as a determinant of NPV contradicts this line of reasoning. The principle of NPV encourages the extraction of greater quantities of ore while minimizing waste during the initial phases of a mining operation. The annual discounting of the value leads to a gradual decrease in the worth of the ore over time. One significant risk linked to conducting a substantial pushback in mining operations is the company's continuous vulnerability to external global influences, including fluctuations in commodity prices, exchange rates and other mining factors (Maepa, 2021).

Figure 2-3 indicates a case where the final pit design is separated into 4 smaller pushbacks. Considering that we continue to extract resources from the uppermost benches, it becomes evident that Figure 2-3 presents a lesser volume of waste to be removed in pushback 1 prior to encountering substantial ore deposits when compared to Figure 2-2. After extracting sufficient ore from pushback 1, it becomes essential to commence the stripping of pushback 2. This strategy prevents the risk of mining oneself into a confined area and guarantees a steady supply of ore to the processing plant. The NPV of this strategy is usually higher than that of the “worst-case” and is referred to as the “best-case” during the pit optimisation process (Maepa, 2021).

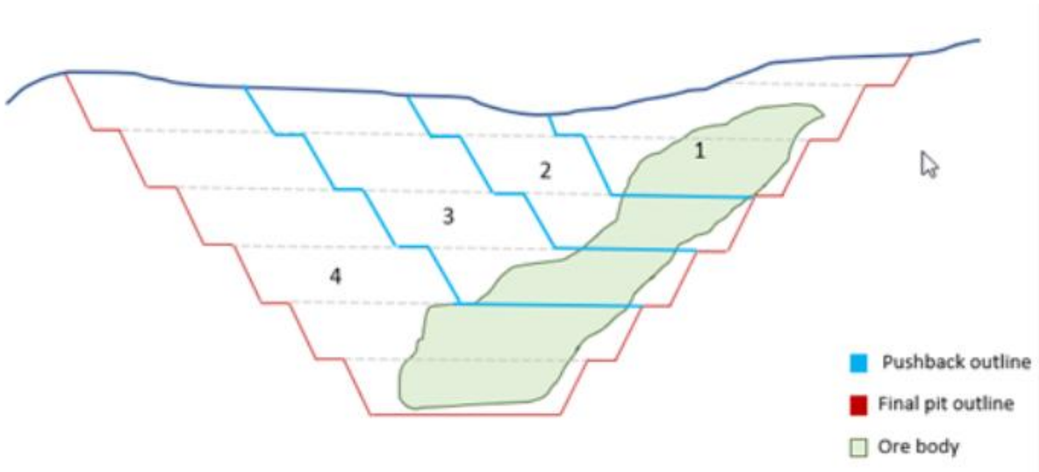

Figure 2-3: Final pit design being cut into 4 operational pushbacks *(Maepa, 2021)*

An effective array of pushbacks enables you to navigate the financial uncertainties linked to external global influences, significantly improving your situation compared to a scenario devoid of such pushbacks. Prior to finalizing the subsequent delay, it is standard practice to re-evaluate your LOM strategy utilising the latest and more accurately predicted engineering and economic variables. In the event that economic indicators, such as pricing, deteriorate significantly, your commitment would be limited to mining a pushback rather than the entire final pit. This strategy may still yield profitability in the pushback phase due to reduced waste management concerns (Maepa, 2021).

Figure 2-4 (a) illustrates the plan view of open pit pushback designs and Figure 2-4 (b) illustrates the section-view indicating the ramp access to each pushback and the mining width for each pushback (Yarmuch, et al., 2021). The two colours represents two different pushbacks.

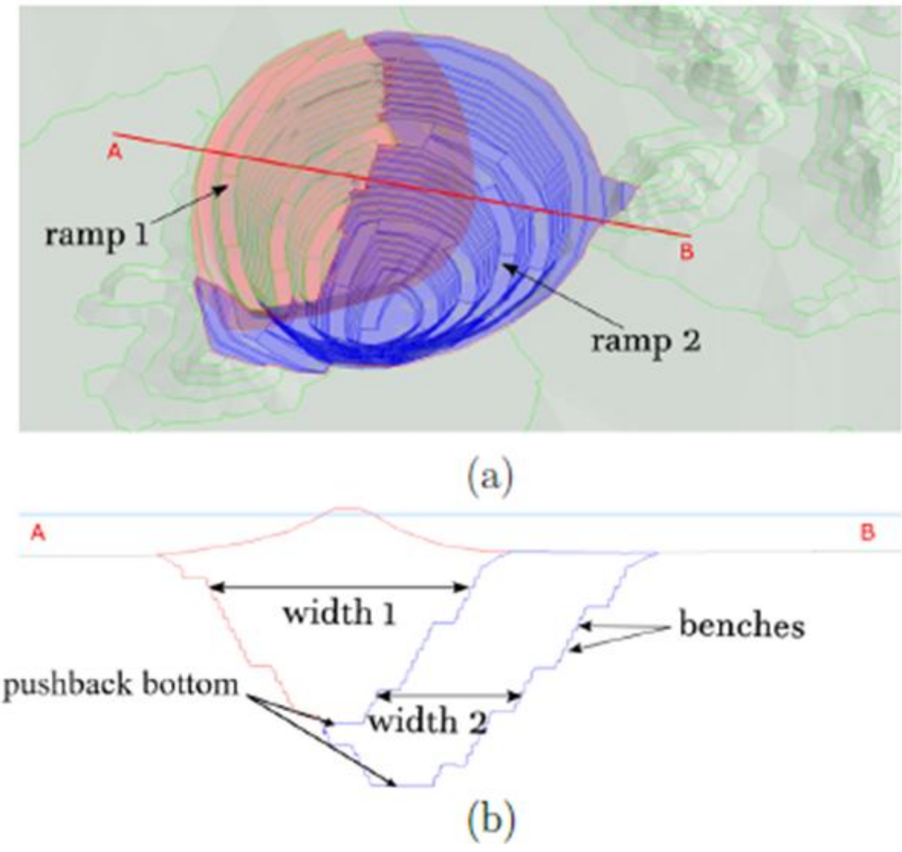

Figure 2-4: Pushback design example, (a) isometric view (b) cross-section *(Yarmuch, et al., 2021)*

Effective mine production is the main goal for mining engineers when they design pushback plans, with a focus on three key operational factors. Firstly, a pushback should be connected and not in separate regions. Secondly, the width of each bench (a subdivision of pushbacks at different levels) must meet a specific minimum requirement determined by the capacity of the mining equipment for extracting ore and waste removal. Lastly, to access each bench of the pushback, there should be a haulage ramp that connects the production areas to the processing facilities and dumps outside the mine (Yarmuch, et al., 2021).

Ideally, a pushback should consist of a distinct, physically connected area that is suitable for mining with the equipment at the mine and adheres to practical and geometric mining limitations. A single pushback is typically excavated for one to two years, with the duration varying based on the scale of the project. The amount of material extracted during a pushback needs to be enough to maintain a steady supply to the processing facility. In extensive mining projects, several mining sections or pushbacks can be excavated at the same time to generate sufficient ore for the needs of mining and processing facilities. Extracting multiple pushbacks simultaneously allows for the flexibility to blend ore, particularly when one pushback is extracting contaminated ore (Bai, et al., 2018).

Whittle (2011) explains that the definition of pushback contains concepts of the worst and best case which both explain the sequence in which the ore is exploited. The worst case is illustrated in Figure 2-5 (a). This is when the ore is exploited sequentially bench by bench, where the first bench is mined out completely before the next bench can be mined. This mining strategy results in the lowest NPV as ore can only be accessed once a large amount of stripping has taken place. The best case illustrated in Figure 2-5 (b), is when the ore is exploited by a series of pits or pushbacks, this mining strategy results in the highest NPV as the ore is accessed with relatively low stripping requirements (Whittle , 2011).

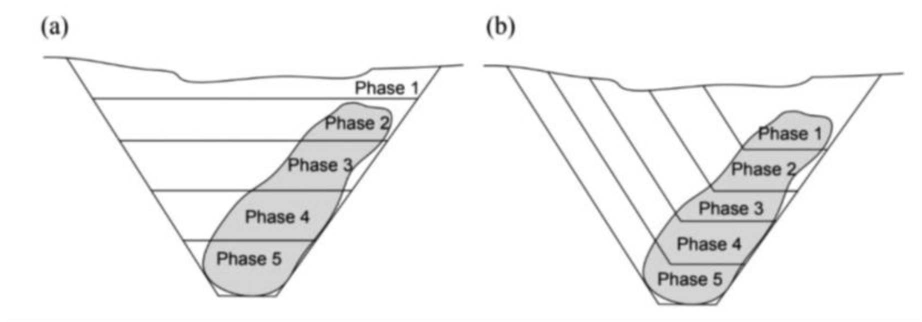

Figure 2-5: Mining sequences *(Whittle , 2011)*

Pushback designs have two main practical considerations that can constrain the design of the pushback. These constraints are:

1. Geometric constraints: These constraints include the width that is required for a ramp system, the minimum width that the mining equipment requires to achieve maximum efficiency, and geotechnical requirements such as slope angles and berm width for the various lithology's; and
2. The quantity and quality of the material that is contained within the pushback will be able to meet production rates (Bai, et al., 2018).

This is essential in order to meet the required production rates effectively and efficiently. The geometric limitations associated with pushbacks are frequently overlooked, yet it is equally crucial to consider factors such as the minimum mining width, the smoothness of the terrain, and the overall continuity of the pushback, among other important aspects. The determination of the minimum width required for mining operations is fundamentally influenced by the dimensions of the equipment that will be utilized, in addition to the specific mining techniques that are planned to be implemented during the extraction process. The concepts of continuity and smoothness hold significant importance and should be thoroughly comprehended in order to effectively enhance and facilitate the operations involved in mining activities (Bai, et al., 2018).

There exists a notable deficiency in the existing body of literature concerning the geometric limitations that are inherently linked to pushback designs. This scarcity of published works on the subject creates a significant opportunity for further investigation (Bai, et al., 2018). Consequently, this study utilizes Sishen Mine as a detailed case study, aiming to thoroughly comprehend the current production capacity of the mining fleet operating within the mine. It is quite possible that other mining operations may choose to implement a similar approach, which could, in turn, inspire researchers in this particular field to delve deeper into their studies. This would not only enhance the current body of literature but also effectively address the existing knowledge gap concerning the geometric limitations associated with pushback designs.

The implementation of pushback designs is fundamentally important in enabling mining operations to effectively achieve their production targets, as these designs are not only practical but also strategically beneficial in optimising workflow and resource management. Typically, impractical designs for pushbacks arise from a failure to adequately consider several crucial parameters, including the minimum width required for mining operations, the overall smoothness of the pit, and the essential interconnections between various pushbacks. All of these factors are vital for ensuring that pushback designs are both effective and feasible. The ability to easily access pushbacks is a crucial characteristic that significantly contributes to the efficient transportation of both ore and waste materials. This ensures that these materials can be transported to their designated locations with notably shorter hauling distances, which is an essential factor to consider in the design of pushbacks (Bai, et al., 2018).

In general, the designs that are considered impractical frequently consist of benches that are narrow and pit bottoms that are not adequately designed. Furthermore, the boundaries of these pits are characterized by irregular shapes, and the ramp systems are often poorly integrated, lacking the necessary connections to both existing and future pushback, which results in unnecessarily long distances for hauling waste or ore. In order to effectively address and correct the numerous impractical designs associated with pushback mechanisms, it often necessitates a significant amount of manual intervention and adjustment (Bai, et al., 2018).

This extensive process typically leads to the more functional pushback designs ultimately being perceived as having considerably less value compared to their original impractical counterparts. Therefore, it becomes exceedingly important to thoroughly consider the geometric limitations associated with pushback designs during the very early stages of planning, prior to the commencement of the scheduling process. This careful consideration is essential to guarantee that any value proposed in the schedule can indeed be effectively realized. (Bai, et al., 2018).

2.2 Geometric Constraints for Pushback

The slope angle that the pushback design must conform to is typically determined by the specific type of rock present, along with the fundamental geotechnical characteristics that are inherent to that particular rock type. Typically, the Geotechnical Department provides the slope angle as an input, which may either remain constant or be divided into various slope domains, often represented through a geotechnical block model for the purpose of pit design (Bai, et al., 2018).

In this comprehensive study, we will thoroughly examine three crucial geometric constraints that play a significant role in our analysis: the width of the mining operation, the overall smoothness and continuity of the pushback design (Bai, et al., 2018).

2.2.1 Mining Width

The smallest allowable width for mining operations is determined by the dimensions of the largest combination of shovel and truck that will be actively engaged in the pushback process during that particular phase of mining. Typically, the expenses associated with operating narrow benches tend to be significantly greater than those incurred by their wider counterparts, primarily due to the enhanced efficiency that is consistently achieved with the wider benches. Nevertheless, it is important to note that the capital expenditures linked to the stripping operations necessary for narrower benches are considerably lower in comparison to the costs associated with wider benches, which can lead to substantial savings in the overall mining cost. When it comes to mining operations, it has been observed that narrow benches tend to reveal ore deposits more quickly than their wider counterparts. This increased efficiency in extracting resources from the narrow benches suggests that they could potentially yield a higher Net

Present Value (NPV) compared to the broader benches, making them a more advantageous choice for mining endeavours (Bai, et al., 2018).

Consequently, the overall width of a pushback operation is influenced by two primary factors. The first of these factors is known as the Target Width (TW), which is determined by the dimensions of the largest piece of mining equipment that will be utilized in the area. The second factor involves the presence of a narrower area that is situated next to the wider section, as well as previously excavated regions that have already been mined. (Bai, et al., 2018).

The TW, as depicted in Figure 2-6, is fundamentally determined by the radius of the shovel's clearance during operation. This means that if the width of the pushback area is sufficiently expansive, the truck will be able to maneuver into position for loading in a single, fluid motion without the need for multiple adjustments. In the event that the width of the pushback is decreased, it will be necessary for the truck to first orient itself at a right angle to the face, as demonstrated in Figure 2-7. Following this initial positioning, the truck will then need to execute a subsequent maneuver to align itself parallel to the face, as depicted in Figure 2-8. This process will inevitably require a greater amount of time for the truck to accurately position itself at the shovel (Araya, et al., 2020).

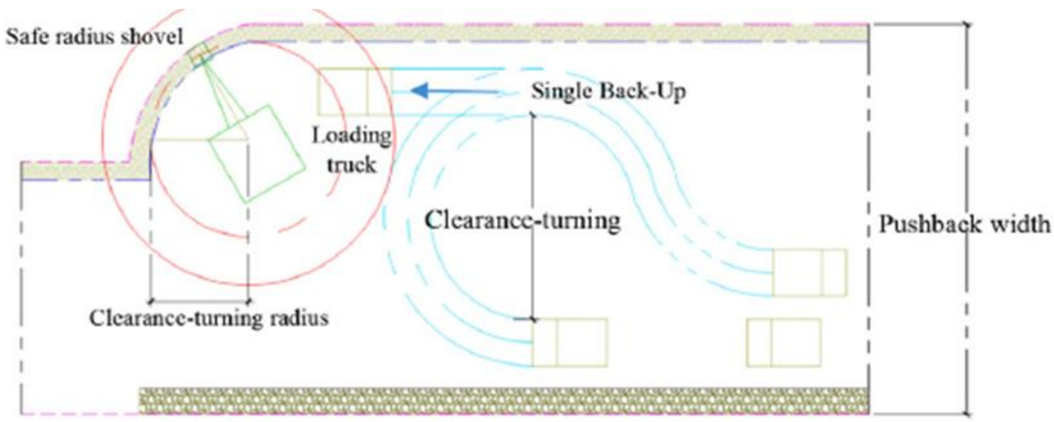

Figure 2-6: Truck-shovel operation in open pit mining *(Araya, et al., 2020)*

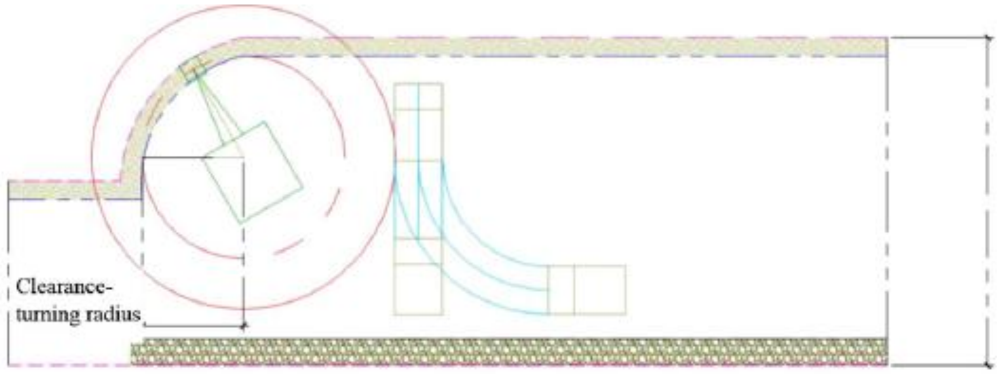

Figure 2-7: First truck movement in a reduced bench width *(Araya, et al., 2020)*

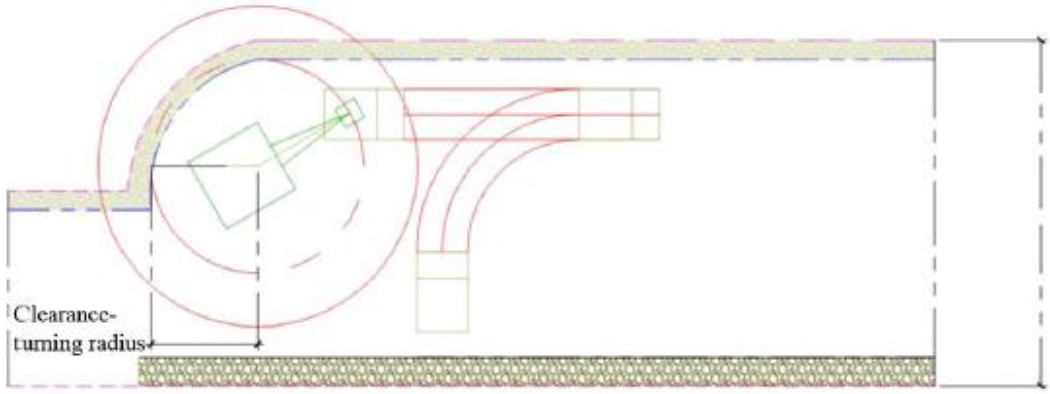

Figure 2-8: Second truck movements of the truck in a reduced bench width *(Araya, et al., 2020)*

2.2.2 Smoothness

The overall geotechnical integrity of the pushback is significantly influenced by the degree of smoothness present in the final pit boundary. In fact, the more meticulously smooth the boundary is crafted, the greater the integrity and stability of the final pit boundary will ultimately be. The presence of pit boundaries that exhibit irregular and unconventional shapes tends to generate a variety of operational difficulties and challenges when attempting to effectively mine these particular areas. Geological block models are constructed from a combination of ore and waste blocks that are determined based on the results of optimisation processes; the economic boundaries that define these models can often be quite irregular, as clearly demonstrated in the illustration provided in Figure 2-9. It is absolutely crucial for designers working on mining projects to thoughtfully incorporate certain waste blocks, such as those specifically indicated as (ii) in Figure 2-9, or alternatively, to deliberately omit certain ore blocks, which are marked as (i) in Figure 2-9. This careful consideration is essential in order to guarantee that the final boundary of the pit will exhibit a smooth and well-defined contour (Bai, et al., 2018).

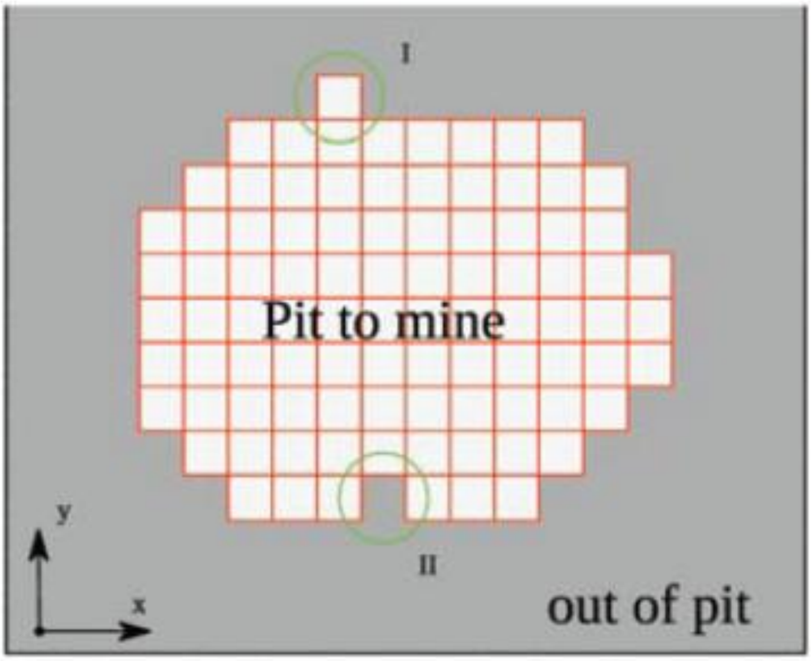

Figure 2-9: Irregular pit boundaries *(Bai, et al., 2018)*

In Figure 2-10, there is a detailed illustration that presents yet another instance of the economic pit boundary, depicted in orange. This boundary is represented on a block that measures 3 meters by 3 meters, which could potentially be situated either on a bench or at the very bottom of the pit. As illustrated in Figure 2-10 (a), it becomes evident that a number of ore blocks will, quite necessarily, have to be omitted from the design, while, conversely, certain waste blocks will need to be incorporated into the bench. This careful selection is crucial to ensure that the overall design maintains a high level of smoothness and operational practicality, thereby enhancing its effectiveness in real-world applications. A boundary that is considerably more functional and applicable in real-world scenarios would resemble the one that has been prominently marked in red (Nacel-Penard & Morales, 2021).

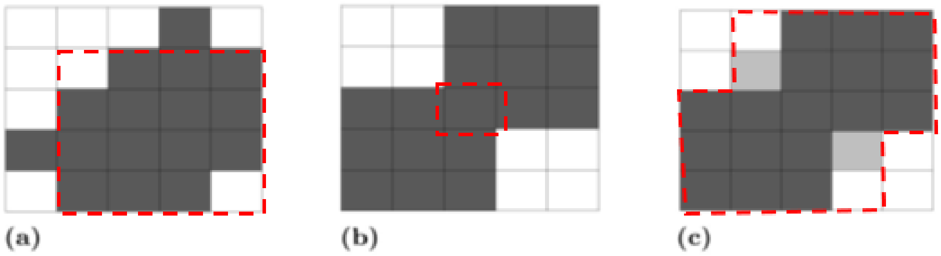

Figure 2-10: Plan-view of examples of economic boundaries *(Nacel-Penard & Morales, 2021)*

In Figure 2-10 (b), it is clearly illustrated that the section marked in red may be excessively narrow, which could hinder the equipment's ability to maneuver effectively. Therefore, it is essential to expand that particular area by adding additional waste blocks, as demonstrated in Figure 2-10 (c), in order to create a bench that is not only smoother but also significantly more practical for operational use. (Nacel-Penard & Morales, 2021).

2.2.3 Continuity

The concept of continuity in pushback designs is fundamentally tied to the intricate connections established among the various pushbacks through a meticulously planned system of ramps. This strategic arrangement is crucial for facilitating uninterrupted mining operations, primarily aimed at minimising hauling distances and significantly lowering operational expenses. By optimizing the adjustments made between different pushback designs, the overall efficiency of the mining process can be greatly enhanced (Nacel-Penard & Morales, 2021).

As depicted in Figure 2-11, the ramp systems that are part of the various pushback operations are interconnected in a manner that promotes continuity. This careful arrangement not only facilitates a seamless integration between the different pushbacks but also effectively reduces the hauling distance, which is beneficial for optimizing the load and hauling processes. By ensuring that this system is well-connected, we can effectively reduce the hauling distances for both waste and ore. This reduction is vital since the load and haul operations generally account for nearly half of the overall operating costs incurred in an open pit mining venture (Nacel-Penard & Morales, 2021).

When ramp systems are strategically and thoughtfully positioned, they can create valuable opportunities for in-pit dumping. This becomes particularly beneficial after one pushback has been completely depleted, allowing the active pushback to seamlessly dump waste into the void that has been left behind by the mine out pushback, thereby reducing the waste hauling distance and reducing the environmental footprint from a waste dump perspective.

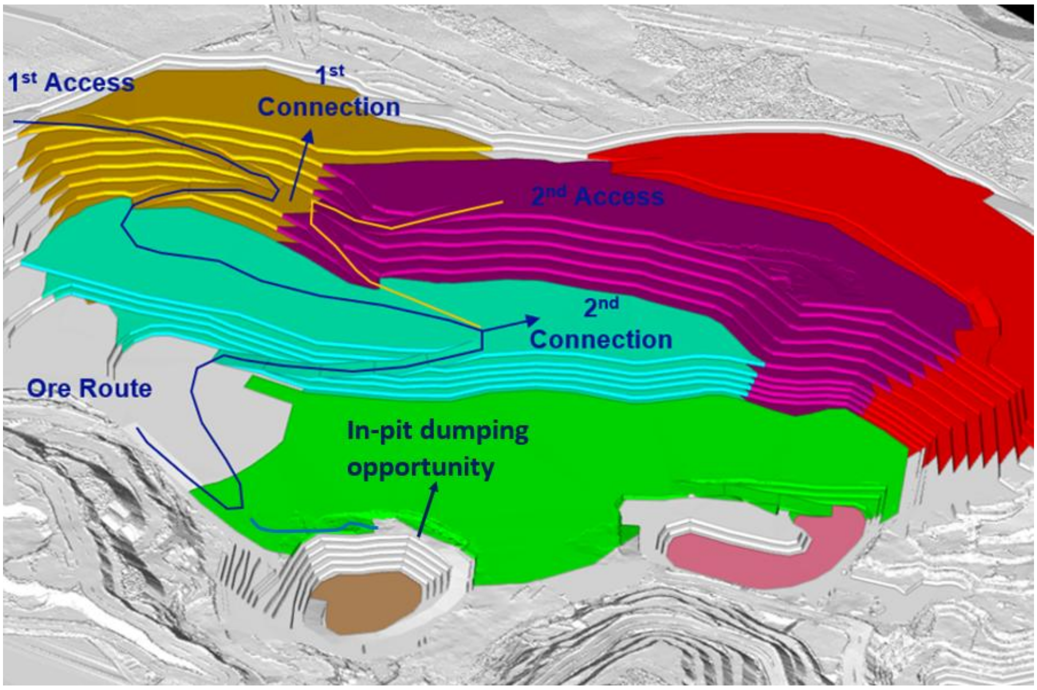

Figure 2-11: Pushback interconnecting ramps

2.3 Key Debates and Controversies

Zhang (2009) developed a simulated annealing meta-heuristic to generate thicker bottom pushbacks that satisfy mining width constraints (though not necessarily connected). A smoothing heuristic is applied to every candidate solution in the optimisation to meet the minimum mining width and fatter bottom.

Groeneveld, et al., (2019) developed a method for generating semi-practical pushbacks by grouping blocks into mineable shapes based on a predetermined block schedule. The maximum NPV may not be achieved as the only optimisation step in the procedure is the direct scheduling of blocks, which impacts the schedule of the resultant pushbacks (Yarmuch, et al., 2021).

Bai et al. (2018) created a method to produce semi-realistic pushbacks using image editing software. Resource-constrained pits, which are created by adjusting the metal price to meet a specific resource constraint, form the foundation for developing their semi-practical pushbacks. The algorithm converts every horizontal segment of a pushback into images, with each pixel symbolizing a block. Morphological tools are applied to these images to ensure the minimum width, smoothness, and continuity constraints are met, as a final step (Yarmuch, et al., 2021).

Recently, Yarmuch et al. (2021) developed a binary linear programming model for a single pushback considering three main practical conditions: mining width, block connectivity, and ramp access. The proposed model takes into account a multi-objective function that aims to maximize profit and minimize block dispersion in the pushback area, by incorporating a compactness factor to balance profit and dispersion. Nevertheless, the compactness factor must be carefully adjusted to create functional designs (Yarmuch, et al., 2021).

Previous studies have been carried out regarding establishing a formula to determine the width of a pushback (Goodfellow & Dimitrakopoulos, 2013). The main achievement of these studies is the development of a computationally effective and universal technique to adjust an established pushback design that accounts for joint local uncertainties in both grade and material types in complex mineral deposits and mining processes. Goodfellow and Dimitrakopoulos (2013) proposed two formulas to achieve this, and both are similar the simulated annealing algorithm formula used for LOM production scheduling. Pushback designs are broader in scope than the techniques employed in LOM production scheduling, which sets specific production goals for mining equipment and destinations, and it does not always have uniform or unchanging targets for each phase (Goodfellow & Dimitrakopoulos, 2013).

Therefore, it is crucial to have an initial pushback design to establish the initial targets for each phase. These targets could be based on a traditional pushback design, pit shells created by a parametric algorithm, or a randomly generated design with specific pushback size targets. By following the proposed methodology, the result is a mine design that replicates the average tonnages in each pushback for each destination as the initial design did, while also decreasing the variability of tonnages sent to different destinations during geological simulations (Goodfellow & Dimitrakopoulos, 2013).

Due to the strong connection between tonnage variability and the economic value of the material in pushbacks, the suggested algorithm also mitigates risks related to the economic value of the design. A third version is suggested, allowing the algorithm to vary the target tonnages for each destination and push back in real time. The discussion, however, does not include the complete pushback design and leaves it for future research (Goodfellow & Dimitrakopoulos, 2013). This study aims to look into practical pushback designs in order to close this gap in literature.

Initial Pushback Width Formula

The first Equation is focused on minimizing the average absolute deviation from a target tonnage overall geological simulations, with the target being defined as the average tonnage over the available simulations and the starting pushback design for each process or destination. Equation 2.1 resembles the objective function suggested for production scheduling, in which the average tonnages for each destination from the initial pushback design are used in place of Godoy's ore and waste production targets. The formulation for the objective function is as follows (Goodfellow & Dimitrakopoulos, 2013):

$$minf(x) = \sum_{d=1}^{D} . \sum_{p=1}^{P} E\left(T_{d.p}(s) - T_{d.p}\right)$$

Equation 2.1: Initial Pushback Width Formula

where:

- d represents the locations or procedures where mined material can be delivered.
- p represents the indices corresponding to the pushbacks.
- S represents the simulations of the input orebody indexes.
- T d.p (s) represents the tonnes.
- T d.p represents the average tonnage quality.

Equation 2.2

Equation 2.1 may have limitations in that it only assesses changes by considering a linear change in the absolute deviation of tonnage. When there is a large gap in target quantities between destinations, the optimiser could lower the variability of material sent to one location while raising the variability of material sent to another smaller location (Goodfellow & Dimitrakopoulos, 2013).

An additional proposed method involves assessing the squared variances from the objectives and standardizing them according to their target dimensions, which gave rise to Equation 2.2 below. By taking this step, it addresses the issues related to significant disparities in material quantities being sent to the processes and provides a more precise evaluation of the material variability directed to each process. The objective function is formulated using the same variables as in Equation 2.1. Equation 2.2 is shown below (Goodfellow & Dimitrakopoulos, 2013).

$$minf(x) = \sum_{d=1}^{D} \cdot \sum_{p=1}^{P} \left(\frac{E(T_{d.p}\,(s) - T_{d.p})}{T_{d.p}} \right)$$

Equation 2.2: Amended Pushback Width Formula

2.4 Equipment Operational Requirements

Throughout the years, the size of the equipment employed in open-pit mining has progressively and remarkably increased, showcasing a trend towards larger and more efficient machinery that can handle the extensive demands of modern mining practices. The substantial expansion of the fleet size has significantly influenced the minimum mining width required for pushback design, as well as the overall production rate. Both critical factors are essential components that play a pivotal role in the comprehensive mine planning process, ultimately affecting operational efficiency and productivity.

There are open pit mines currently operating with mining trucks with capacities over 267 m^3 and mining shovels with bucket capacities reaching up to 67 m^3. The area of such trucks exceeds 140 m^2 and approximately 225 m^2 for mining shovels. Given the fact that mining operations are employing a considerably larger fleet of equipment, it stands to reason that the costs associated with operating these machines could be effectively lowered, primarily due to the exceptional productivity levels that these sophisticated tools are known to deliver (Araya, et al., 2020).

2.5 NPV and IRR

The process of capital budgeting holds significant value for an organization, as it seeks to identify and select projects or investments that will yield advantages for the enterprise. Capital budgeting decisions encompass evaluating the relative worth of one project compared to another, assessing the potential benefits of launching a new mine for the organization, and determining the advisability of acquiring new machinery (Wang, 2021).

The procedure of capital budgeting involves three main stages:

1. Determining the initial cash outlay.
2. Forecasting the anticipated cash flows and the project's lifespan, and
3. Establishing the decision-making rules to apply.

Among the various capital budgeting decision-making techniques NPV and IRR stand out as the most prevalent and extensively utilized methods (Wang, 2021).

2.5.1 The Concept of NPV

The concept of NPV denotes the present worth of a series of forthcoming cash flows. The expression used to calculate Net Present Value is:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

Equation 2.3: NPV equation

Where:

- Rt represents the cash inflow for period t.
- i denotes the rate of discount, and
- t indicates the total number of periods associated with the project.

The guideline for employing NPV in capital budgeting dictates that one should proceed with a project or investment when the NPV is positive, while rejecting it if the NPV turns out to be negative. Despite its widespread application in corporate decision-making, the NPV approach became popular only after other capital budgeting techniques had already established themselves. (Behringer, 2016) determined that prohibiting interest in religious and philosophical disputes serves as the primary reason for this phenomenon. In 1877, an American civil engineer named Arthur Wellington authored a book titled The Economic Theory of the Location of Railways. He employed the present value approach to evaluate the choice of not constructing a line (Wang, 2021) .

2.5.2 Disadvantages and Advantages of NPV

Textbooks for finance courses at universities internationally frequently cover the concept of NPV. Textbooks predominantly advocate for the NPV method, even though many companies tend to favour the IRR as their preferred decision-making criterion. One fundamental rationale for the NPV rule is the belief that a dollar in hand today is more valuable than a dollar in the future, since individuals can invest their current resources and generate interest by the time they would receive the future dollar (Wang, 2021).

In the process of determining NPV, future cash flows undergo discounting based on the returns for each respective period, leading to the overall present value that represents the project's NPV. Additionally, because NPV is expressed in quantitative terms, shareholders can easily ascertain the potential value they may derive from the investment or project. Project managers can evaluate the net present value (NPV) of various projects in terms of current monetary value. The sum of NPVs of projects A and B is:

$$NPV(A+B) = NPV(A) + NPV(B)$$

Equation 2.4: Multiple Project NPV Calculation

If the aggregated NPV is lower than the separate NPVs, managers can deduce that the project causing this reduction is considered a poor investment. The last notable benefit of NPV is its consideration that future cash inflows are reinvested at diverse rates over time. Given the annual changes in the economic landscape, it is logical for discount rates to vary across different time periods (Wang, 2021).

The difficulty and time investment required to estimate discount rates represent a significant limitation of the NPV rule. An inaccurate assessment can lead to erroneous outcomes in NPV calculations, which may ultimately compromise the precision of the final decision. While calculating the expenses associated with acquiring new machinery, technologies, and materials may be straightforward, determining the depreciation of existing equipment and the costs incurred for personnel can prove to be quite challenging. This results in a significant discrepancy between the real initial investment and the projected initial investment.

A further limitation of NPV arises when it is utilized to evaluate projects of varying scales. The application of NPV to assess projects of different magnitudes presents an additional constraint. Nevertheless, there exists a possibility that the return percentage of the smaller project exceeds that of the larger project. While companies may generate higher profits from extensive projects, the significant initial cash expenditure presents a critical challenge that must be addressed. Businesses generally depend on borrowing from financial organizations to obtain the necessary resources for their projects (Wang, 2021).

2.5.3 The Concept of IRR

IRR is defined as the interest rate at which the net present value of all cash inflows and outflows becomes zero. The equation to calculate IRR is:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$$

Equation 2.5: IRR calculation

Where:

- t the number of periods.
- Ct is the new cash inflow during the period of t, and
- C0 represents the initial cash outflow.

This financial method assists in assessing the likely returns of an investment opportunity. When the IRR for an investment project falls below the capital's opportunity cost, we proceed with acceptance; conversely, if the IRR exceeds the opportunity cost, we opt for rejection.

2.5.4 Disadvantages and Advantages of IRR

Unlike NPV, which demands the assessment of capital costs over different periods, IRR is more user-friendly and easier to understand. Employing the IRR method without calculating the cost of capital can mitigate the risks associated with inaccurate estimations. The IRR presents an easily understandable metric, delivering a direct percentage that illustrates the anticipated returns associated with a particular investment or project. By expressing profitability as a percentage, the IRR allows for convenient comparisons against the required rate of return and other investment opportunities. Moreover, the calculation of IRR reflects the importance of the time value of money in financial assessments. A consistent discount rate is utilized by IRR to bring each future cash inflow back to its current worth (Wang, 2021).

When employing the IRR decision rule for project analysis, analysts frequently operate under the assumption that the project will consistently generate positive cash flows during its operational period. The assumption may not be valid in cases where a project displays a non-standard cash flow pattern, which involves cash flows reversing direction more than once, resulting in the complication of multiple IRRs.

Table 2-1 provides a detailed example to demonstrate the issue of multiple internal rates of return (IRRs), while Figure 2-12 offers a visual representation of the net present value (NPV) in relation to the discount rate.

Table 2-1: Problem of multiple IRRs

Period	1	2	3	4	5
Cash flow	-300	200	200	200	-520

IRR 1 = 4.4%	IRR 2 =26.2%

Figure 2-12: Problem of multiple IRRs *(Wang, 2021)*.

This case demonstrates that the project possesses two distinct internal rates of return, namely 4.43% and 26.18%, which leads to a net present value that equals zero. The presence of multiple internal rates of return (IRRs) creates a dilemma for project managers, as they often find themselves uncertain about which IRR to utilize for comparison against the hurdle rate, which represents the minimum return required to cover project costs.

With budgets and resources frequently being limited, organizations usually can only support one project at a time, requiring them to make choices between projects that cannot be executed together.

2.6 Chapter Summary

It is evident from the literature review that several research has been done in terms of understanding the various stages of open pit mining such as pit optimisation, pit design, and scheduling as well as the cost drivers. Mining engineers take into consideration two main operational conditions when developing practical pushback designs. The first is geometric constraints include the width required for a ramp system, the minimum width required by the mining equipment to achieve maximum efficiency, and geotechnical requirements such as slope angles and berm width for the various lithology's. Secondly, the quantity and quality of the material that is contained within the pushback will be able to meet production rates.

Previous researchers such as Zhang (2009), Bai et al. (2018) and Yarmuch et al. (2021) have all developed various models to determine the optimal pushback width. These studies have successfully created a practical and versatile method to modify an existing pushback design to accommodate uncertainties in grade and material types within intricate mineral deposits and mining operations. Despite the ability of these research studies to determine the ideal pushback width, there remains uncertainty regarding how the pushback width influences the resulting production rate during mining operations. This research seeks to explore the topic and address the existing void in literature.

A key factor influencing the project's decision-making process will be the execution of a comprehensive financial model following the scheduling of design sets, which will assist the business in identifying the most cost-effective option. This question will be examined using the two specified matrices as analytical frameworks. The matrixes that will be used for decision-making will be NPV and IRR. The study will assess the multiple pros and cons associated with each alternative, ultimately guiding the decision-making process based on these evaluations.

3 METHODOLOGY

This research seeks to identify the most effective mining width that aligns with the existing fleet utilized at Sishen mine. This research will employ a structured methodological framework, as illustrated in Figure 3-1, to explore and address the posed question. This methodological framework will include six sequential steps, with each step being essential for the successful execution of the next.

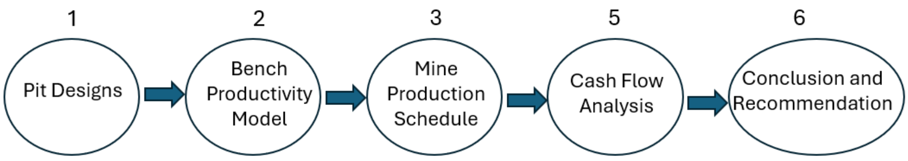

Figure 3-1: Study methodology

3.1 Pit Design

The initial phase of the methodology employed in this research involves a thorough examination of the existing design with respect to its dimensions. As indicated in Figure 3-2 the current pushback D design has an average of 600m mining width and an average strike length of 2.5km. The 2023 LOM plan demonstrated that the current scheduling of the pushback D design will not facilitate the timely exposure of the necessary ore. Consequently, the delayed exposure will lead to an ore shortage starting in 2029, as the stripping process in that area requires excessive time.

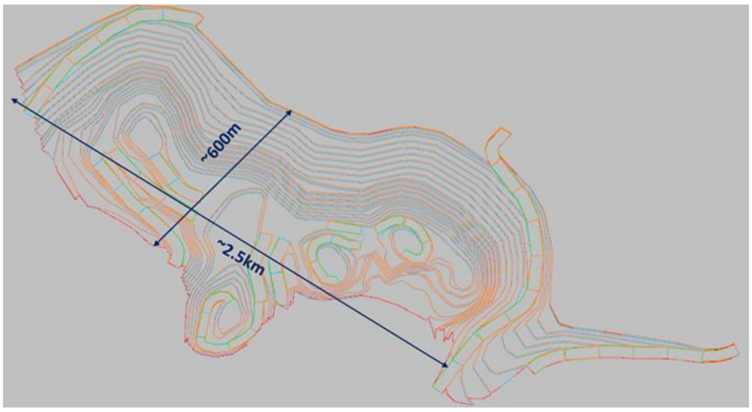

Figure 3-2: Current pushback D design

The existing width fails to support the mining fleet's efficiency in exposing the ore within the necessary time constraints, as indicated by the observed production rate of the equipment. Ensuring timely access to the ore requires the strategic division of the area into smaller pushbacks, making effective use of the current fleet.

Understanding the minimum and maximum mining widths necessary for each piece of equipment is crucial for effectively segmenting the area into narrower pushbacks. The collaboration between the Original Equipment Manufacturer (OEM) specifications and the Sishen mine planning standard will facilitate the process. The sole reliance on the OEM's recommendations proves inadequate due to the existence of additional regulatory mandates, including safety berms and the required operating distance from these berms, which are integral to the Sishen mine planning standards. These additional requirements will not necessarily be incorporated into the OEMs recommendations as site regulatory requirements vary based on the region, lithology etc. Each of these factors will be analysed thoroughly, detailing the ways in which they affect both the minimum and maximum widths of mining operations.

After establishing the minimum and maximum widths for mining, an analysis of sensitivities will be conducted to identify the various mining width segments into which pushback D can be subdivided, ensuring that operational safety remains intact. An important aspect of this possible mining widths split is to ensure that each split is still practical.

After determining the feasible mining widths, the Sishen Mine Design Criteria (MDC) will guide the design of potential pushbacks. The 2024 optimised pit shells will be used as a boundary when designing the design sets. For each design set each pushback will be interrogated to understand the ore and waste quantities in each pushback and the design sets will be compared with each other. The first comparison that will be done with the design sets is to compare the ore quantity contained in each. This is important as all the design sets must have similar ore quantities to validate that the same pit shells and MDC was used of the design sets.

The stripping ratio and associated waste for each design set will also be looked at and compared to each other to try and understand why there is a variance between the design sets, if there is. Based on the strip ratio the design sets will be ranked from best to worst and the study will proceed with the next step.

3.2 Bench Productivity Model

A mining production schedule is an outcome based on a set of inputs. A critical factor in developing a mining production schedule is the output levels that each piece of equipment can achieve. Sishen mine comprises of various lithology's and the same equipment may not achieve the same production rates in different lithology's. Some mining equipment needs a certain minimum mining width to achieve optimal mining rates. In theory, the width on a particular bench should be the same but in reality certain areas of a bench may be narrower and the equipment may not achieve its optimal productivity in that area due to the narrower mining width. It is important to identify such areas and proactively schedule equipment that is suited for that mining width in the production schedule.

Certain of the Sishen mine mining fleet have an ore bucket and some have a waste bucket. Equipment with a waste bucket should not be scheduled to mine ore as the average waste density is 2.9t/m^3 and the average ore density is above 4t/m^3. Based on the geological block model there might be ore and waste on the same bench and two loaders needs to be allocated to mine out that bench. Integrating all these variables into the production rates designated for the schedule can prove to be quite difficult and, at times, nearly impossible to include within the production timeline.

To try and be more accurate in the realistic rates of the production schedule the bench productivity model will examine each bench on an individual basis to determine what if the optimal rate that can be scheduled on that bench. The bench productivity model firstly looks at the number of accesses to the bench, if there is more than one access to the bench then two loaders can be scheduled on the bench. If there is only one access to a bench, then the model looks from a timing perspective can two loaders be incorporated on that bench. This will be a factor of how many blocks needs to be mined out to open the bench to be able to have sufficient space to incorporate two loaders.

The type of loaders that can load then bench based on the bench properties are then be identified. Theses loaders production rate will be kept at 100% should the bench dimension do not allow for the loader to operate at maximum productivity. If the bench dimensions not allow for the loader to operate at maximum productivity, then the loaders production rate will be de-rated. This methodology is applied in each bench.

As the pit narrows in certain sections, the larger loaders, which necessitate more space for their operations, will be removed, leaving only the smaller loaders to continue working on that specific pushback. The same concept applies when the smallest loader operates within a pushback; the productivity achievable by the loader on each bench will be dictated by the area, and the production rate will be modified accordingly until the pushback is fully mined-out. As a result, these rates will act as foundational elements in the creation of the mining production schedule.

3.3 Mining Production Schedule

The study seeks to assess the economic viability of each design set. The production schedule is the first and important step to answer that question. Sishen mine has multiple of other mining areas that will be mined simultaneously with the pushback D in reality. The study ignores this and focuses on the pushback D area in isolation.

Based on the number of the possible design sets that have been identified in the pit design step. Each design set will be scheduled independently. Each pushbacks production rate that will be scheduled will be based on the bench productivity model. This includes the number of loaders scheduled on a bench to the productivity of each loader on the bench.

For the study to be consisted, all the three design sets will be scheduled until the area has been depleted. The consequence of this approach might mean that the results of the production schedule may illustrate the some of the design sets will have a longer and unusual or non-optimized ramp down. This in reality will not happen but to ensure that the study does not have a fixed time frame for all of the designs which may lead into some designs not mining the entire pushback D area, which will result in not all of the ore being depleted but the design sets. This factor will similarly affect the NPV of design configurations that do not completely extract the entire designated region, consequently introducing a bias in the results toward designs that achieve full extraction within the specified timeframe.

3.4 Cash Flow Analysis

For the cash flow analysis, Sishen’s financial assumptions, which will be adjusted by a factor will be used to do a cash flow analysis of the design set options. The importance of conducting a cash flow analysis for the design sets is that ranking designs based on strip ratios may be misleading. This is because a design set with a higher strip ratio may contain higher grade than that of the design set with a lower stripping ratio. The value that will be generated from the high-grade ore may offset the costs with the additional stripping meaning that the design set with the higher strip ratio is more valuable than the design set with the lower stripping ratio.

The cash flow analysis will calculate the NPV and associated IRR for each design set which will be used for the design making purposes. Since the design sets will cover the same area the NPV will not favour or disfavour another design set. So both the IRR and NPV will be evaluated and a decision will be based on which design sets yields the highest NPV and IRR.

3.5 Chapter Summary

The methodology that will be followed in the study will be systematic starting with identifying possible mining width to split the pushback D area. Once those possible mining widths have been identified, then the possible mining widths will be designed in pushbacks covering the pushback D area.

A bench productivity model will be developed by looking firstly looking at the number of accesses available on a bench and when will the bench be open enough to accommodate more than one loader. The bench dimensions will be used to dictate which loader size can be allocated to the bench; The material type of the bench will also be used to determine what loader type can be scheduled on a particular bench.

The outputs of the bench productivity model will be used as inputs into the mining production schedule where each design set will be scheduled. The outputs of the production schedule will be run through a cash flow analysis where each design set will have an associated NPV and IRR. Based on the NPV and IRR then most economical design will be recommended.

4 PIT DESIGN

4.1 Introduction

Sishen mine utilizes an extensive assortment of mining excavators and shovels, sourced from a variety of reputable manufacturers, including well-known names like P&H and Liebherr. These machines are available in a wide range of sizes, allowing for flexibility and efficiency in the mining operations. At the Sishen mine, one can observe the P&H 4100 rope shovel, which is the largest shovel currently in operation. This piece of equipment is matched with the Komatsu 960E dump truck, which boasts a of approximately 327Mt. This dump truck is noteworthy for being recognized as the largest of its kind at the mine, showcasing the scale of operations taking place there. The primary responsibilities assigned to these two machines involve the efficient loading of waste materials and the subsequent hauling of the waste to the designated waste dumps or in-pit dump locations.

Measuring 10 meters in width, the Komatsu 960E dump truck requires a turning radius of at least 16 meters. Figure 4-1 displays the recommended DSL (Double-Sided Loading) configuration for the P&H 4100 rope shovel and Komatsu 960E dump truck combination.

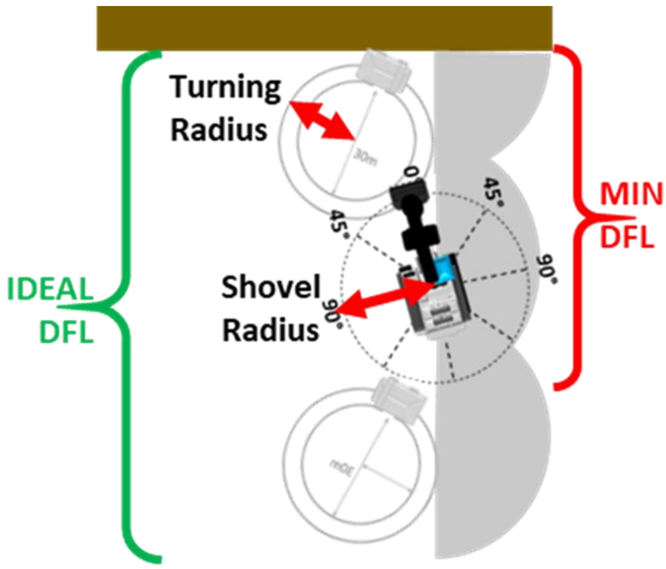

Figure 4-1: Ideal DSL configuration *(Anglo-American, 2020)*

Figure 4-2 displays the elements that Sishen mine considers when determining the minimum DSL for the P&H 4100 with a Komatsu 960E pairing.

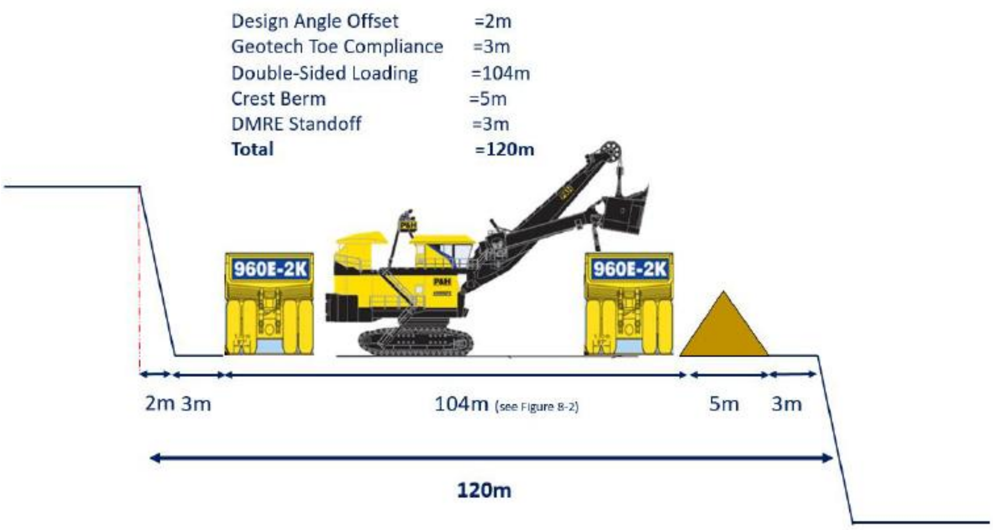

Figure 4-2: Minimum P&H 4100 - Komatsu 960E pair double-sided-loading

A mining width of 120m is mandated for the P&H 4100 and Komatsu 960E, prompting the scrutiny of the first design set. The first design set will split the pushback D area into 120m wide designs as indicated in Figure 4-2. The current pushback D area has a width ranging between 450m to 650m.

In order to ensure the integrity of the high wall during the blasting operations, it is crucial to adhere to the guidelines outlined in the Sishen Standard Operating Procedure (SOP). The geotechnical experts have recommended that buffer blocks be strategically incorporated in front of the high wall, and these blocks must have a width of 27 meters to effectively serve their purpose. In the context of the final designs for the pit boundaries, it is important to note that buffer blocks are exclusively included at this stage. This is primarily because the interim pushbacks are intentionally designed to be five degrees less steep than what will ultimately be established in the final pit configuration, as there are no buffer zones incorporated in accordance with the SOP.

The final pushbacks in a sequence are referred to as final pit pushbacks, with the ones in between being called interim pushbacks. In Figure 4-3, a clear distinction is presented between the concepts of interim designs and final designs. Specifically, Pushback 1 serves as an example of an interim pit, indicating that it is not the ultimate pushback that will be mined from within that designated boundary. Pushbacks 2 and 3 illustrate final pit as they are the last pushbacks on the boundary in that area.

Figure 4-3: Interim versus final pushbacks

The absence of buffer blocks in interim pushbacks is due to their specific design of having a stack angle that is 5 degrees shallower than the final pushback configuration, as recommended by geotechnical experts. The introduction of the 27m buffer block leads to the development of a second design set width configuration measuring 147m, as indicated in Figure 4-4.

Challenges in operations can occur when toes remain on production blocks after blasting, particularly in the absence of an alternative block for mining that could pause the pushback until the operational problem is addressed. The introduction of a second production block spanning about 73m is suggested as option three, to minimize this risk and maintain a steady mining operation. The loading orientation for the second production block will be perpendicular to the face, and the mining rate will be decreased in the schedule to address the shovel's modified movements while operating in this perpendicular position. The main goal of the third design set is to mitigate risks in the plan by establishing a backup production block in case of any problems with the primary block.

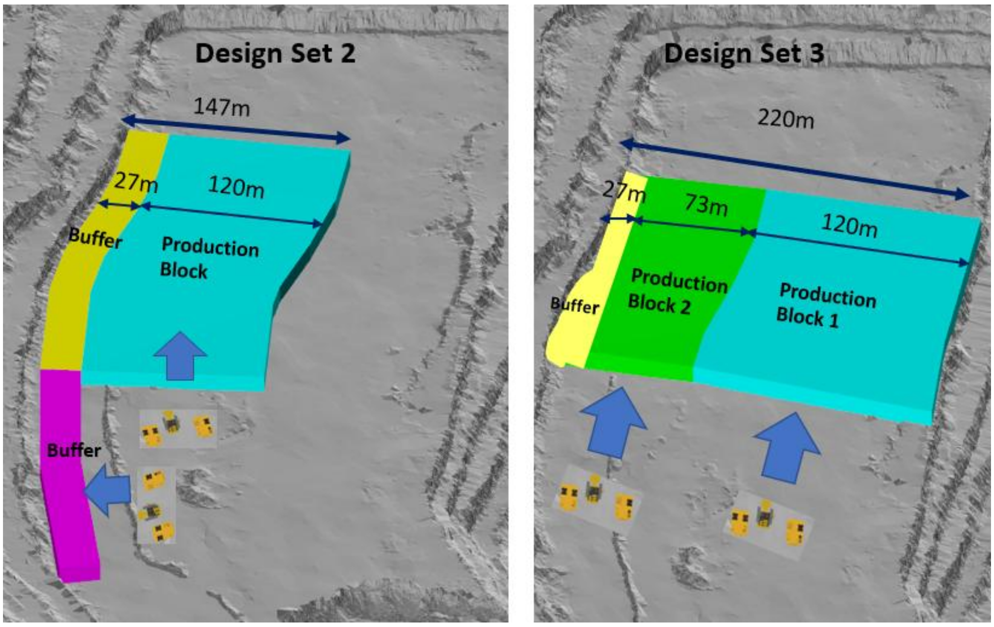

Figure 4-4: 147m and 220m design set configurations

Three design sets with mining widths of 120m, 147m, and 220m were designed using the Deswik CAD software. The 120m design configuration provides a crucial basis that is necessary for conducting the bare minimum of mining activities, which are required for the efficient operation of a P&H 4100 rope shovel alongside Komatsu 960 dump trucks. The 147m mining width aims to effectively accommodate the implementation of protective buffers adjacent to the primary production block that spans 120 meters in length. The proposed mining width of 220 meters is strategically designed to effectively address and alleviate various operational challenges that may arise during the mining process. This expanded width also provides the opportunity to utilize alternative mining blocks, which can significantly help in reducing any potential delays that might occur with the existing 120-meter mining block. Table 4-1 summarizes the mine design criteria that was followed during the pit design process.

Table 4-1: Mine design criteria

Parameter	Value
Bench Height	12.5m
Ramp Width	51m
Ramp Gradient	10%
Switchback Radius	16m
Switchback Length (Single Ramp)	70m
Switchback Length (Dual Ramp)	150m
Switchback Gradient	0% (flat)
Slope Angle	As per the geotechnical block model

4.1.1 120m design set

The pushback D area was subdivided into five smaller pushbacks, D1 to D5, by following the 120m minimum width design configuration. Pushbacks D1 and D3 appear wider compared to other pushbacks due to the prior excavation of the top benches in pushback C in those areas. Figure 4-5 displays the five designs in the order they will be scheduled based on the optimized Whittle pit shells. The combined amount of ore within the pushbacks totals 168Mt, while the waste material accounts for 793Mt, resulting in a strip ratio (SR) of 4.7. The total tonnage of pre-strip waste to be excavated across all pushbacks is 634Mt as indicated in Table 4-2. The Sishen mine SOP defines prestrip waste as all the waste that is contained from surface until the last bench where the ore contained on that bench is more than 20% of the total bench tonnage. Once the ore percentage on a bench is greater than 20%, then the waste is then referred to as internal waste. The area of interest is from Pushbacks D1 to D5.

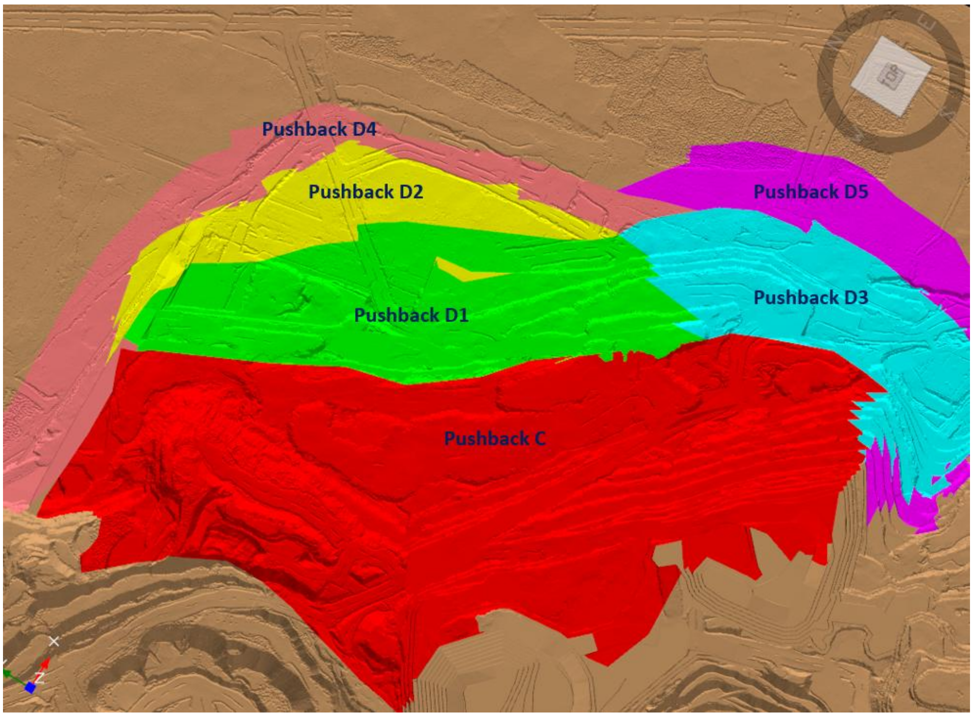

Figure 4-5: 120m design set

Table 4-2: 120m design set tonnes

	120m Design Set					
	High Grade Ore (Mt)	Low Grade Ore (Mt)	Total Ore (Mt)	Waste (Mt)	SR	Prestrip Waste (Mt)
Pushback D1	28	5	33	138	4.2	104
Pushback D2	16	3	19	119	6.2	99
Pushback D3	30	6	36	139	3.9	107
Pushback D4	45	9	54	233	4.3	187
Pushback D5	22	4	26	164	6.3	138
Total	141	27	168	793	4.7	634

4.1.2 147m Design Set

The 147m design set divided the pushback D area into four distinct and smaller pushback sections. In the accompanying Figure 4-6, one can observe the five different designs presented in the precise order in which they are scheduled to be executed, all of which have been arranged in accordance with the optimized Whittle pit shells. The total ore contained in the pushbacks is 167Mt and the waste is 759Mt with a strip ratio of 4.5. The pre-strip waste that will be mined in all of the pushbacks is 627Mt as indicated in Table 4-3

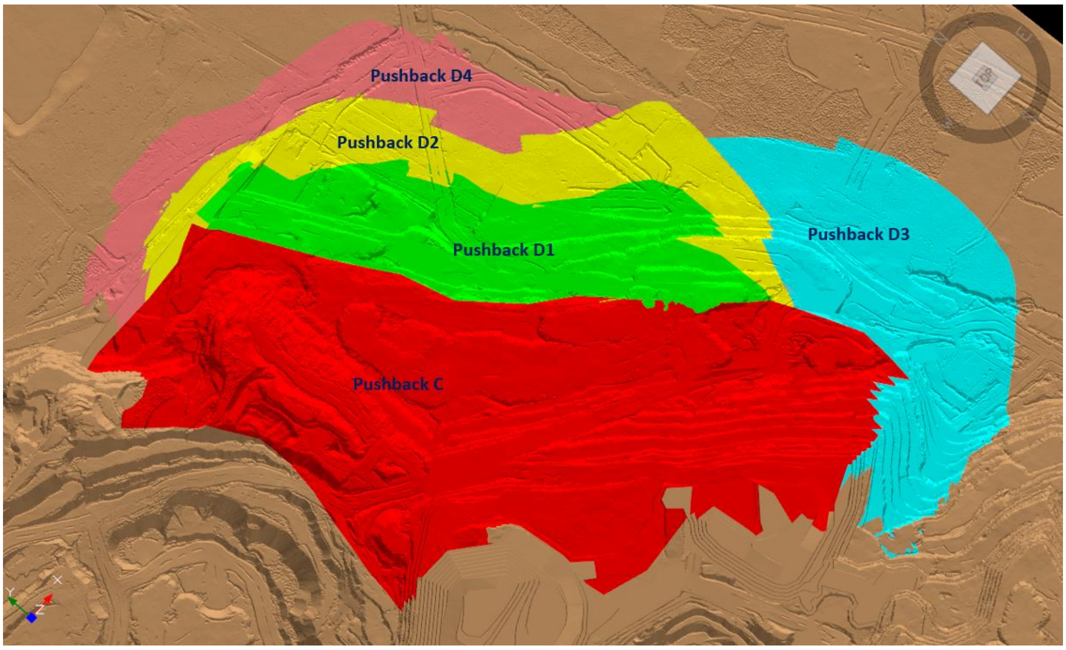

Figure 4-6: 147m design set

Table 4-3: 147m design set tonnes

	147m Design Set					
	High Grade Ore (Mt)	Low Grade Ore (Mt)	Total Ore (Mt)	Waste (Mt)	SR	Prestrip Waste (Mt)
Pushback D1	33	6	39	140	3.6	111
Pushback D2	30	5	34	174	5.1	142
Pushback D3	28	5	34	175	5.2	156
Pushback D4	51	9	60	269	4.5	218
Total	142	25	167	759	4.5	627

4.1.3 220m Design Set

The 220m design set divided the pushback D area into three distinct pushback sections within the D area, specifically for the purpose of enhancing operational efficiency. In Figure 4-7, you will find a detailed illustration show cases the five different designs arranged in the precise order in which they are scheduled to be executed. All of which have been carefully optimized according to the Whittle pit shells. The total ore contained in the pushbacks is 170Mt and the waste is 715Mt with a strip ratio of 4.2. The pre-strip waste that will be moved in all of the pushbacks is 551Mt as indicated in Table 4-4.

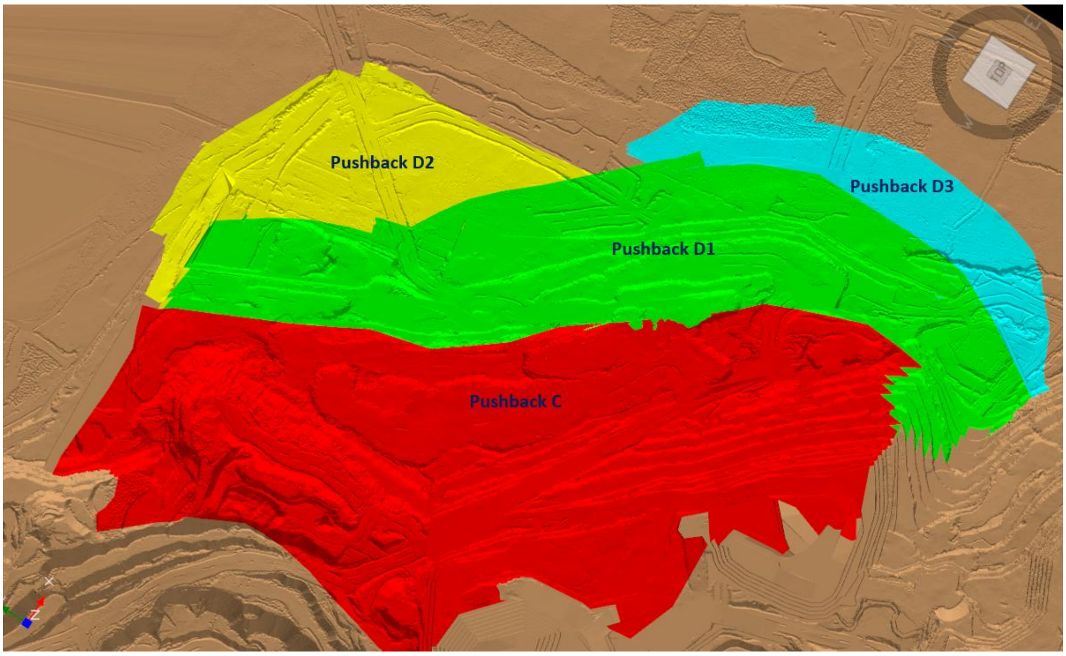

Figure 4-7: 220m design set

Table 4-4: 220m design set tonnes

	220m Design Set					
	High Grade Ore (Mt)	Low Grade Ore (Mt)	Total Ore (Mt)	Waste (Mt)	SR	Prestrip Waste (Mt)
Pushback D1	43	8	52	230	4.4	187
Pushback D2	52	10	61	271	4.4	211
Pushback D3	48	10	57	214	3.7	153
Total	143	28	170	715	4.2	551

Table 4-5 summarizes the design set comparisons in terms of the total ore and waste contained in each of the design sets.

Table 4-5: Mining design set comparisons

Mining Width (m)	High Grade Ore (Mt)	Low Grade Ore (Mt)	Total Ore (Mt)	Waste (Mt)	SR	Prestrip (Mt)
120	141	27	168	793	4.7	634
147	142	25	167	759	4.5	627
220	143	28	171	715	4.2	551

4.2 Chapter Summary

The objective of this chapter was to explore how the quantity of mining in a specific area is influenced by utilizing three distinct mining widths. Pushback D's current design features a mining width varying from 400m to 650m. The current pushback D design contains a total ore of 178 Mt, a total waste of 729 Mt, and 570 Mt of pre-strip waste.

Three design sets with different mining widths were incorporated into the area's layout. The first design iteration featured 120m mining widths, with the pushback D zone being separated into five smaller pushbacks. In comparison to the current pushback D design, the 120m design set has approximately 11 Mt (6%) less ore, 64 Mt (9%) more waste, 64 Mt (11%) more pre-strip waste and the SR in 16% higher than in the current design set.

The second design set was designed at 147m mining widths and the pushback D area was divided into four smaller pushbacks. In comparison to the current pushback D design, the 147m design set has approximately 11 Mt (6%) less ore, 29 Mt (4%) more waste, 57 Mt (11%) more pre-strip waste and the SR in 11% higher than in the current design set.

The third design set was designed at 220m mining widths and the pushback D area was divided into four smaller pushbacks. In comparison to the current pushback D design, the 220m design set has approximately 8 Mt (5%) less ore, 15 Mt (2%) more waste, 57 Mt (11%) more pre-strip waste and the SR in 2% higher than in the current design set.

Figure 4-8 illustrates the comparisons of the three design sets in terms of the total ore and waste contained in each design set versus the current design.

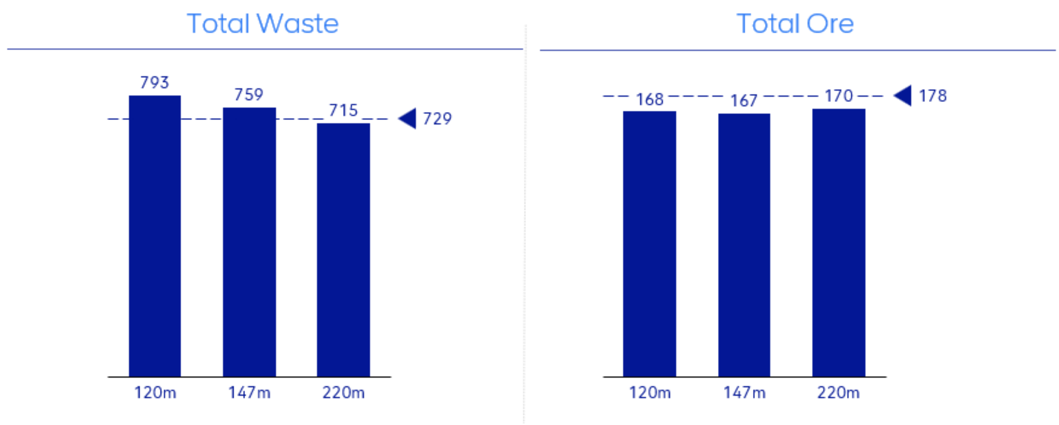

Figure 4-8: Total ore and waste versus current design

The 220m design set has the least amount of waste and has a better ore recovery on to the current design when compared to the 120m and 147m design sets. The design sets suggest that as the pushback width increases, there is a decrease in waste and an increase in ore recovery.

The three design sets also highlight that the smaller the pushbacks that are contained in an area the lower the ore that will be recovered. This is because pushback has its own independent ramp system which may not be easily integrated from a design perspective with the proceeding pushbacks leading into some ore being sterilized. The waste also increases the more pushbacks in an area especially when trying to be strict to the mining width as in the study as the last pushback can fall outside of the optimised pit shells just to maintain the minimum mining width.

From an efficient ore recovery perspective, the wider the pushback the lower the strip ratio and the more ore that will be recovered from that pushback. The question that remains to be answered is what impact will the volumes have on the schedule and which design set will result in the highest NPV when scheduled.

5 BENCH PRODUCTIVITY MODEL

The sequence of activities in open pit mining starts with prospecting and exploration, followed by resource modelling, mine planning, and eventually mine production. The activities in mine production include drilling and blasting, loading and loading, crushing to release and separate the valuable mineral, refining further, and ultimately delivering to the market. The loading and hauling phases are important in the total output of open pit mining activities as the efficiency at this point significantly impacts the mining operation's output capacity. The loading and hauling process is typically the bottleneck that hinders the entire open-pit mining value chain (Aguayo, et al., 2021).

To develop a mining schedule that is both practical and strategic, mine planners need to incorporate loading and hauling production rates as key elements. This data relies heavily on past performance records and poses a challenge when initiating mining operations in new areas without any historical mining data to rely on. Previous demonstrations of production rates may be deceptive because various factors such as the climate during a specific period, the type of materials extracted, and the operator's skill level can influence those historic rates.

The process of mine planning becomes increasingly complex due to the fact that historical data, at certain times, may not provide a sufficiently accurate representation of the production rates that can realistically be achieved in the future. This is so especially when considering the diverse and ever-changing conditions that can impact operations. Thus, it is of great importance to devise a model that can aid mine planners in identifying the optimal production rates to use in their scheduling activities.

The bench productivity model concentrates exclusively on the three types of loaders presently utilised at Sishen mine, which include the following loaders:

1. P&H 4100.
2. P&H 2800.
3. Liebherr 996.

5.1 Proposed Bench Productivity Model

The bench productivity model that has been proposed in Figure 5-1 provides a systematic and organized approach for accurately assessing the output levels that mine planners can effectively employ for a designated bench within the mining operation. The very first step in developing the productivity model involves thoroughly identifying the various properties of the bench. These bench characteristics include not only the total tonnage that is available but also the specific dimensions of the bench, which are measured in both length and width. Additionally, it is crucial to determine whether the bench is categorized as pre-strip or internal, as this classification can significantly impact the overall productivity assessment.

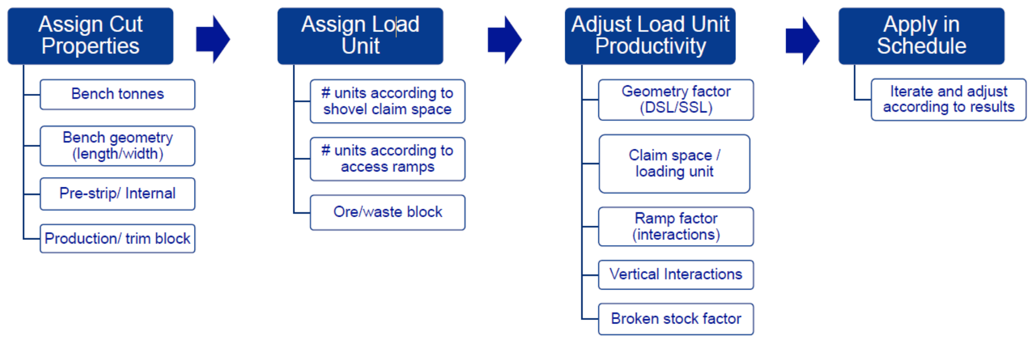

Figure 5-1: Proposed bench productivity model

Benches classified as pre-strip contain less than 20% ore. When the ore concentration on a specific bench surpasses this threshold, the pushback process shifts to internal benches. It is crucial to emphasize that specific types of loaders are exclusively capable of handling pre-strip benches, primarily because of the higher density present in the internal waste materials. Typically, pre-strip waste exhibits a density that is generally lower than 3t/m^3, which is precisely the scenario in which the P&H 4100 excavator is predominantly utilised. In contrast, the P&H 2800 model takes over the responsibilities of the P&H 4100 when it comes to internal benches, as it possesses the capability to efficiently load materials that have a density exceeding 3t/m^3. Pre-strip and internal benches are assessed for every pushback.

The bench productivity model assumes that load and haul is the constraint in the mining cycle. The approach utilised in productivity models involves initially designating the pushback characteristics, such as the mining width and the dimensions of the bench in both length and width, to determine the tonnage available for extraction from that specific bench. It is essential to ascertain whether the bench in question is classified as a pre-strip bench or an internal bench, as this distinction is crucial for determining the loading capabilities of a P&H 4100 loader on the bench. The existence of trim blocks, measuring 27m in width as detailed in the preceding chapter, will significantly affect the efficiency of operations on that specific bench.

After designating the pushback characteristics, the subsequent task involves selecting the appropriate loader for bench loading operations. The selection of the loader type for bench loading will depend on the width of the shovel used in mining and the classification of the bench as either pre-strip or internal. The number of accesses will also be used to determine the number of loaders that can be assigned on a bench. A dual-ramp bench can accommodate two P&H 4100 loaders, allowing each truck fleet to access the bench independently, thereby minimizing congestion.

Once the loader has been assigned on a bench then the productivity that the loader can achieved is then calculated. This is based on the looking at the width of each block on the bench if it meets the minimum Double Sided Loading (DSL) rate that a loader needs and if it does meet that requirement then the loader is assumed to load at 100% efficiency. A productivity factor is applied to areas that are narrower than the minimum mining width for DSL. The proposed productivity model is indicated in Figure 5-1.

It is crucial to consider the amount of material present on a bench to determine the appropriate number of loaders that can be utilised. For instance, each P&H 4100 loader must have a sufficient supply of material to support 28 days of production loading. The first step of the bench productivity model is to understand the bench geometry. The configuration of the bench is closely linked to the bench capacity, influencing the amount of material available for loading and the suitable loader for each bench.

The internal or pre-strip bench definition also is an important factor to consider since the P&H 4100 is unable to load material with a density greater than 3t/m^3 hence a different loader needs to be allocated once the density exceeds 3t/m^3.

5.1.1 Assigning Loading Units

The number of accesses on a bench is an important factor influencing the productivity achieved on a bench. A bench with a greater number of accesses allows for increased flexibility and the ability to schedule more loaders on it. Figure 5-2 illustrates a bench that has a dual ramp system, where two loaders can be scheduled. Two shovels can effectively operate on the bench due to its strike length, resulting in maximum productivity. Benches designed with this geometry allow for the scheduling of two shovels with 100% efficiency, as any congestion on the bench can be effectively managed.

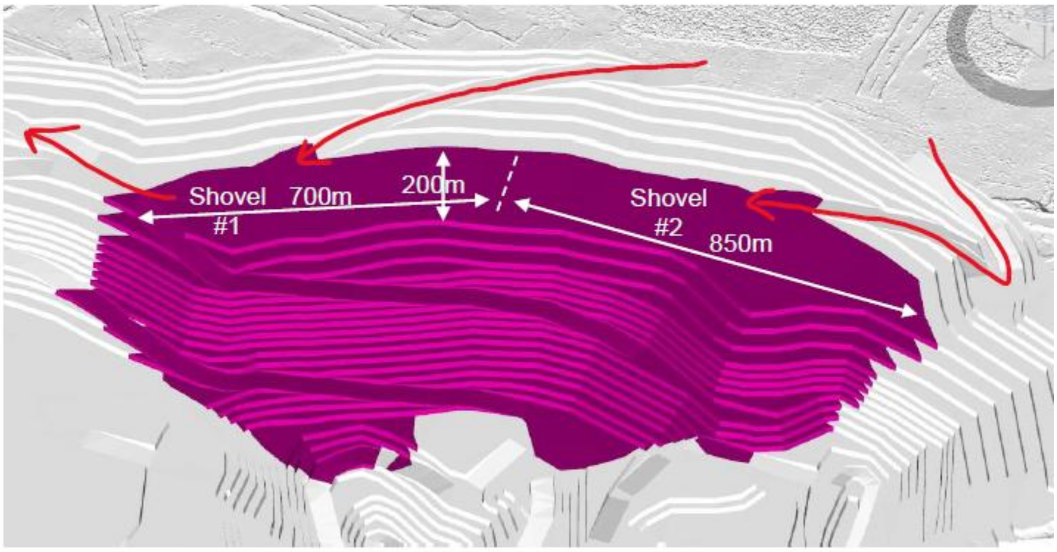

Figure 5-2: Dual ramp access

Dual access may not be available on all benches, as illustrated in Figure 5-3. Benches that come with a single access ramp will need a slot to be made first to create enough space for two loaders. The scheduling of two loaders can take place once the slot has been created. Considering both traffic management and bench geometry, the first loader is planned to work at maximum efficiency, with the second loader operating at 90% efficiency. Priority will be given to the loader that operates over the least distance, ensuring it is scheduled to function at full efficiency, thereby minimising the total operating costs of the bench.

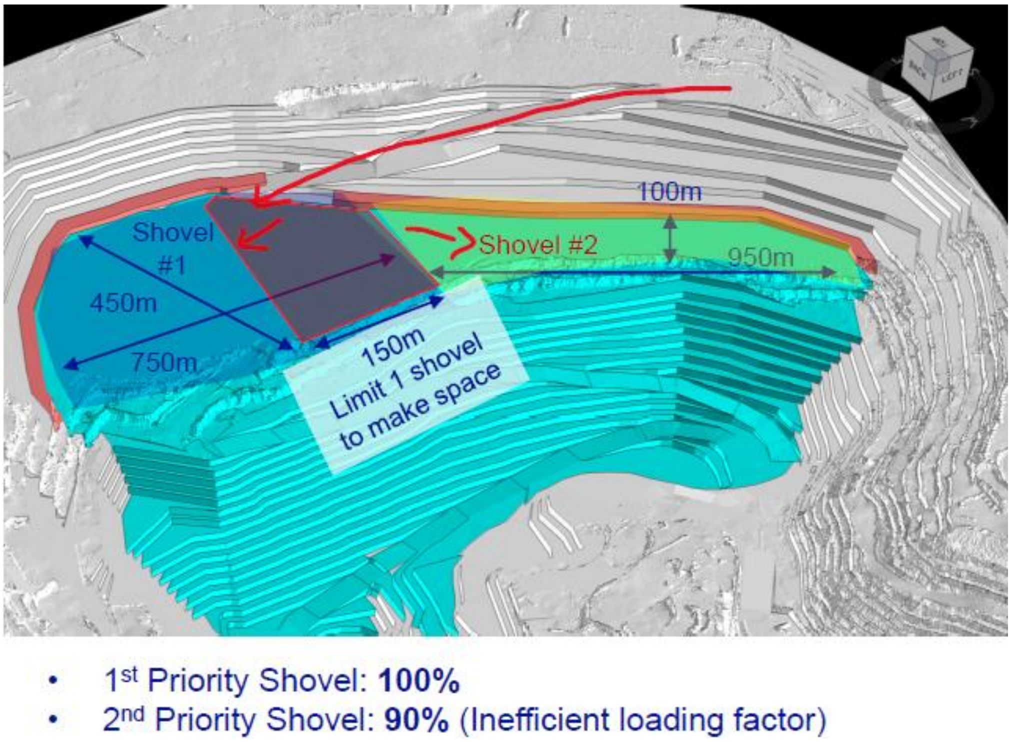

Figure 5-3: Single ramp access

5.1.2 Bench Width Impact

Each loader has a minimum width for Single-Sided-Loading (SSL) as well as for Double-Sided-Loading (DSL) as indicated in Table 5-1. Each bench is analysed in isolation as indicated in Figure 5-4 to determine the width on bench and the corresponding shovel productivity that can be scheduled on the bench.

Table 5-1: Loader mining widths

Loader	SSL Width (m)	DSL Width (m)
P&H 4100	72	120
P&H 2800	64	96
Liebherr 996	50	78

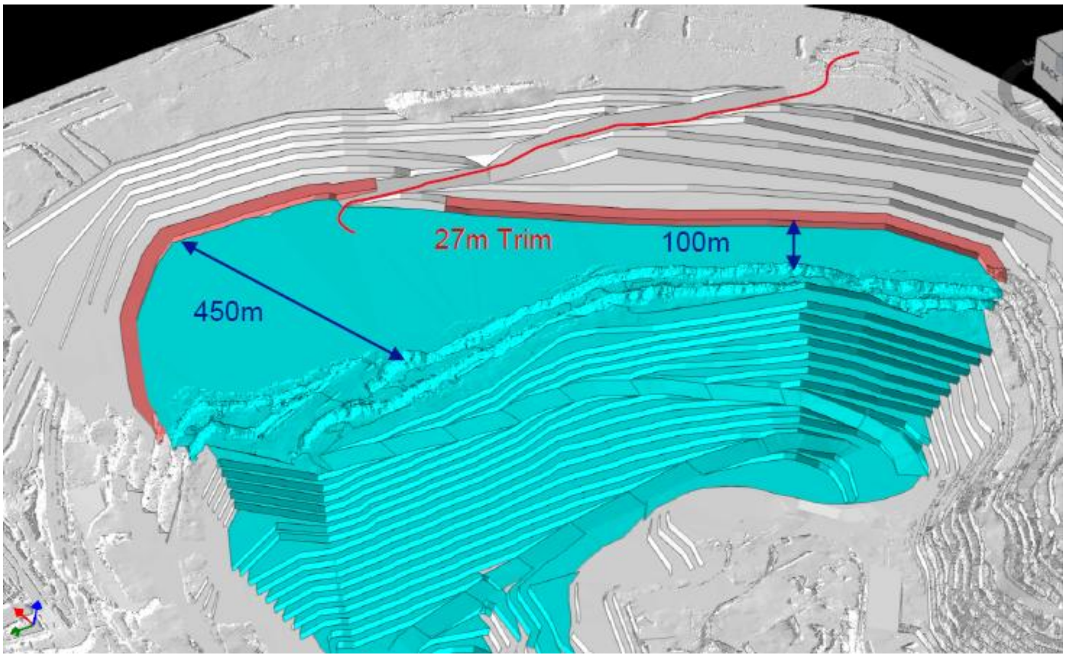

Figure 5-4: Bench width impact

The productivity model assumes the following de-rating factors based on the bench width as illustrated in Table 5-2

Table 5-2: Loader Productivity

	SSL		DSL	
Loader Type	**Width (m)**	**Productivity (%)**	**Width (m)**	**Productivity (%)**
Liebherr 996	>80	100	50-80	75
P&H 2800	90-120	100	65-90	75
P&H 4100	100-120	100	70-100	75

5.1.3 Claim Space per Shovel

Claim space is a matrix that is used to determine the minimum strike length for an associated mining width that will be required to maintain sufficient floor stock for a loader. The targeted period for blasted floor stock that should be available for a loader to load is 28 days as per the Sishen SOP. The reasoning for maintaining a 28-day supply of floor stock in advance of a loader, particularly a rope shovel. Lies in the objective of reducing the frequency of blasting and the movements of the shovel, as it must relocate outside the blasting zone during blasting. The assumption made on the production rate of the shovel is 6,000 tph. The average strike length to maintain 28 days of blasted floor stock depending on the bench width is between 500-900m. The required strike length increases to 743m for a 120m wide bench.

The P&H 4100 rope shovel is equipped with a bucket that can only load material with a density lower than 3 t/m^3 and is allocated to load low-density waste material. The study assesses various pushback designs, all equipped with a dual ramp system to accommodate up to 2 P&H 4100 loaders for scheduling, which is indicated in Tables 5-2 to 5-4. Each individual bench is assessed separately to establish if there is sufficient floor stock present to sustain a 28-day supply for a P&H 4100 loader, considering the width and strike length that can accommodate a P&H4100. If the strike length is 2km then 2 P&H loaders can be scheduled.

Table 5-3: P&H 4100 bench productivity

No of P&H 4100s	Width (m)	Strike Length (m)	Height (m)	Bench Tonnes (t)	Daily Capacity (t)	28 Day Inventory (t)	Floor Stock Availability
1	220	250	12.5	1,986,875	102,000	2,856,000	70%
1	220	500	12.5	3,973,750	102,000	2,856,000	139%
2	220	1,000	12.5	7,947,500	204,000	5,712,000	139%
2	220	1,500	12.5	11,921,250	204,000	5,712,000	209%
2	220	2,000	12.5	15,895,000	204,000	5,712,000	278%
1	147	250	12.5	1,327,594	102,000	2,856,000	46%
1	147	500	12.5	2,655,188	102,000	2,856,000	93%
1	147	1,000	12.5	5,310,375	102,000	2,856,000	186%
2	147	1,500	12.5	7,965,563	204,000	5,712,000	139%
2	147	2,000	12.5	10,620,750	204,000	5,712,000	186%
1	120	250	12.5	1,083,750	102,000	2,856,000	38%
1	120	500	12.5	2,167,500	102,000	2,856,000	76%
1	120	1,000	12.5	4,335,000	102,000	2,856,000	152%
1	120	1,500	12.5	6,502,500	102,000	2,856,000	228%
2	120	2,000	12.5	8,670,000	204,000	5,712,000	152%

To achieve the ideal floor stock for a particular loader is a function of the no of loaders loading on a bench, the width and strike length of the that bench. Table 4-6 summarizes the minimum strike length required to maintain a 28-day floor stock for each of the loaders in the study.

3 indicates that for the 220m wide design set, the strike length needs to a more than 500m to be able to accommodate a P&H 4100 loader. If the strike length surpasses 1.5km, there will be ample floor stock on the bench to support 2 P&H 4100s operating at a lower capacity, and a third loader can be arranged if deemed feasible.

For the 147m design set, the minimum strike length needs to be 1km to accommodate a P&H4100. If the strike length is 1.5km then 2 P&H loaders can be scheduled. For the 120m design set, the minimum strike length needs to be 1km to accommodate a P&H4100. If the strike length is 2km then 2 P&H loaders can be scheduled.

Table 5-3: P&H 4100 bench productivity

No of P&H 4100s	Width (m)	Strike Length (m)	Height (m)	Bench Tonnes (t)	Daily Capacity (t)	28 Day Inventory (t)	Floor Stock Availability
1	220	250	12.5	1,986,875	102,000	2,856,000	70%
1	220	500	12.5	3,973,750	102,000	2,856,000	139%
2	220	1,000	12.5	7,947,500	204,000	5,712,000	139%
2	220	1,500	12.5	11,921,250	204,000	5,712,000	209%
2	220	2,000	12.5	15,895,000	204,000	5,712,000	278%
1	147	250	12.5	1,327,594	102,000	2,856,000	46%
1	147	500	12.5	2,655,188	102,000	2,856,000	93%
1	147	1,000	12.5	5,310,375	102,000	2,856,000	186%
2	147	1,500	12.5	7,965,563	204,000	5,712,000	139%
2	147	2,000	12.5	10,620,750	204,000	5,712,000	186%
1	120	250	12.5	1,083,750	102,000	2,856,000	38%
1	120	500	12.5	2,167,500	102,000	2,856,000	76%
1	120	1,000	12.5	4,335,000	102,000	2,856,000	152%
1	120	1,500	12.5	6,502,500	102,000	2,856,000	228%
2	120	2,000	12.5	8,670,000	204,000	5,712,000	152%

To achieve the ideal floor stock for a particular loader is a function of the no of loaders loading on a bench, the width and strike length of the that bench. Table 4-6 summarizes the minimum strike length required to maintain a 28-day floor stock for each of the loaders in the study.

Table 5-3 summarizes the Liebherr 996 bench productivity. The Liebherr 996 loader represents the smallest type of loader utilized at Sishen mine, it is primarily being used for sinking ramps and mining in confined spaces, particularly when the pushbacks deepen and the configuration resembles a cone, thereby enhancing ore extraction efficiency. The Liebherr 996 loader possesses the capability to operate across all three mining widths, regardless of the strike length, and it will maintain an adequate floor stock to support the shovel's operations for a duration of 28 days.

Table 5-4: P&H 2800 loader bench productivity

No of P&H 2800s	Width (m)	Strike Length (m)	Height (m)	Bench Tonnes (t)	Daily Capacity (t)	28 Day Inventory (t)	Floor Stock Availability
1	220	250	12.5	1,986,875	51,000	1,428,000	139%
1	220	500	12.5	3,973,750	51,000	1,428,000	278%
2	220	1,000	12.5	7,947,500	102,000	2,856,000	278%
2	220	1,500	12.5	11,921,250	102,000	2,856,000	417%
2	220	2,000	12.5	15,895,000	102,000	2,856,000	557%
1	147	250	12.5	1,327,594	51,000	1,428,000	93%
1	147	500	12.5	2,655,188	51,000	1,428,000	186%
1	147	1,000	12.5	5,310,375	51,000	1,428,000	372%
2	147	1,500	12.5	7,965,563	102,000	2,856,000	279%
2	147	2,000	12.5	10,620,750	102,000	2,856,000	372%
1	120	250	12.5	1,083,750	51,000	1,428,000	76%
1	120	500	12.5	2,167,500	51,000	1,428,000	152%
1	120	1,000	12.5	4,335,000	51,000	1,428,000	304%
1	120	1,500	12.5	6,502,500	51,000	1,428,000	455%
2	120	2,000	12.5	8,670,000	102,000	2,856,000	304%

As shown in Table 5-4, the Liebherr 996 loader exhibits a loading capacity that may be considered too limited, particularly when analysing the dimensions of the pushback D area. As shown in Table 5-4, the study examines a minimum mining width of 120m, while the shortest strike length under consideration is 250m, given that the average strike length for the pushback D area is roughly 2km. When operating a mining width of 120m and a strike length of 250m with a single Liebherr 996, the available floor stock exceeds the optimal level by 90%, surpassing the ideal 28-day floor stock requirement. Meaning that a Liebherr 996 will require approximately 53 days to fully load the floor stock. This finding demonstrates that the Liebherr 996 loader does not serve effectively as a primary production loader but is more appropriate for secondary loading applications for Sishen mine. Hence, the reason why at Sishen mine the Liebherr 996 loader is used to primarily used to sink ramps and mine in confined areas of the pit.

Table 5-5: Liebherr 996 bench productivity

No of Liebherr 996s	Width (m)	Strike Length (m)	Height (m)	Bench Tonnes (t)	Daily Capacity (t)	28 Day Inventory (t)	Floor Stock Availability
1	220	250	12.5	1,986,875	20,400	571,200	348%
1	220	500	12.5	3,973,750	20,400	571,200	696%
2	220	1,000	12.5	7,947,500	40,800	1,142,400	696%
2	220	1,500	12.5	11,921,250	40,800	1,142,400	1044%
2	220	2,000	12.5	15,895,000	40,800	1,142,400	1391%
1	147	250	12.5	1,327,594	20,400	571,200	232%
1	147	500	12.5	2,655,188	20,400	571,200	465%
1	147	1,000	12.5	5,310,375	20,400	571,200	930%
2	147	1,500	12.5	7,965,563	40,800	1,142,400	697%
2	147	2,000	12.5	10,620,750	40,800	1,142,400	930%
1	120	250	12.5	1,083,750	20,400	571,200	190%
1	120	500	12.5	2,167,500	20,400	571,200	379%
1	120	1,000	12.5	4,335,000	20,400	571,200	759%
1	120	1,500	12.5	6,502,500	20,400	571,200	1138%
2	120	2,000	12.5	8,670,000	40,800	1,142,400	759%

The analysis of each bench occurs independently, as shown in Figure 5-5. The design permits the scheduling of two P&H 4100 loaders on the illustrated bench, facilitated by the strike length and the availability of dual ramp access.

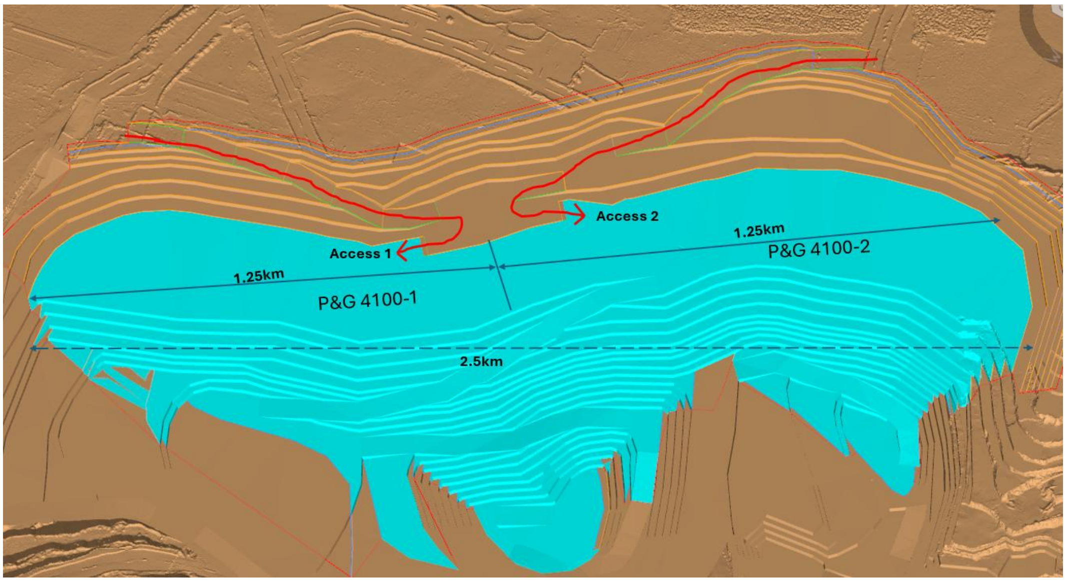

Figure 5-5: P&H 4100 bench productivity

Figure 5-6 illustrates that the Liebherr 996 loader, being the smallest loader, is deployed in areas where pushbacks are limited. The analysis in Table 5-6 helps ascertain whether one or two loaders can fit on a specific bench.

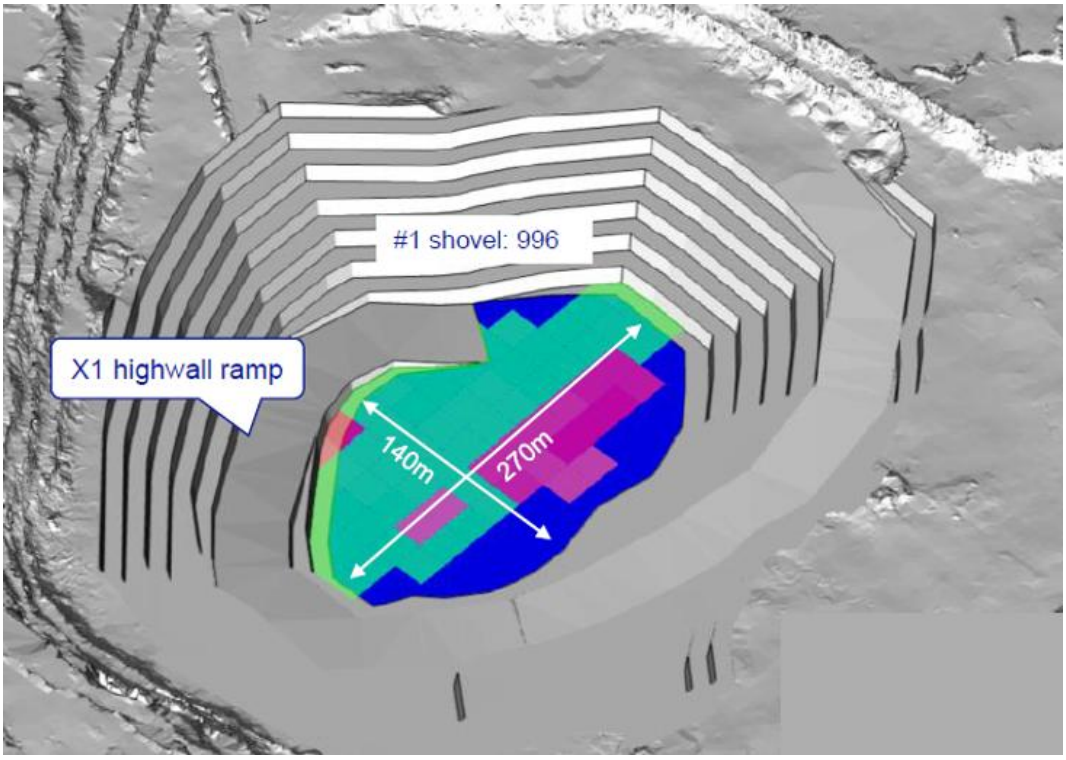

Figure 5-6: Liebherr bench productivity

5.2 Bench Productivity Analysis

Tables 5-2 to 5-4 present a summary of the results derived from the bench productivity model applied to the three loaders operating at Sishen mine, which evaluated the available floor stock on a designated bench based on its geometric characteristics. The P&H 4100 loader is projected to achieve a daily output of 102kt, while the P&H 2800 loader is expected to produce 51kt, and the Liebherr 996 is anticipated to produce 20.4kt. These figures are derived from previously demonstrated production levels attained by each loader at the Sishen mine.

The results of the productivity model are summarized in Table 5-5-. The results indicate that the for the 220m mining width the minimum strike length that should be available on a bench for a P&H 4100 loader to be scheduled at 100% of the daily capacity is 360m, 180m for the P&H 2800 and 72m for the Liebherr 996. For the 147m mining width the minimum strike length that should be available on a bench for a P&H 4100 loader to be scheduled at 100% of the daily capacity is 540m, 270m for the P&H 2800 and 108m for the Liebherr 996 loader. For the 120m mining width the minimum strike length that should be available on a bench for a P&H 4100 to be scheduled at 100% of the daily capacity is 660m, 330m for the P&H 2800 loader and 1130m for the Liebherr 996 loader.

Table 5-6: Bench productivity model results

Loader	Width (m)	Strike Length (m)	Height (m)	Bench Tonnes (t)	Daily Capacity (t)	28 Day Inventory (t)	Floor Stock Availability
P&H 4100	220	360	12.5	2,861,100	102,000	2,856,000	100%
P&H 2800		180	12.5	1,430,550	51,000	1,428,000	100%
Liebherr 998		72	12.5	572,220	20,400	571,200	100%
P&H 4100	147	540	12.5	2,867,603	102,000	2,856,000	100%
P&H 2800		270	12.5	1,433,801	51,000	1,428,000	100%
Liebherr 998		108	12.5	573,521	20,400	571,200	100%
P&H 4100	120	660	12.5	2,861,100	102,000	2,856,000	100%
P&H 2800		330	12.5	1,430,550	51,000	1,428,000	100%
Liebherr 998		130	12.5	563,550	20,400	571,200	100%

According to Table 5-5, benches with an extended strike length maintain a consistent daily production rate for the loader, suggesting potential areas for the production team to enhance performance beyond the planned demonstrated rate. In the production schedule that rate will be kept constant as it has never been demonstrated before but will be highlighted as a potential upside.

When benches exhibit a strike length shorter than the minimum necessary for each loader to operate at full capacity, as outlined in Table 5-5, the production rate decreases in accordance with the availability of floor stock. For example, in Table 4-5, the P&H 4100 loader is set to operate within a mining width of 220m, but the bench's strike length of 250m falls short of the minimum width necessary for the P&H 4100 loader to operate at its full capacity. On that particular bench, the loader will be de-rated by 70% and only 71.4kt daily tonnes will be scheduled on that bench instead of the 102kt at its full capacity.

By applying the methodology outlined earlier, the bench productivity model strategically lowers the number of shovels designated for each bench, and these modified inputs play a vital role in shaping the production schedule that follows.

5.3 Chapter Summary

The design of the pit constitutes a crucial aspect of the mine planning process. However, the scheduling of these designs serves to assess whether modifications are necessary to ensure alignment with business objectives. The assumptions regarding rates made by mine planners play a crucial role in determining the outcomes of their schedules. Typically, these planners depend on historical data to establish trends to forecast mining rates they can incorporate into their production schedules. Analysing historical data can prove challenging due to fluctuations, which may complicate the scheduling process. Historical data at times may also be misleading especially if different material types were mined at a particular point in time.

The proposed productivity model aims to try to bridge the gap in the mine planning cycle. Mine planners utilise the productivity model as a resource to engage in discussions with all pertinent stakeholders, allowing for essential modifications prior to the scheduling phase. Once the schedule is published, it becomes possible to analyse the results. If the outcomes deviate from expectations, stakeholders can revisit the productivity model to identify potential areas for enhancement and adjust the production rates accordingly.

The mine planning cycle currently lacks this crucial phase, which plays a significant role in the overall process which the study aims to address. This phase will actively engage all stakeholders not limited to, mining production personnel, engineering personnel and mine technical services in examining ways to enhance future productivity. It emphasizes the comprehensive grasp of the various factors that must be investigated to achieve the desired outcomes. Proactive identification and integration of these facilitators into the planning phase is essential, particularly when capital investment is linked to enhancing productivity outcomes.

The suggested productivity framework employs a sequential methodology, initially segmenting each pushback into distinct benches. Analysing the tonnage present on each bench is essential. Subsequently, the geometry of the bench is examined to determine which loader can be assigned, considering the minimum mining width necessary for each type of loader. Secondly, the number of accesses available to access the bench will be important in determining if and when a second loader can be scheduled on a bench.

Defining the pre-strip and internal bench plays a crucial role in determining the appropriate loader that can be assigned for a particular bench in the production schedule. Loaders lacking buckets capable of handling materials with a density exceeding 3 t/m^3 are restricted to operating on pre-strip benches. The productivity of each loader is determined according to the bench's geometry and will be scheduled accordingly. This productivity can be interrogated and changed based on the practicality of achieving it. A 28-day floor stock inventory is required for the loader as per the Sishen mine SOP. Based on the bench geometry, the productivity of each loader is determined.

The bench productivity framework facilitates numerous revisions, with all parties involved reaching a consensus on the parameters. This framework provides mine planners with a foundational reference for organising the scheduling of any bench.

6 MINING PRODUCTION SCHEDULE AND CASH FLOW ANALYSIS

After designing the three design sets, dissecting each pushback into benches, and aligning the productivity of every bench with the productivity model, the design sets were ready for scheduling. The design sets were scheduled using RPM's Mine Planner software. The production rates were built from the productivity model and applied to the scheduler.

The schedule assumed that loading was the constraint, and three different loaders were available for scheduling based on the productivity model. The loaders were scheduled with their respective rates and the rates were then adjusted as per the productivity model. The loaders, assigned with their designated maximum production capacities, already account for an 85% availability in the summarized production figures presented below:

1. P&H 4100 – 35 Mtpa
2. P&H 2800 - 20 Mtpa
3. Liebherr 996 – 12 Mtpa

In the earlier chapters, it has been clearly emphasized that gaining a comprehensive understanding of the final pre-strip bench is crucial, as this aspect serves as a significant limitation regarding the maximum load capacity that the P&H 4100 loader can effectively handle. The quantity of pre-strip tonnes serves as a measure of the waste material that must be removed to reach the ore deposits. The average pre-strip tonnage for the 120m design configuration is approximately 9Mt. In contrast, the pre-strip tonnage for the 147m design configuration rises by 17% as is shown in Figure 6-1, reaching around 10Mt. For the 220m design configuration, the pre-strip tonnage further increases to about 14Mt.

The pre-strip tonnes also offer an indication of how soon each on the designs set will access the ore. The 220m design set has the least pre-strip material which just based on the that, it should reach ore quicker than the other two design sets but that hypothesis will be tested in the production schedule by taking the bench productivity model into account.

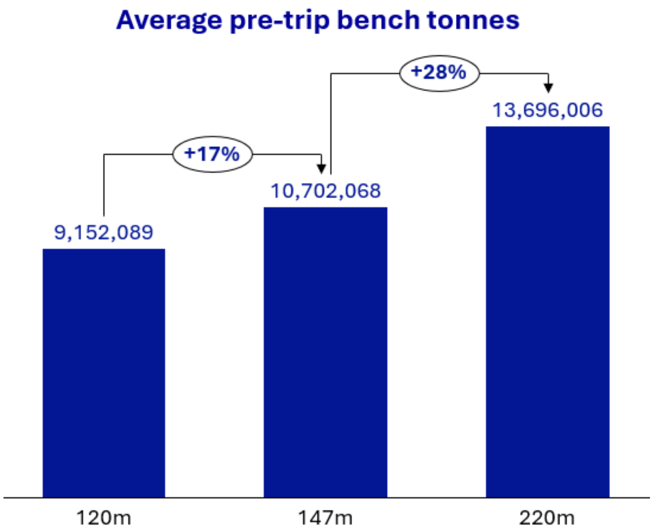

Figure 6-1: Average pre-strip tonnes per bench

The last pre-strip bench that was used as a guide in the schedule when to remove the P&H 4100 loader in each pushback is summarized in Table 6-1. The P&H 4100 loader would then be replaced by the P&H 2800 as the P&H 2800 is able to load materials that has a density greater than $3t/m^3$. The density of the material increases from the pre-strip benches to the internal benches.

Table 6-1: Design sets last pre-strip bench

Last pre-strip bench			
Pushback	120m	147m	220m
D1	16	16	16
D2	17	18	19
D3	17	21	20
D4	20	20	
D5	19		

6.1 Mining Production Schedule

The three design sets were scheduled independently using the bench productivity model's rates per bench as inputs. As mentioned earlier in the report the study avoids biasness by scheduling the design sets for the required duration to mine out the entire area. This may result in a production schedule that has a long ramp down period for some design sets. This long ramp down is ignored as the aim is to ensure that all of the area is mined out by each of the design sets. The results of the mining production schedule for the design sets are summarized below.

6.1.1 120m Design Set Schedule Results

The schedule results for the 120m design set are summarized in Figure 6-2. The first ore material will be mined in 2027, and steady ore production is reached from 2029-2037 with approximately 10Mt ore annual production and a ramp down until 2049. The current schedule focuses exclusively on the pushback D area, leading to an extended ramp down due to its lack of a comprehensive schedule of the entire mining operation.

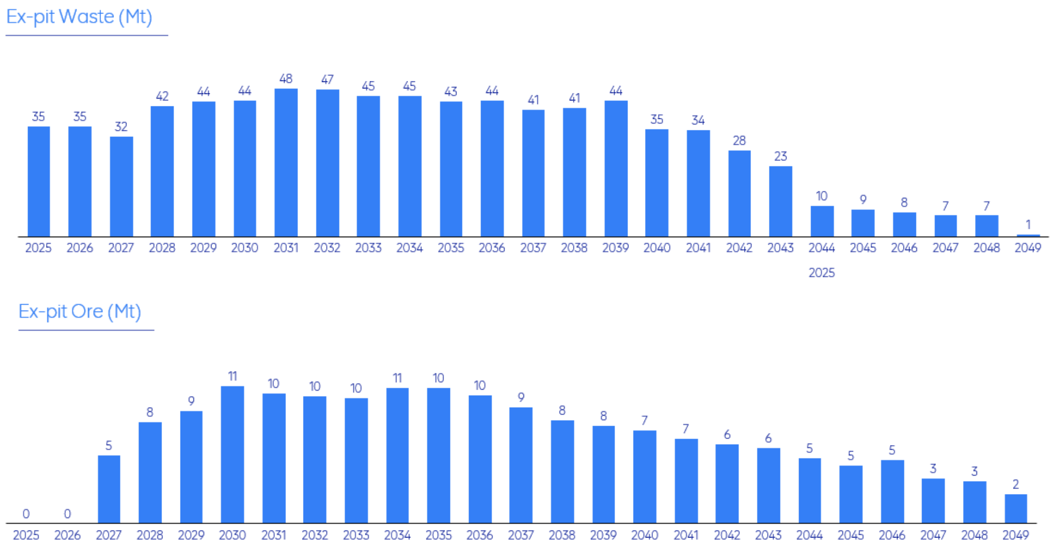

Figure 6-2: 120m design set schedule results

6.1.2 147m Design Set Schedule Results

The schedule results for the 147m design set are summarized in Figure 6-3 Figure *6-3*. The first ore material will be mined in 2027, and steady ore production is reached from 2030-2038 with approximately 12Mt of ore per annum and with a ramp down until 2049. The 147m design sets get ore material the same year as the 120m design set although it mines approximately 4Mt less or in the first year. The steady ore production state for the 147m design set is approximately 2Mt higher than the 120m design set. The schedule is four years shorter than the 120m schedule.

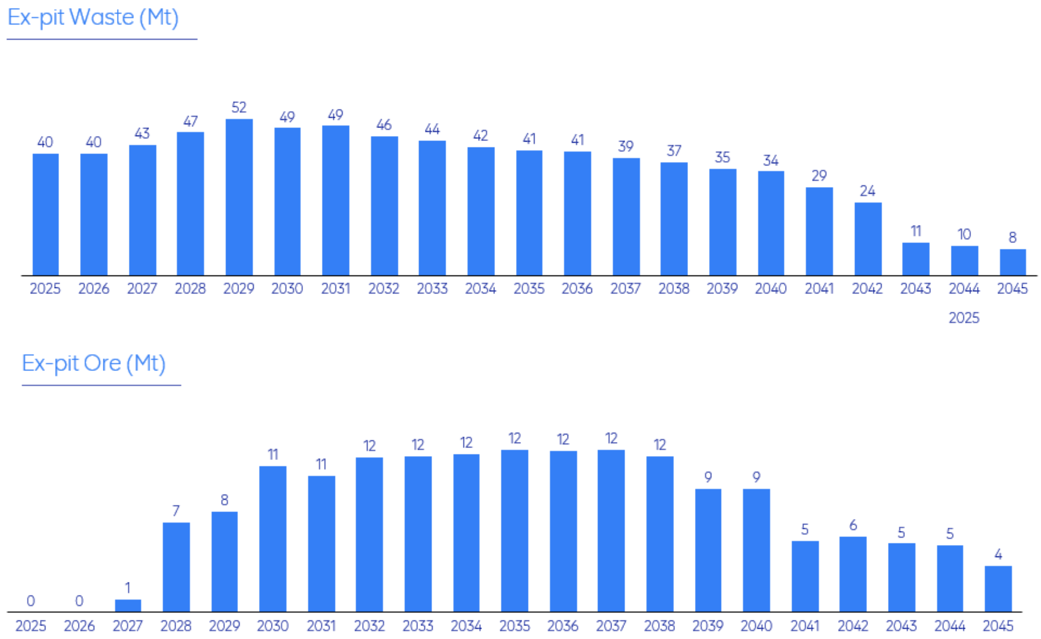

Figure 6-3: 147m design set schedule results

6.1.3 220m Design Set Schedule Results

The schedule results for the 220m design set are summarized in Figure 6-4. The first ore material will be mined in 2027 like the 120m and 147m design sets. This is because the claim space on the top benches is sufficient to allow for two P&H 4100 loaders to be scheduled increasing the stripping volumes per annum thus reducing the stripping time. Steady ore production is achieved in 2030 to 2036 with approximately 15Mt ore production per annum. The annual steady-state ore production exceeds the 120m and 147m design sets. The schedule is 4 years and 8 years shorter than the 120m and 147m design sets respectively.

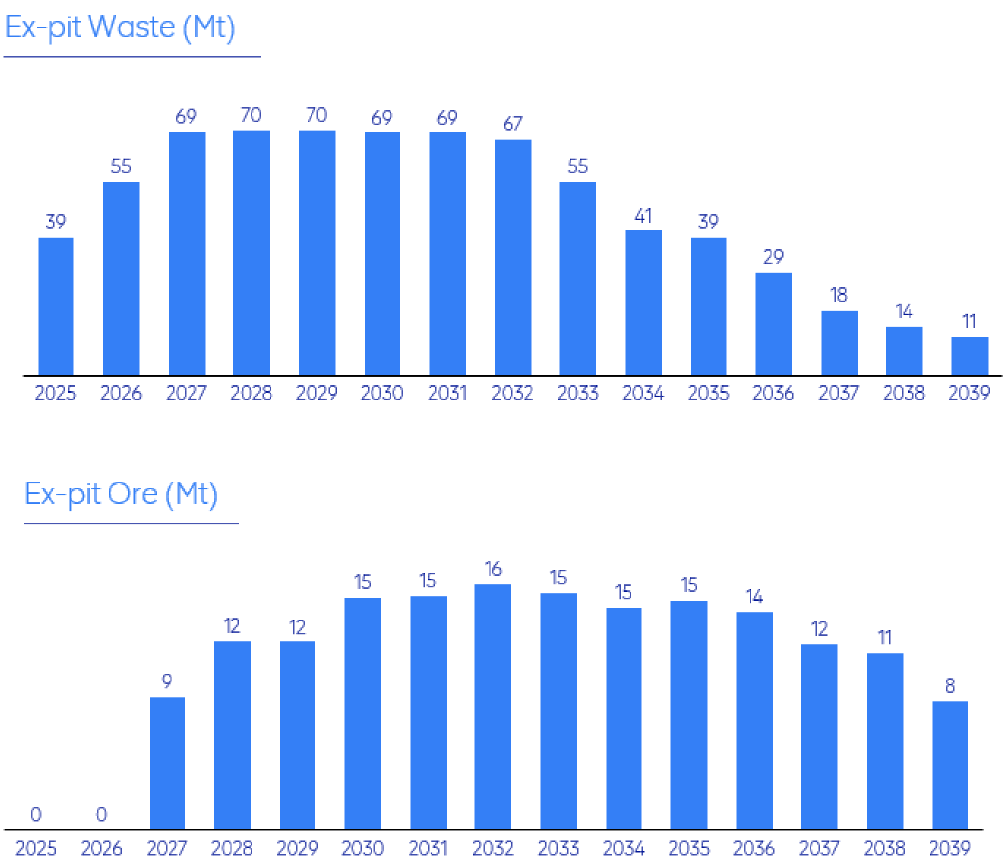

Figure 6-4: 220m design set schedule results

Figure 6-5 summarizes the schedule results of the three design sets. The 220m design set has the least amount of waste and the ore is slightly higher than the other design sets. The schedules indicated that the three design sets get the ore deposit at the same year with the 220m design set due to the claim space. More loaders are scheduled hence exposing more ore in a shorter period. This results in the 220m design set mining more ore in a shorter time. The 120m design sets gets more ore in a shorter time period in comparison to the 147m design set, but due to the productivity of the 147m design set, post 2037, it mines ore more cumulatively than the 120m design set.

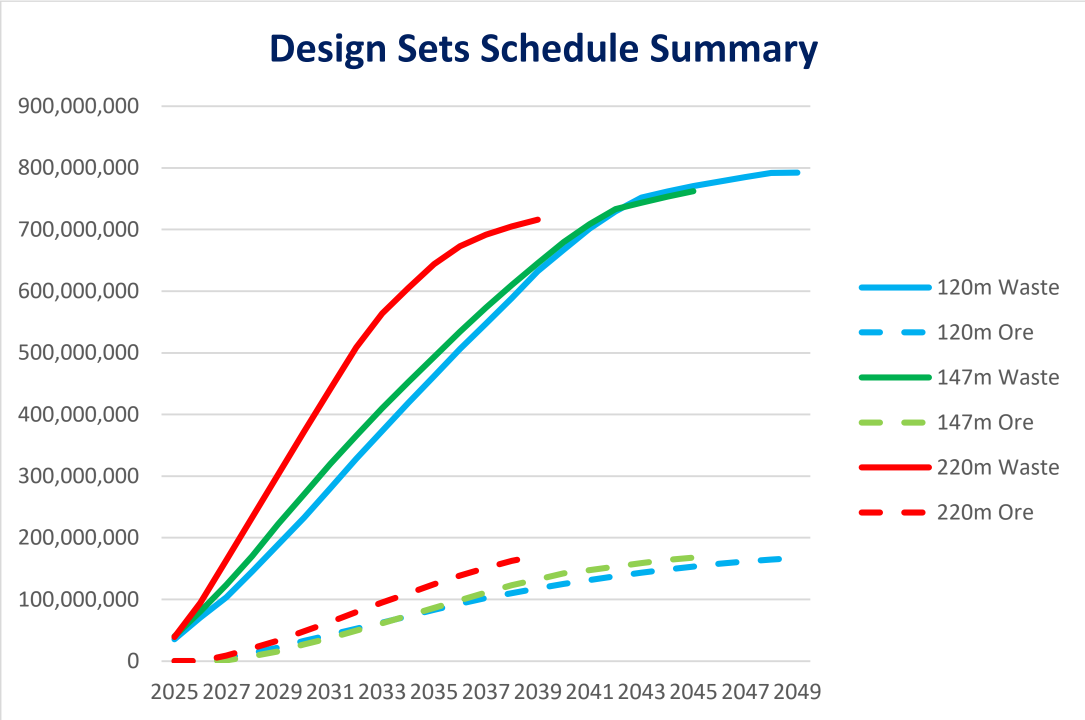

Figure 6-5: Design sets schedule summary

6.2 Cash Flow Analysis

The design set schedule indicates that the 220m design looks like it is the most economical option of the design sets. The 220m design sets mines less waste and ore is mined within a shorter period than the other design sets. A detailed cash flow is required to confirm which design set is the most economical. The cash flow analysis will examine both the IRR and the NPV to determine which design set would be the most economical for mining pushback D area it with the current Sishen mining fleet. Since all design sets originate from the same geographical region, evaluating the NPV will not prioritize larger projects over smaller ones, as the focus remains consistent across the area of interest.

Table 6-2 summarizes the financial assumptions that were used in the cash flow analysis. A factor was used in the financial analysis to protect the company’s financial information.

Table 6-1: Financial assumptions

Revenue		
Iron Ore Price	112.6	$/t
Plant Recovery	70%	%
Costs		
Mining Cost	3.7	$/t
Processing Cost	4.6	$/t
General and Administrative Expenses	6.3	$/t
Rehabilitation	0.1	$/t
Stay in Business	0.6	$/t
Rail Transportation	14.3	$/t
Port	3.2	$/t
Marketing and Sales	1.9	$/t
Shipping freight	24.4	$/t

The discounted cash flow analysis of the three design sets is illustrated in Figure 6-6. Table 6-2 illustrates the detailed cash flow analysis for the 120m design set and indicates that the NPV is R466m with a 15% IRR. Table 6-3 illustrates the detailed cash flow analysis for the 147m design set and indicates that the NPV is R445m with a 9% IRR.

Table 6-4 illustrates the detailed cash flow analysis for 220m design set indicating that the 220m design set has the highest NPV of $741m with a 16% IRR. It is evident that the 220m design set is the most economical split of the three design sets

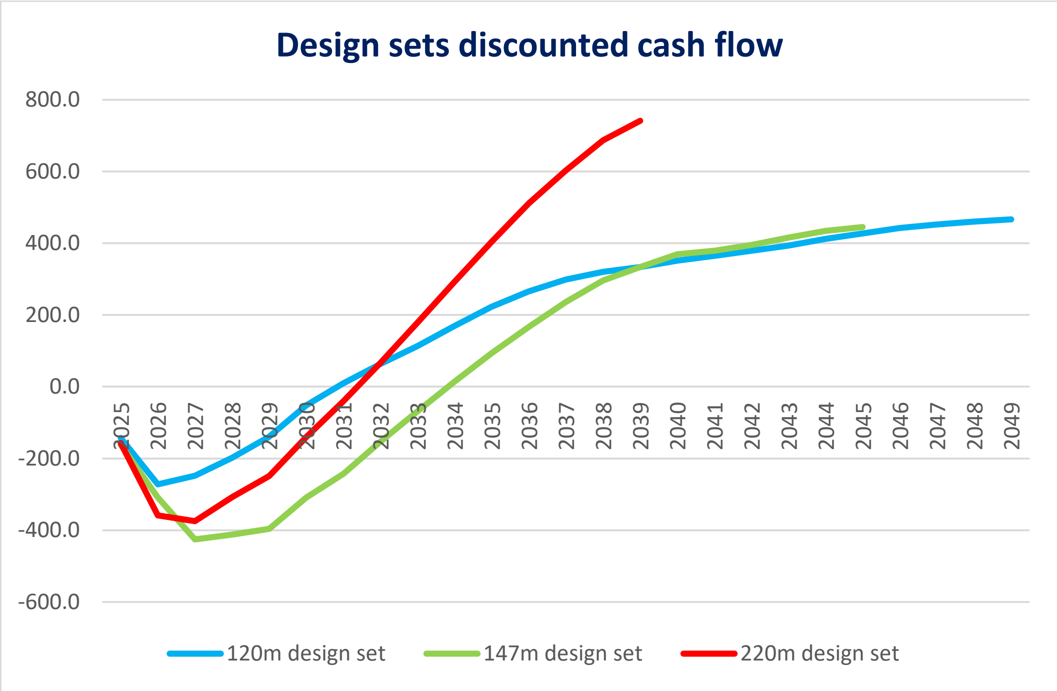

Figure 6-6: Design sets discounted cash flow analysis

Table 6-2: 120m Design set cash flow

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Mining	Waste (Mt)	35.4	35.4	32.4	42.1	43.6	43.9	47.8	47.4	45.4	45.3	43.5	43.9	41.0	41.5	43.9	34.7	34.3	27.9	22.7	9.8	8.6	7.7	6.8	6.8	0.7
	Ore (Mt)	0	0.0	5.3	7.9	8.7	10.6	10.1	9.8	9.7	10.5	10.5	10.0	9.0	8.0	7.6	7.2	6.6	6.2	5.9	5.1	4.5	4.9	3.5	3.3	2.3
	Total (Mt)	35.4	35.4	37.7	50.0	52.3	54.5	57.9	57.2	55.1	55.8	54.0	53.9	50.0	49.5	51.4	41.9	40.9	34.0	28.6	14.9	13.1	12.6	10.3	10.0	3.0
Processing	Plant Yield (%)	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
	Product (Mt)	0.0	0.0	3.7	5.5	6.1	7.4	7.1	6.9	6.8	7.4	7.3	7.0	6.3	5.6	5.3	5.0	4.6	4.3	4.1	3.6	3.2	3.4	2.4	2.3	1.6
Costs (Rmil)	Mining	131.6	131.6	139.9	185.8	194.2	202.4	215.1	212.5	204.7	207.3	200.3	200.0	185.7	183.9	190.9	155.5	151.7	126.3	106.1	55.1	48.7	46.9	38.1	37.3	11.0
	Processing	0.0	0.0	24.5	36.5	40.4	49.2	46.7	45.5	44.8	48.7	48.5	46.0	41.8	37.1	34.9	33.3	30.5	28.5	27.1	23.5	21.0	22.8	16.1	15.2	10.5
	G&A	0.0	0.0	33.4	49.7	55.0	66.9	63.6	62.0	61.1	66.4	66.1	62.7	57.0	50.5	47.6	45.3	41.6	38.8	36.9	32.0	28.5	31.0	21.9	20.7	14.4
	Rehab & Carbon	4.8	4.8	5.1	6.8	7.1	7.4	7.9	7.8	7.5	7.6	7.3	7.3	6.8	6.7	7.0	5.7	5.6	4.6	3.9	2.0	1.8	1.7	1.4	1.4	0.4
	SIB	20.2	20.2	21.5	28.6	29.9	31.1	33.1	32.7	31.5	31.9	30.8	30.8	28.6	28.3	29.4	23.9	23.3	19.4	16.3	8.5	7.5	7.2	5.9	5.7	1.7
	Rail	0.0	0.0	53.0	78.8	87.2	106.2	100.8	98.4	96.8	105.2	104.8	99.4	90.3	80.1	75.4	71.8	65.9	61.5	58.5	50.7	45.3	49.2	34.8	32.8	22.8
	Port	0.0	0.0	11.9	17.7	19.6	23.9	22.7	22.1	21.8	23.7	23.6	22.4	20.3	18.0	17.0	16.2	14.8	13.8	13.2	11.4	10.2	11.1	7.8	7.4	5.1
	Sales	0.0	0.0	7.2	10.7	11.9	14.5	13.7	13.4	13.2	14.3	14.3	13.6	12.3	10.9	10.3	9.8	9.0	8.4	8.0	6.9	6.2	6.7	4.7	4.5	3.1
	Shipping Freight	0.0	0.0	90.5	134.6	148.9	181.3	172.1	167.9	165.3	179.7	179.0	169.8	154.2	136.8	128.8	122.6	112.5	105.0	99.9	86.5	77.3	84.0	59.4	55.9	38.9
	Total Costs	156.6	156.6	387.1	549.3	594.2	682.8	675.7	662.4	646.8	684.8	674.8	652.0	597.0	552.4	541.2	484.1	455.0	406.3	369.8	276.6	246.3	260.6	190.1	180.7	107.9
Revenue	Total Revenue	0.0	0.0	418.5	622.4	688.7	838.3	796.0	776.7	764.7	830.9	827.7	785.1	713.3	632.7	595.7	567.2	520.5	485.6	461.9	400.2	357.3	388.4	274.6	258.6	179.8
Cashflow	Cashflow	-156.6	-156.6	31.3	73.2	94.5	155.5	120.3	114.3	117.9	146.1	152.9	133.1	116.3	80.3	54.4	83.2	65.5	79.3	92.1	123.6	111.1	127.9	84.5	77.9	71.9
	Discount	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15	0.14	0.12	0.11	0.10	0.09
	Discounted Cash Flow	-142.4	-129.5	23.5	50.0	58.7	87.8	61.7	53.3	50.0	56.3	53.6	42.4	33.7	21.1	13.0	18.1	13.0	14.3	15.1	18.4	15.0	15.7	9.4	7.9	6.6
	NPV	466.8																								
	IRR	15%																								

Table 6-3: 147m Design set cash flow

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Mining	Waste (Mt)	40.2	40.2	43.0	47.1	51.5	48.6	49.2	45.8	44.3	42.2	41.1	40.8	38.8	37.2	35.2	34.2	29.0	24.2	10.7	9.9	8.5
	Ore (Mt)	0.0	0.0	1.0	6.9	7.7	11.3	10.5	11.9	12.0	12.2	12.5	12.4	12.5	12.0	9.5	9.5	5.5	5.9	5.3	5.2	3.6
	Total (Mt)	40.2	40.2	44.0	54.0	59.3	59.8	59.8	57.8	56.4	54.5	53.6	53.3	51.3	49.3	44.7	43.7	34.5	30.0	16.0	15.0	12.1
Processing	Plant Yield (%)	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
	Product (Mt)	0	0	0.7	4.9	5.4	7.9	7.4	8.4	8.4	8.6	8.7	8.7	8.7	8.4	6.6	6.6	3.8	4.1	3.7	3.6	2.5
Costs (Rmil)	Mining	149.4	149.4	163.5	200.6	220.1	222.1	222.0	214.5	209.3	202.2	198.9	197.8	190.4	182.9	166.1	162.4	128.2	111.5	59.5	55.8	44.9
	Processing	0.0	0.0	4.8	32.1	35.8	52.0	48.8	55.2	55.6	56.5	57.7	57.5	57.8	55.5	43.9	43.9	25.4	27.2	24.5	24.0	16.7
	G&A	0.0	0.0	6.5	43.6	48.7	70.9	66.4	75.2	75.8	76.9	78.6	78.3	78.7	75.6	59.8	59.8	34.6	37.0	33.4	32.6	22.7
	Rehab & Carbon	5.5	5.5	6.0	7.3	8.1	8.1	8.1	7.9	7.7	7.4	7.3	7.2	7.0	6.7	6.1	5.9	4.7	4.1	2.2	2.0	1.6
	SIB	23.0	23.0	25.2	30.9	33.9	34.2	34.2	33.0	32.2	31.1	30.6	30.4	29.3	28.1	25.6	25.0	19.7	17.2	9.2	8.6	6.9
	Rail	0.0	0.0	10.3	69.2	77.3	112.4	105.3	119.3	120.2	122.0	124.7	124.2	124.8	119.9	94.8	94.8	54.9	58.7	52.9	51.7	36.1
	Port	0.0	0.0	2.3	15.6	17.4	25.3	23.7	26.8	27.0	27.4	28.0	27.9	28.1	27.0	21.3	21.3	12.4	13.2	11.9	11.6	8.1
	Sales	0.0	0.0	1.4	9.4	10.5	15.3	14.4	16.3	16.4	16.6	17.0	16.9	17.0	16.3	12.9	12.9	7.5	8.0	7.2	7.1	4.9
	Shipping Freight	0.0	0.0	17.6	118.2	132.0	191.9	179.8	203.7	205.2	208.3	212.8	212.1	213.1	204.7	161.9	161.9	93.7	100.2	90.3	88.3	61.6
	Total Costs	177.9	177.9	237.5	527.0	583.7	732.2	702.7	751.9	749.3	748.5	755.7	752.5	746.1	716.8	592.5	588.0	381.2	376.9	291.1	281.8	203.5
Revenue	Total Revenue	0.0	0.0	81.3	546.6	610.3	887.4	831.6	942.1	948.8	963.3	984.3	980.7	985.4	946.9	748.8	748.8	433.6	463.2	417.7	408.5	284.8
Cashflow	Cashflow	-177.9	-177.9	-156.2	19.6	26.6	155.2	129.0	190.1	199.5	214.8	228.6	228.3	239.3	230.1	156.3	160.8	52.3	86.3	126.7	126.7	81.3
	Discount	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15	0.14
	Discounted Cash Flow	-161.7	-147.0	-117.4	13.4	16.5	87.6	66.2	88.7	84.6	82.8	80.1	72.7	69.3	60.6	37.4	35.0	10.4	15.5	20.7	18.8	11.0
	NPV	445.4																				
	IRR	9%																				

Table 6-4: 220m Design set cash flow

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Mining	Waste (Mt)	39	55.2	69.3	69.7	69.6	69.2	69.2	67.4	55.0	41.2	39.2	29.2	18.3	13.7	10.7
	Ore (Mt)	0.0	0.0	8.7	12.3	12.3	15.2	15.2	16.0	15.4	14.5	15.0	14.2	12.1	11.5	8.4
	Total (Mt)	39.2	55.2	77.9	82.0	81.9	84.3	84.4	83.4	70.4	55.7	54.1	43.4	30.4	25.2	19.1
Processing	Plant Yield (%)	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
	Product (Mt)	0.0	0.0	6.1	8.6	8.6	10.6	10.7	11.2	10.8	10.2	10.5	9.9	8.5	8.0	5.9
Costs (Rmil)	Mining	145.4	204.8	289.4	304.6	304.1	313.1	313.4	309.6	261.5	206.8	201.0	161.0	112.9	93.4	70.9
	Processing	0.0	0.0	40.1	57.1	56.7	70.1	70.4	73.9	71.4	67.2	69.2	65.6	56.1	53.2	38.7
	G&A	0.0	0.0	54.6	77.7	77.2	95.5	95.9	100.7	97.2	91.5	94.2	89.4	76.3	72.4	52.7
	Rehab & Carbon	5.3	7.5	10.6	11.2	11.1	11.5	11.5	11.3	9.6	7.6	7.4	5.9	4.1	3.4	2.6
	SIB	22.4	31.5	44.5	46.9	46.8	48.2	48.2	47.6	40.2	31.8	30.9	24.8	17.4	14.4	10.9
	Rail	0.0	0.0	86.6	123.2	122.4	151.5	152.1	159.7	154.2	145.2	149.5	141.8	121.1	114.8	83.6
	Port	0.0	0.0	19.5	27.7	27.5	34.1	34.2	35.9	34.7	32.7	33.6	31.9	27.2	25.8	18.8
	Sales	0.0	0.0	11.8	16.8	16.7	20.7	20.7	21.8	21.0	19.8	20.4	19.3	16.5	15.7	11.4
	Shipping Freight	0.0	0.0	147.8	210.4	209.0	258.7	259.7	272.7	263.3	247.9	255.2	242.0	206.7	196.0	142.7
	Total Costs	173.1	243.9	704.8	875.5	871.5	1003.4	1006.1	1033.3	953.0	850.5	861.4	781.7	638.4	589.2	432.4
Revenue	Total Revenue	0.0	0.0	683.7	973.0	966.6	1196.3	1201.0	1261.0	1217.5	1146.4	1180.1	1119.4	956.1	906.7	660.0
Cashflow	Cashflow	-173.1	-243.9	-21.2	97.5	95.1	192.9	194.9	227.8	264.5	295.9	318.8	337.6	317.7	317.5	227.6
	Discount	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39	0.35	0.32	0.29	0.26	0.24
	Discounted Cash Flow	-157.4	-201.5	-15.9	66.6	59.0	108.9	100.0	106.3	112.2	114.1	111.7	107.6	92.0	83.6	54.5
	NPV	741.6														
	IRR	16%														

6.3 Chapter Summary

The mining production schedule in conjunction with the bench productivity model were based on the assumption that the annual production rates of a P&H 4100 loader is 35Mt, 20Mt for a P&H 2800 loader and 12Mt for a Liebherr 996 loader. These rates are based on the average annual demonstrated rates from 2021 to 2024. These are the loader capacities that were used in the bench productivity model to de-rate the shovels where the space was too confined for the loader to load at its maximum capacity. Only the areas that are contained in the design sets were scheduled and the rest of the mining areas on the mine were neglected to ensure that the outcome of the schedule were comparable.

The impact of only scheduling the areas contained in the design sets as illustrated in Figures 6-2 to 6-4 is that the tail-end of the schedule is long. For example, the 120m design set has a tail-end that extends for approximately 11 years, approximately 7-years for the 147m design set and approximately 5-years for the 220m design set. This long tail-end will be optimised in the mine’s production schedule when the other mining areas are incorporated in the schedule.

A cash flow analysis was also run post the production schedule after incorporating the economic assumptions that have been slightly adjusted to protect company’s data. This is an important step since looking at a production schedule without cost associated with that schedule can be misleading as the finances may point in a different direction that is expected.

The following finding were seen from the mining production and financial model. The three design sets were scheduled based on the loader annual production rates and the then they adjusted per bench as per the bench productivity model. The production schedule was only based on the pushback D area ignoring other mining areas. This was done for comparativeness purpose. The outcomes of the mining production schedule and cash flow analysis indicate the following:

- The 120m design set, is set to commence the extraction of ore starting in the year 2027. Furthermore, the mining operations in the pushback D area are projected to be fully completed by the year 2049. During this period, it is anticipated that the production of ore will stabilize at an approximate rate of 10Mtpa from the year 2032 through to 2036. Upon conducting an analysis of the schedule using a financial model, the findings revealed that the 120m design set demonstrates a notably positive NPV of $467 million, alongside an IRR of 15%.

- The 147m design set, is set to commence the extraction of ore starting in the year 2027. Furthermore, the mining operations in the pushback D area are projected to be fully completed by the year 2045, 4-years shorter than that of the 120m design set. During this period, it is anticipated that the production of ore will stabilize at an approximate rate of ~12Mtpa from the year 2032 through to 2038, 2-years longer than the 120m design set. Upon conducting an analysis of the schedule using a high-level financial model, the findings revealed that the 147m design set, demonstrates a notably positive NPV of $445 million, lower by $22 million when compared to the 120m design set. The IRR is 15%, 6% higher than the 120m design set.
- The 220m design set, is set to commence the extraction of ore starting in the year 2027. Furthermore, the mining operations in the pushback D area are projected to be fully completed by the year 2039, 10-years shorter than that of the 120m design set and 6 years shorter than the 147m design set. During this period, it is anticipated that the production of ore will stabilize at an approximate rate of 15Mtpa from the year 2030, two years shorter than both design sets, through to 2038. Upon conducting an analysis of the schedule using a high-level financial model, the findings revealed that the 220m design set, demonstrates a notably positive NPV of $742 million, alongside an IRR of 16%. Both the NPV and IRR is higher in the 220m design when compared to the other two design sets.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

The primary aim of this study is to evaluate which pushback width will enhance the performance of the mining fleet operating at Sishen mine the most. To explore the research question, the preliminary stage required the formulation of three separate design sets, each with mining widths measuring 120m, 147m, and 220m. The objective of this methodology was to identify the design configuration that would produce the most advantageous stripping ratio for the pushback D area from a design perspective.

To ensure that the assessment is fair and impartial, the same mine design criteria, in conjunction with the block model and the optimised pit shells, was uniformly applied across all three design configurations. Table 7-1 provides an overview that details the results obtained from the three separate design sets, with particular emphasis on the amounts of ore and waste present in each design set.

Table 7-1: Design sets comparisons

Mining Width (m)	High Grade Ore (Mt)	Low Grade Ore (Mt)	Total Ore (Mt)	Waste *(Mt)*	SR	Pre-strip (Mt)
120	141	27	168	793	4.7	634
147	142	25	167	759	4.5	627
220	143	28	171	715	4.2	551

Across all three design configurations, both high-quality and low-quality ores demonstrate a similarity, with only a minor difference of around 2% noted between the configuration with the greatest ore quantity and that with the smallest. All three design sets consistently aim to improve ore extraction from the pushback D area. This objective is realized by maintaining a uniform optimized pit shell across each design iteration, and the comparable outcomes demonstrate that each design set successfully met this goal.

An analysis of the different design configurations reveals that the 220m setup produces the least waste and recovers a slightly higher volume of ore than the 120m and 147m configurations as indicated in Table 7-1. The results obtained from the various design sets clearly indicate that by significantly widening the pushback area, there is a notable increase in the amount of ore that can be recovered, all while effectively reducing the quantity of waste material that needs to be mined to expose the same ore quantities.

One of the main reasons for this is that because the study aims to test a particular mining width to ensure that a certain productivity can be assigned in the schedule based on the mining width, so all the pushback designs had to adhere to a strict mining width. Unfortunately, the block model and the optimised shell does not adhere to that strict mining width and as a result the 120m and the 147m design sets were mining outside of the optimised pit shell. This gave the 220m design set an advantage over the other two design sets as due to the wider mining width, the designs were able to better align to the shape of the optimised whittle shell and as a result, mining less waste than the other design sets.

The significance of measuring the amount of pre-strip material that is contained in each of the design sets already gives an indication on the amount of time that each of the design sets will require to access the ore. The 220m design has the least amount of pre-strip waste which gives an indication that depending on the productivity model it should be the design set that gets to ore quicker in comparison to the 120m and the 147m design sets.

The schedule confirmed this as when analysing the cash flow in Tables 6-3 to Table 6-5, the 120m design sets mines ~5.3Mt in 2027 while the 147m and 220m design sets mines 1Mt and 8.7Mt respectively in 2027. Although the mining schedule was not only based on the design but also on the bench productivity model, from just the designs the 220m design set had an advantage of getting to ore quicker in comparison of the other two design sets and that is a result of the design set having the least amount of pre-strip waste.

The bench productivity model aims to close the gap in the mine planning process of mine planners not having a reference to why they decide to reduce mining rates in the production schedule. In most instances, it is up to the discretion of the mine planner as to how much they choose to de-rate or to increase the rate of a particular loader. This is usually based on their knowledge on that particular mine or sometimes the decision may be based on previous experience. The problem is that when the mine planner presents their mine schedule to various stakeholders, some stakeholders have not agreed with increasing or reducing production rates of certain loaders as per the production schedule. Mine planners are usually questioned regarding the rates that they used and what considerations were taken into account in order to support the assumptions. Mine planners usually find this difficult to explain and may lead to other stakeholders not having confidence in the mine plan.

The bench productivity model is a tool that helps mine planner to involve various stakeholders in developing the model before the production schedule is conducted. This is done so that all the stakeholders can agree and have buy-in in the inputs that will be used in the production schedule. The bench productivity model can be amended to suit the particular mine. It is a model that can always be updated with the latest production figures and go through the process again to ensure that all stakeholders are in agreement with it.

For Sishen mine, this model was non-existent and the production rates that were used in the production schedule were based on past demonstrated rates as indicated in Table 7-2. By analysing the data, there is quite a difference in the individual loaders of the same type. When establishing the bench productivity model this provides an opportunity to dig deep into understanding the reason behind that. Reasons could be the material type that the loader was mining in a particular year or the availability of the loader in a particular year was low. During the establishment process of the bench productivity model, the engineering team should be involved to give their inputs to ensure that their concerns are taken into consideration before the production schedule is run. This is to ensure the successful implementation of the bench productivity model.

Table 7-2: Past demonstrated production rates

Demostrated Daily Rates (kt)					
Loader	2021	2022	2023	2024	Average (kt/day)
P&H 4100 A	108	80	91	108	97
P&H 4100 B	90	88	73	93	86
P&H 4100 C	105	91	105	107	102
P&H 2800 A	45	60	55	50	53
P&H 2800 B	62	53	40	54	52
P&H 2800 C	32	45	47	48	43
Liebherr 996 A	15	18	16	20	17
Liebherr 996 B	20	26	29	18	23
Liebherr 996 C	10	15	18	19	16

The bench productivity model is a real-time model that all stakeholders can access and contribute equally to its formulation and constantly be updated to the changing conditions to ensure that all stakeholders have confidence in the production schedule.

7.2 Recommendations

The pit designs sets indicated that the 220m design set due to the number of pushbacks in the pushback D area, had an advantage going into the production schedule as it had the best strip ratio when compared to the other two design sets. The pit designs indicated that the less pushbacks in the area, the lower the strip ratio. The bench model showed that 220m strike designs achieved maximum loader productivity, while 120m and 147m designs reduced production on most benches due to strike length and mining width.

The mining production schedule also indicated that due to the 220m design set having loaders mining at maximum productivity, the ore was exposed sooner. As the ore depletes in the first pushback, stripping is already completed in the second pushback which ensure a consistent ore supply without variations during the years. This is one of the reasons that the 220m design set has the highest NPV in comparison with the other two design sets. The ramp down in production is also shorter than the other two design sets. From a time value of money perspective, the 220m design set mines similar ore tonnes in a shorter time period hence also contributing to the higher NPV. The cash flow analysis also supported the 220m design sets indicating that the sooner the ore is mined out the greater the value.

Table 7-3: Cash flow results

Design Set (m)	NPV (M$)	IRR
220	741.6	16%
147	445.4	9%
120	466.8	15%

The recommendation from the study is that for the deployment of the current mining fleet at Sishen mine indicates that the 220m design set represents the most effective mining width for the pushback D area.

7.3 Limitation of Study and Future Research Work

The main limitation of the study is that it is solely based on the current Sishen mining fleet. Not all mining operations use the same or even similar mining fleet than the ones that is being used at Sishen mine. When analysed alongside other mining operations, particularly smaller ones that deploy a compact fleet, the results of this study may present notable differences.

Certain operations that share the same mining fleet as the Sishen mine may utilize their equipment with varying levels of efficiency compared to Sishen, resulting in slight differences in their production rates. Findings from the study indicate that the production rate assumption plays a crucial role in shaping the optimal mining width tailored to a given fleet size. Different countries and regions may lack extra regulatory stipulations like safety berms and minimum crest stand-offs in their mining operations. Furthermore, employing narrower mining widths can result in enhanced productivity relative to what is realized at Sishen mine.

The financial projections rely on data from the Sishen mine; however, the financial parameters for other operations may differ significantly from those associated with Sishen. It is important to note that Sishen mine operates under the Anglo-American group. A large organization typically incurs significant overhead expenses, in contrast to a smaller enterprise that operates with minimal overhead costs.

Future research should focus on identifying the key factors that influence the efficiency of open pit mining operations and exploring strategies to enhance these factors, particularly in contexts where mining widths are narrower. Some people that SSL from an operational perspective is still more optimal than DDL especially in third world countries where the loader operators are not as skilled to optimal load double sided. An interesting case study to look at in the future is get real data from operation operating in a third world mining loading single-sided versus the same operation loading double sided to determine which is more valuable. If SSL is found to be more optimal under certain conditions, then that could open the doors for mining operations that are operating in those conditions to investigate even going for narrower mining widths.

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