AN EVALUATION OF THE ECONOMIC VIABILITY OF MINING BENCH 7B AT GROOTEGELUK COLLIERY.

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

DECLARATION

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

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ABSTRACT

The profitable exploitation of a resource is the aim of any mining operation. Grootegeluk coal mine (GCM) extracts coal reserves from the Volksrust and Vryheid Formations within the Waterberg coalfield. These Formations are sub-divided into mining benches for practical exploitation. Each mining bench is unique in its average thickness, quality and optimal extraction characteristics. Considering the thickness of the coal bench, the stripping ratio, the expected yield and quality, it may not be profitable to exploit all the coal benches defined at GCM.

The purpose of this research project was to investigate if the mining of Bench 7B at GCM is profitable as this bench was being mined intermittently. Specific questions that the research aimed to answer are: (1) What effect does dilution have on coal product yield and quality? (2) What is the effect of yield on profitability? (3) Is there any economic benefit to mining Bench 7B at GCM?

Coal quality analysis data from mining blocks representing a five (5) year window of exploitation was collected from GCM. This data was obtained from Bench 7B, Bench 7A and Bench 8 which lie directly above and below Bench 7B. The mining costs and the expected revenues associated with exploiting Bench 7B were also obtained from the finance department at GCM. Lastly the coal quality specifications were obtained from Eskom. These specifications were used to compare the mine's resultant coal qualities to Eskom's quality penalisation and rejection limits.

A minimum yield cut-off for the profitable exploitation of Bench 7B was determined to be 27.68% using the yield cut-off function. This yield cut-off was compared to the resultant yield when Bench 7B is processed at different relative densities (RD's) of 1.8g/cm^3, 1.9 g/cm^3 and 2.0g/cm^3. The yield achieved for each wash RD were 52%, 62% and about 69%. These achieved yields are significantly higher than the minimum yield cut-off. This is an indication that this bench is potentially profitable if Eskom's quality specifications are met.

The coal product qualities realised after processing were compared to Eskom's coal requirements to ensure that they were within specification. Dilution scenario testing were undertaken by adding incremental amount of Bench 7A or Bench 8 to Bench 7B. This was done to determine the effect of dilution on yield, yield cut-off and coal qualities. The results confirmed that it is possible for Bench 7B to be diluted to a maximum of 1.5 m of Bench 7A before the yield cut-off is reached

when beneficiating at a RD of 1.8 g/cm^3. At a beneficiation RD of 1.9 g/cm^3, the yield cut-off is reached when 1.2 m of dilution material from Bench 7A is added. The results further confirmed that at a beneficiation RD of 2.0g/cm^3, it is not possible to tolerate any dilution material from Bench 7A. However, the results indicated that it is not practical to dilute Bench 7B with material from Bench 8 because it does no contribute to the overall yield of the product.

It was established that qualities also have an impact on profitability as they can result in the penalisation or rejection of products that are delivered to the customer. If the product qualities do not meet the Eskom qualities they can be rejected. This means that there will be no revenue realised and therefore mining will be conducted at a loss.

When mining, the impact on qualities must be considered in conjunction with yield cut-off. In some of the evaluated dilution scenarios the resultant yield is above the yield cut-off, whilst the resultant ash qualities exceed Eskom's quality specification of 33%. Therefore, in these instances, the coal product would be rejected or in some cases incur penalties.

Lastly, the research has indicated that the variables that are inputs to the yield cut-off function all impact profitability differently. The selling price was found to be the most sensitive to change. The results obtained from the research project indicate that the exploitation of Bench 7B is profitable when mined without any dilution. In addition, certain amounts of the Bench 7A and Bench 8 can be added to Bench 7B whilst profitability and product specifications are maintained. Based on these results, it is recommended that Bench 7B be mined as it is profitable. It is further recommended that this mining should be undertaken with little to no dilution be included to Bench 7B. The material obtained from this Bench should be mined at a wash density that is less than 2.0 g/cm^3.

DEDICATION

“It takes a village to raise a child”. This work is dedicated to the core of my little village. My parent Mr. Sipho Mhlongo and Dr. Maned Mhlongo, my sister Ms. Kethabile Mhlongo, my aunts Ms. Ntjantja Ned and Mrs. Ntoiseng Mbusi and my late grandmother Mrs Mantoiseng Ned. Your hands have moulded me into the man I am today.

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- My friend and brother Mr. Madoda Khumalo for always being a willing ear in difficult times.

To God be the Glory!

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LIST OF ABBREVIATIONS

AR: As received

BIC: Bushveld Ingenious Complex

CV: Calorific Value

DMS: Dense Medium Separation

EDA: Exploratory data analysis

ENE: East-North-East

EW: East-West

GCM: Grootegeluk Coal Mine

g/cm^3: grams per cubic centimetre

GG: Grootegeluk

Km: Kilometre

LOM: Life of Mine

m: Meters

MJ/Kg: Mega-joules per Kilogram

Ma.: Mega annum (million years)

MRA: Mining right area

Mtpa: Million tonnes per annum

NAR: Net as received

NS: North-South

PSC: Power station coal

PRD: Product

RD: Relative density

RoM: Run-of-Mine

SACS: South African Committee on Stratigraphy

SAMREC: The South African code for the reporting of exploration results, mineral resources and mineral reserves

SANS: Standards South Africa

SSCC: Semi-Soft coking coal

Su: Sulphur

t: Tonnes

WSW: West-South-West

YCO: Yield cut-off

YLD: Yield

1 INTRODUCTION

1.1 Chapter overview

The purpose of this chapter is to provide the background of the Waterberg coalfield and to introduce the Grootegeluk Coal Mine (GCM). The background will discuss the history surrounding the discovery of coal in the Waterberg coalfield, as well as its regional geology. The section on the GCM will introduce the GCM operation. Emphasis is placed on describing the local geological setting of Vryheid Formation as well as its mining and processing. A section on the challenges of mining Bench 7B is included in this chapter. This section introduces some mining concepts and highlights the challenges currently experienced in the exploitation of Bench 7B.

The problem statement is then defined, and a list of specific questions to be answered as part of this research project are provided. The hypothesis around which the research is based, is also provided. Lastly, an outline of the research project structure is given.

1.2 Background

1.2.1. History of coal discovery in the Waterberg Coalfield

In 1920 coal was discovered in the north-western Transvaal, now the Limpopo Province, on the farm Grootegeluk 459 LQ 25 km west of the town of Lephalale (formerly Ellisras). What was originally deemed to be a discovery of scientific interest, was investigated further in the 1940's and 1950's by the Geological Survey and the Fuel Research Institute. The aim of these investigations was to determine the extent and economic potential of the Waterberg coalfield. The results of these studies indicated large reserves of metallurgical and power station coal (Dreyer, 1994). The Highveld and Witbank coal fields are nearing depletion and the Waterberg coalfield has been recognised as the future of coal mining in South Africa (Fourie, et al., 2009). It is estimated that the Waterberg contains 40% of South Africa's remaining coal reserves (Theunissen, 2012)

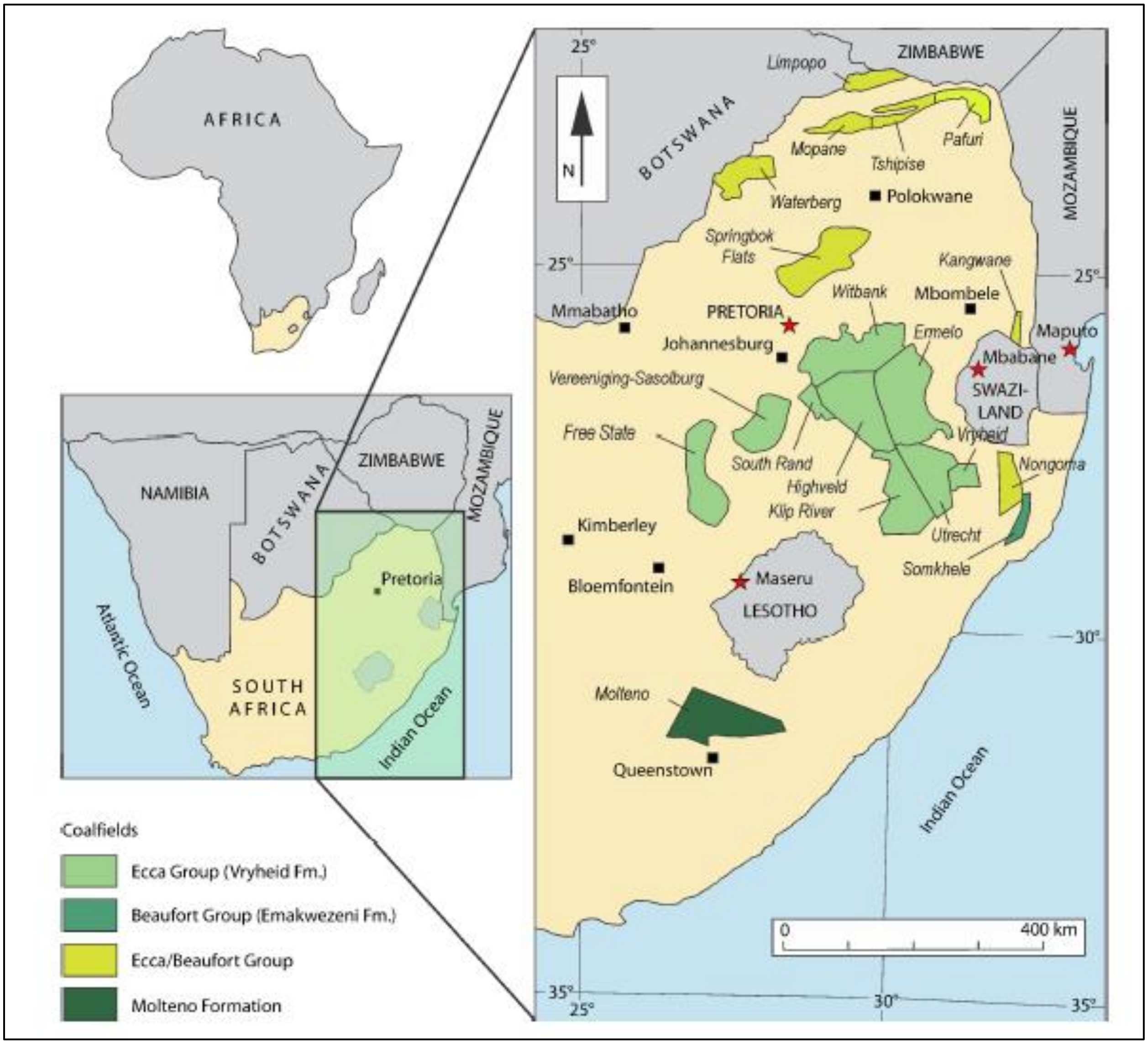

Figure 1.1: Location of the Waterberg coalfield *(Hancox, 2016)*

1.2.2. Regional geology

The Waterberg coalfield occurs in the fault-bounded Ellisras basin (Hancox, 2016). The Ellisras basin is a graben hosted basin that strikes approximately 88km East-West (EW) and 40 km North-South (NS). The basin is in the western portion of the Limpopo province of South Africa, as shown in Figure 1.1, but also extends into Botswana (Dreyer, 1994). It is considered to form an embayment of the much larger Kalahari basin (Hancox, 2016). An embayment refers to a low area of coastal land where the shoreline is pushed back from the sea (Marshak, 2002). At its southern margin, the Ellisras basin is bounded by the Eenzaamheid fault where rocks of the Mogalakwena

Formation occur south of the fault. The northern boundary of the basin is delineated by the Zoetfontein fault, where Archaean granite occur north of its location. Unlike most of the faults that are present within the basin, the Zoetfontein fault predates the deposition of the Karoo aged rocks. For this reason, the southern boundary of the original basin extended further south of the Eenzaamheid fault. The Daarby fault is situated north of the Eenzaamheid fault in the southern portion of the basin. The fault separates the basin into a shallow western portion and a deep north-eastern portion where the first appearance of coal occurs approximately 250 m below surface (Dreyer, 1994). The locations of all the major faults are shown in Figure 1.2.

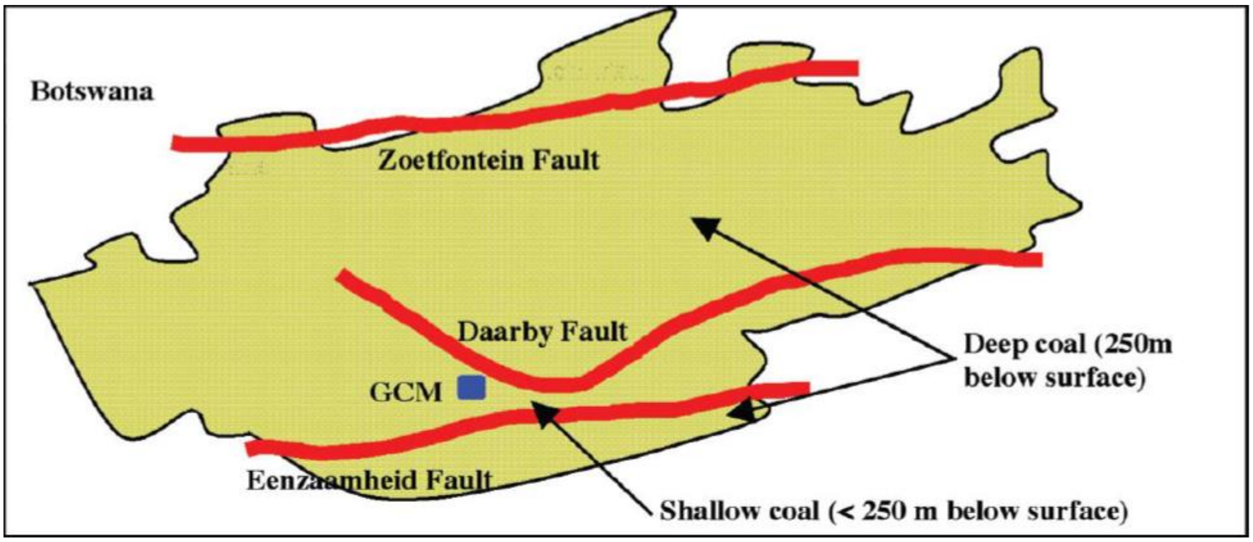

Figure 1.2: Position of the major faults within the Waterberg coalfield *(Jeffrey, 2005)*

Sedimentation within the basin occurred within a shallow East-West (EW) trough where the direction of transportation was generally East-North-East (ENE) to West-South-West (WSW). During deposition, Karoo sediments were transported into the basin (Dreyer, 1994). These sediments were generally deposited onto a basement of Paleoproterozoic (the geological Era from 2500-1600 Mega annums) aged metaconglomerates and metaquartzites rock types of the Waterberg Group and Transvaal Supergroup. The sediments are also deposited on basic igneous rocks of the Bushveld Igneous Complex (BIC) (Johnson, *et. al*. 1996 as cited in (Hancox, 2016)). The entire Karoo Supergroup stratigraphy, shown in Table 1.1, occurs within the Waterberg Coalfield. For this reason, the same nomenclature is applied.

Table 1.1: The Karoo sequence. Adapted from *(Van Heerden, 2016)*

SUPERGROUP	GROUP	FORMATION	DESCRIPTION	THICKNESS
KAROO SUPER GROUP	STORMBERG	Drakensberg	Basalt	95 m
		Clarens	Sandstone	80 m
		Elliot	Mudstone	90 m
		Molteno	Sandstone	15 m
	BEAUFORT	Beaufort	Mudstone	90 m
	ECCA	Volksrust	Intercalated shale and bright coal	60 m
		Vryheid	Sandstone, intercalated carbonaceous shale, siltstone, coal seams	55 m
		Pietermaritzburg	Shale and sandstone, grit in lower portions	150 m
	DWYKA	Dwyka	Tillite	3 m

Coal bearing units within the Waterberg coalfield

The coal bearing units within the Karoo stratigraphy are represented by the Volksrust and Vryheid Formations. The Volksrust Formation occurs in the upper portion of the Ecca Group, while the Vryheid formation occurs in the middle portion of the Ecca Group. It is important to note that the Volksrust formation has been renamed to the Grootegeluk Formation by the South African Committee for Stratigraphy (SACS), however the original name is still widely used. The Volksrust and Vryheid Formations represent two distinctly different depositional environments, and as such, two different types of coal deposition (Dreyer, 1994).

1.3 Grootegeluk Coal Mine (GCM)

GCM, is located approximately 25 Km west of the town of Lephalale (Figure 1.3). The mine exploits coal from both the Volksrust and Vryheid Formations within the Waterberg coalfield. These Permian aged Formations form part of the Ecca Group and were deposited between 260 Mega annums (Ma) and 190 Ma ago (Wagner & Tlotleng, 2012). Iscor (now separated into multiple entities which include Arcelor Mittal, Anglo American Kumba and Exxaro) started extensive exploration activities on the six (6) farms that comprise the GCM mining right area (MRA) in 1973 before trialling a box cut in 1975. The purpose of the box-cut was to obtain bulk-samples for beneficiation studies. The positive results of these studies led to the official commissioning of the mine in 1980 (Exxaro Resources (Pty) Ltd., 2015).

Figure 1.3: Location of Grootegeluk Coal Mine (Van Heerden, 2016).

Exploitation of the coal resource and interburden is achieved through truck and shovel terrace mining of thirteen (13) benches. The Volksrust Formation comprises of four (4) coal benches and one (1) overburden bench. The Vryheid Formation is made up of five (5) coal benches and three (3) interburden benches. Approximately 50 million tonnes per annum (Mtpa) of Run-of-Mine (RoM) coal is extracted from the pit (Van Heerden, 2016). The coal is processed in the world's largest coal beneficiation complex, currently consisting of eight (8) coal processing plants, to produce approximately 24 Mtpa of saleable product. The product mix consists of power station coal (PSC), semi-soft coking coal (SSCC) and metallurgical coal of different specification for local and export markets (Exxaro Resources (Pty) Ltd., 2015).The coal processing plants at GCM are named according to a standard naming convention. The prefix GG stands for Grootegeluk and the number after the prefix indicates the sequence in which the beneficiation plants were commissioned at the mine. An example of the application of this naming convention is GG1 or the Grootegeluk one (1) plant. In this research project, the beneficiation plants are referred to according to the standard GCM naming convention. GCM is currently the only commercially producing mine in the Waterberg coalfield (Exxaro Resources (Pty) Ltd, 2016).

1.3.1. Local geology of the Vryheid Formation

The Vryheid Formation, as shown in Table 1.2, represents depositional conditions like those present in the Witbank and Highveld coalfields and has a stratigraphic thickness of approximately 55 m at GCM. This Formation is representative of a distal depositional environment (Wagner & Tlotleng, 2012). A distal depositional environment refers to one that is far from the source of the sediments.

The Vryheid Formation consists of dull coal seams that vary in average thickness from 1.5 m to 7.8 m. The interburden benches comprise of carbonaceous shales, siltstones and sandstones rock types that vary in average thickness between 4.1 m and 12.5 m. In keeping with the nomenclature used for in the Volksrust Formation, the coal seams in the Vryheid are referred to as zones and are named from the base upwards. These zones are mined as individual benches and the generalised stratigraphy of the Vryheid Formation is shown in Table 1.2. According to the guideline provided in South African National Standards (SANS) 10320 called "The Systematic Evaluation of Coal Deposits, Coal Exploration Results, Inventory Coal, Coal Resources and Coal Reserves", the Vryheid Formation is referred to as a multiple seam deposit (Standards South Africa, 2004).

Table 1.2: Generalised stratigraphy of the Vryheid Formation

	Coal Zones		Average Thickness	Mining Benches
Vryheid Formation	ZONE 4		4.1m	Bench 6
	Interbeds		5.7m	Bench 7A
	ZONE 4A		1.5m	Bench 7B
	Interbeds		4.3m	Bench 8
	ZONE 3		7.8m	Bench 9A Bench 9B
	Interbeds		4.1m	Bench 10
	ZONE 2		4.3m	Bench 11
	Interbeds		12.5m	UNMINED
	ZONE 1		1.5m	Bench 13

1.3.2. Mining and beneficiation of the Vryheid Formation

Bench 6 is the first bench at the top of the Vryheid formation and is on average 4.1 m thick. It consists predominately of dull coal, with some bright coal as well as minor occurrences of shale and carbonaceous shale layers. Bench 6 is blasted and mined as a single bench using a face shovel. The coal is trucked to the GG3 or GG7 crush and screen plants to be used to produce a PSC product (Van Heerden, 2016).

Bench 6 is underlain by Bench 7A which is an interburden waste bench. Bench 7A is on average 5.7 m and consists predominately of fossiliferous siltstone as well as dark coloured mudstones and shales. Minor coal and carbonaceous bands also occur within the bench. Bench 7A is blasted as a single bench and mined using a face shovel before the waste is trucked to be used in backfill operations (Van Heerden, 2016).

Bench 7A is underlain by Bench 7B which is, on average, 1.5 m thick and consists of lower quality dull coals and carbonaceous shale materials. Bench 8, which is below Bench 7B, is on average 4.3 m thick and consist of fossiliferous siltstone and shale. The current mining practice is that Bench 7B and 8 are blasted together and the Bench 7B coal is removed off the top of the blasted material. The removal of the Bench 7B material is typically by a Caterpillar 994F series front end loader (994) or a Komatsu P&H L-1850 LeTourneau (LeTourneau) series front end loader. The dimensions of these machines are included in Appendices 1 to 3. The approximate dimensions of the loading buckets are included in Appendix 4. The Bench 7B coal is trucked to GG2 or GG8 for beneficiation. The GG2 and GG8 processing plants are both single stage, dense medium separation (DMS) wash plants that used to produce PSC at a cut density of between 1.8 and 2.0 grams per cubic centimetre (g/cm^3) (Van Heerden, 2016). The wash density is generally used is between 1.9 and 2.0 g/cm^3, but can be adjusted depending on the quality of the RoM feed.

Bench 8 is underlain by Bench 9 which is on average 7.8 m and consists of predominately dull coal with a few thin shale bands present near the top of the coal bench. The lower portion of the coal bench is lower in ash and has a few bright coal laminae within it. For mining and beneficiation purposes, Bench 9 is subdivided into two (2) sub-benches referred to as Bench 9A and 9B. Bench 9A has an average thickness of 2.4 m, while Bench 9B has an average thickness of 5.4 m. Bench 9A is blasted first and mined using a face shovel. The coal from Bench 9A is then trucked to either the GG3 or GG7 dry crush and screen plant to produce PSC. After Bench 9A is removed, Bench 9B is also blasted and mined using a face shovel. The coal derived from Bench 9B is trucked to either GG4 or GG5 for processing. GG4 and GG5 are both single stage DMS wash plants that are used to produce metallurgical grade coal (Van Heerden, 2016).

Bench 9 is underlain by Bench 10 which is an interburden waste bench. Bench 10 is on average 4.1 m thick and consists of medium grained sandstone with a few thin shale bands. Bench 10 is blasted and mined as a single bench before it used in backfill operations (Van Heerden, 2016).

Bench 10 is underlain by Bench 11 which is the last coaling bench that is currently mined at GCM. Bench 11 is on average 4.3 m and is made up of dull coal with a few bright coal laminae. A few thin shale bands are also present within the coal which exhibits slight coking properties. Bench 11 is blasted and mined as a single bench using a face shovel or a front-end loader. The coal produced from Bench 11 is then taken to either GG4 or GG5 for beneficiation to produce a metallurgical grade coal product. The mining and beneficiation of the Vryheid Formation and the coal products of produced is illustrated in Figure 1.4 (Van Heerden, 2016).

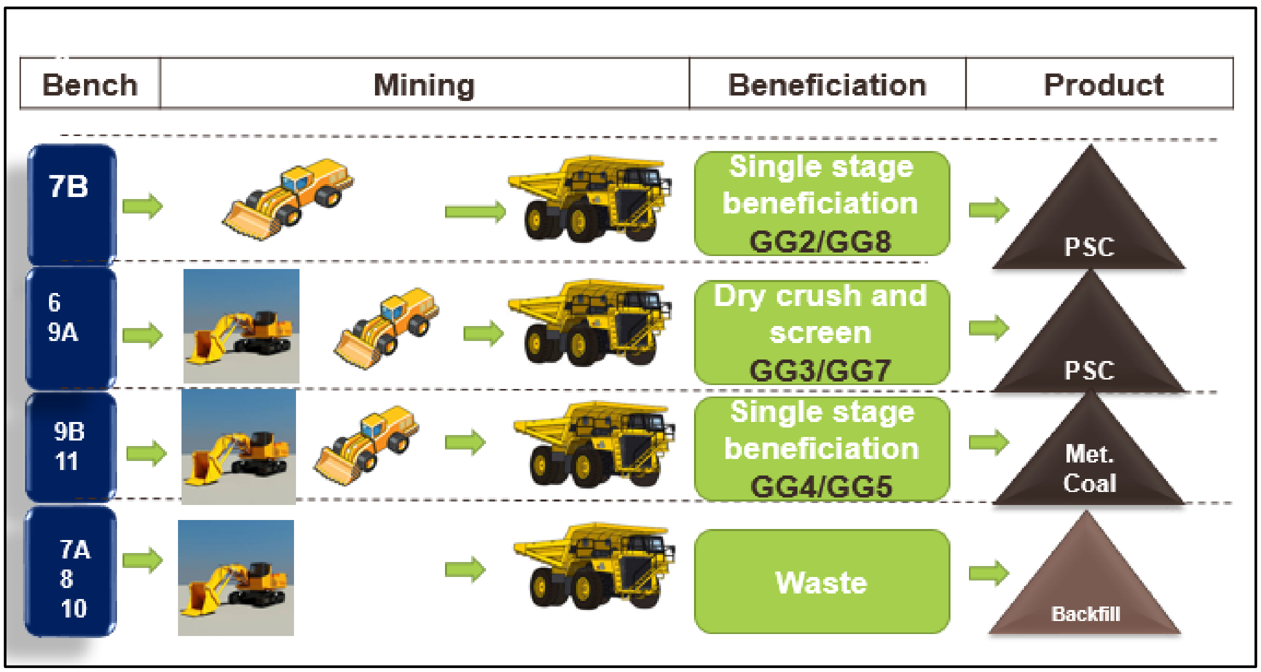

Figure 1.4: The mining and processing of the Vryheid Formation.

1.4 The challenges associated with mining Bench 7B

In any mining environment, material that is removed from the pit is subdivided into ore and waste. Ore, is defined as the natural aggregation of one or more solid minerals that can be extracted and sold for a profit. Waste is the material that must be removed to access the ore (Thompson, 2005). For the purposes of this research report, ore should be considered synonymous with coal. The cut-off grade is defined as the minimum amount of valuable material that must be present in a unit of material for it to be sent to the plant for processing (Rendu, 2014). The use of cut-off grades to determine what is, and what is not profitable to mine is well documented in metalliferous mining environments. The term yield cut-off is used as a proxy for cut-off grades in this research project. This is not the case in coal as it is often assumed that a favourable stripping ratio is the only consideration for profitable mining. In a multi-seam, multi-product mine such as GCM it may not necessarily be true that all material below a certain stripping ratio is profitable. This is because most of the coal measures at GCM must be beneficiated to meet the product specifications as per the customer's requirements. Situations may therefore exist, where it is not profitable to beneficiate certain coal benches as is the current practice. One such instance where profitability must be confirmed is the mining of Bench 7B.

Estimated yield, and consequently the profitable mining of Bench 7B, assumes that the bench is mined accurately so that no non-coal material (waste) from the surrounding benches is included in the coal feed to the plant. The current mining practice is however subject to unplanned dilution. This is commonly referred to as contamination. As a result, the yields achieved are below what is expected. It is however difficult to quantify the current effect of a diluted Bench 7B on the plant yields. This is because Bench 7B is mixed with other coal benches in the plant feed. It is therefore important to determine if the mining of Bench 7B, when exploited accurately to minimise contamination, is profitable. It is also important to determine the effect of various amounts of contamination on coal quality and profitability.

Due to the challenges outlined above, it has been suggested that Bench 7B simply be discarded instead of exploited. In this scenario, Bench 7A, Bench 7B and Bench 8 would be mined together as a complete interburden package. Such a change in the mining strategy would entail writing-off approximately 43.3Mt of proved and probable coal reserves (Van Heerden & Van Staden, 2016). This equates to roughly 3% of the proved and probable life-of-mine (LOM) reserves.

1.5 Problem statement

The purpose of this research is to determine if the mining of Bench 7B at GCM is profitable with the mine’s current equipment. To determine the profitability of the mining of Bench 7B, the following questions must be addressed:

1. What is the effect of dilution on the coal product yield and quality?
2. What is effect of yield on profitability?
3. Is there any economic benefit to mining Bench 7B at GCM?

1.6 Hypothesis

It is economically viable to mine Bench 7B. The profitability of mining Bench 7B is dependent on the of amount of dilution material included, as well as the yield of the saleable product.

1.7 Research project outline

The first chapter discusses the Waterberg coalfield and its regional geology. In addition, the chapter presents a brief overview of the GCM operation before discussing the geology of the Vryheid Formation, where Bench 7B is located. The mining and beneficiation of the Vryheid formation and the challenges associated with mining Bench 7B are introduced. The problem statement, the specific questions to be addressed, as well as the hypothesis of the research project are also presented in this chapter.

The second chapter is the literature review. This chapter discusses the literature that was used in this project report. The literature served as a basis upon which the investigations were conducted. Included in this chapter are a discussion on dilution and its effect on coal product yield, coal product quality and ultimately profitability. The impacts of yield cut-offs and stripping ratios on profitability in opencast mining are also discussed. Lastly the economic considerations in open cast mining are discussed.

The third chapter describes the methodology followed in determining whether the mining of Bench 7B is profitable. In this chapter, the methodology followed in investigating the impact of dilution on coal product yield and coal product quality is also described. Lastly the methodology used to investigate the impact of yield on profitability and how yield cut-offs and stripping ratios impact profitability is also discussed.

The fourth chapter discusses the results obtained in the investigation. An interpretation of the results is then discussed. The fifth and final chapter of the research project discusses the conclusions and recommendations.

2 LITERATURE REVIEW

2.1 Chapter overview

The literature review is subdivided into four (4) sections that are in line with the questions to be answered as part of this research project. The aim of the chapter is to provide background to the literature that was reviewed in solving the problem presented. In the first section, an introduction to coal qualities is given. The aim of this section is to introduce the concept of coal qualities and their importance to GCM and Eskom which is the customer.

In the second section, the impact of dilution on coal quality and profitability is discussed. In this section, the term dilution is defined and the factors that have an impact on dilution are also discussed. Thereafter, the impact of dilution on coal quality, yield and the impact of yield on profitability are discussed and illustrated in the context of GCM.

In the third section, the impact of yield cut-offs and stripping ratios on profitability is discussed. The relationship between the yield cut-off, waste and the stripping ratio is discussed first. Examples of methods used for calculating the yield cut-off and the stripping ratio are illustrated. Lastly some factors to be considered when calculating yield cut-off are discussed.

In the fourth section, the factors influencing the economic exploitation of multi-seam surface operations are discussed. Specifically, the challenges that GCM faces with regards to exploiting Bench 7B.

In the fifth and final section of this literature review, an overview of exploratory data analysis is given. The term exploratory data analysis is first defined and the purpose of this form of analysis is explained. Lastly, the purpose of each statistical metric that will be determined as part of this research project is also explained.

2.2 Coal quality

The term coal quality refers to the specifications of either raw, unprocessed coal or a beneficiated coal product. A coal's quality is typically classified in terms of a composite of its proximate analysis, ultimate analysis, calorific value (CV), forms or sulphur and milling properties. Customers, do however have the option to request additional analyses for their purposes. These may include but are not limited to ash composition and ash fusion temperature (Steyn & Minnitt, 2010). Proximate analysis is group empirical tests performed on a coal specimen to determine its ash, volatile, inherent moisture and fixed carbon contents. Each analyte is expressed such that together they sum to 100 percent. In ultimate analysis the proportions of carbon, hydrogen, nitrogen, oxygen and sulphur are determined and expressed as percentage out of 100. These elements are the organic derived chemical components of coal and the results of the ultimate analysis can assist in determining the rank of a coal specimen (MineSkill Australia, 2010).

Coal qualities are particularly important for thermal coal products due to the problems that can occur when boilers are not suited to combust coal of certain characteristics. It is therefore preferable that boilers are designed to match the coal types that will be consumed (Falcon & Ham, 1988). The coal qualities of importance to GCM and their customer Eskom, are the ash content (ash) and sulphur content (sulphur). They are defined as follows:

Ash content: The ash content measurement is one of the results obtained from a proximate analysis. It is the amount of residue that remains after the coal is completely combusted. This residue is made up of oxides of silica, calcium, iron, and manganese to name but a few (Falcon & Ham, 1988)

Sulphur content: The measurement of the total sulphur content as obtained from the ultimate analysis (Falcon & Ham, 1988). Sulphur generally occurs in three forms in coal; in sulphate, sulphide and organic sulphur (MineSkill Australia, 2010). The sulphur content reported in the ultimate analysis is the total sulphur content and is what will be referred to in this project.

2.3 Impact of dilution on quality and profitability

Dilution, as defined in The South African code for the reporting of exploration results, mineral resources and mineral reserves (SAMREC), refers to either “low or zero grade (waste) material that is mined during mining operations. This material then forms part of the Mineral Reserve”. Dilution can also be referred to contamination (SAMCODES standards committee, 2016). Dilution can include material from either the roof or floor of a coal seam and can also include partings within the coal seam which exceed the maximum thickness cut-off for what is defined as a parting within the specific resource (Standards South Africa, 2004).

Dilution results in an increase in the mined tonnes but a decrease in average yield. Factors that can influence the amount of dilution obtained in a mining operation can be divided into two (2) categories; deposit related and operation related factors. Deposit related factors include the general shape of the ore body, structural geology, thickness of the orebody and distribution of qualities and yields. Operations related factors include the mining method, mine geometry, mining directions, the size of the equipment used and the skill of the operators (Ebrahimi, 2013).

Unplanned dilution can lead to multiple impacts on the overall profitability of mining (Ebrahimi, 2013). Firstly, it can lead to coal product qualities that fall outside of the customer's quality specifications. This may result in the rejection or penalisation of products which has financial implications. GCM has a fixed term contract with Matimba and Medupi power stations. In these contracts, the minimum and maximum quality specifications that will be accepted for consumption are outlined. Depending on the quality of coal delivered to the power station, it can either be;

- accepted for consumption unconditionally;
- accepted for consumption but at a reduced price to the seller; or
- completely rejected and therefore not paid for by the customer.

The penalty or rejection of a coal product by the power station has financial impacts as the cost incurred in mining the coal may not be offset by the price received for it. In addition to the impact on coal quality, by diluting a coal bench with a waste bench, the saleable product yield realised is lower than that of a coal bench that is mined on its own. This again has an impact on the profitability as less product is realised than was planned. The general specification and rejection ranges for all of Eskom's power stations are shown in Table 2.1. The coal qualities are reported as Net- as Received (NAR) or As Received (AR). When qualities are reported on an AR basis, they are reported with total moisture included i.e. with surface moisture and moisture that is contained within the coal structure. CV is reported NAR and that is defined as the absolute energy value obtained when burning a unit mass of coal at a consistent volume such that all the water of the reaction products remains as water vapour (MineSkill Australia, 2010).

Table 2.1: Eskom's general specification and rejection ranges Adapted from *(Eskom SOC Ltd., 2009)* in *(Steyn & Minnitt, 2010)*

Parameter	Unit	Eskom limits	Rejection
Calorific value	MJ/Kg (NAR)	21	20
Total Moisture	Maximum % (AR)	10	12
Ash	Maximum % (AR)	33	>35
Volatile matter	Minimum % (AR)	20	20
Sulphur	Maximum % (AR)	1	2.0
Abrasiveness index	Maximum	50	55.0

By processing more material at lower yields, the unit cost of processing will increase directly in proportion to the amount of waste added to the feed (Ebrahimi, 2013). The impacts of dilution affect the profitable mining of Bench 7B at GCM. It is therefore necessary to investigate the impact of mining Bench 7B considering the impact of dilution. Due to the relatively thin nature of Bench 7B (on average 1.5 m), and the size of equipment used at GCM, mining this bench without dilution is difficult. In trying to mine Bench 7B with the existing mining fleet using the current mining methodology, some material from Bench 8 is inevitably included in the RoM coal and this is not planned. Therefore, a change in bench design that entails the inclusion of a certain amount of dilution to better suit the existing mining fleet may be warranted. In changing the bench design to be thicker, it may be possible to include an intended amount of dilution to achieve a more practical mining height. In addition, the estimated yields used for mining purposes would be more accurate.

2.4 Impact of yield cut-offs and stripping ratios on profitability

Da Gama (2013) recognised that mining was driven by knowledge obtained from three disciplines; geology, mining engineering and economics. The four main variables that influence the economic feasibility of a mineral project are the coal resources, the size of the mine, production costs and yield cut-offs (Gentry & O'Niel, 1984). Understanding the interaction of these variables is important in gaining the required knowledge from the three disciplines. This project will focus on yield cut-off and will evaluate its impact on coal resources and profitability in the long term.

For a given coal resource an increase in the yield cut-off will result in an increase in the amount of material classified as waste. This will in turn result in an increase in the stripping ratio. In addition, this increase in yield cut-off will result in a higher average yield above the cut-off value. Lastly, the increase in the yield cut-off will decrease the amount of coal that is classified as being of the correct specification to sell to customers. This relationship is shown in Figure 2.1. It is important to note the quality specifications of the coal that is deemed to be above the yield cut-off must be sufficient to meet the customer's requirements. Coal qualities must therefore be assessed when a change in the yield cut-off is made.

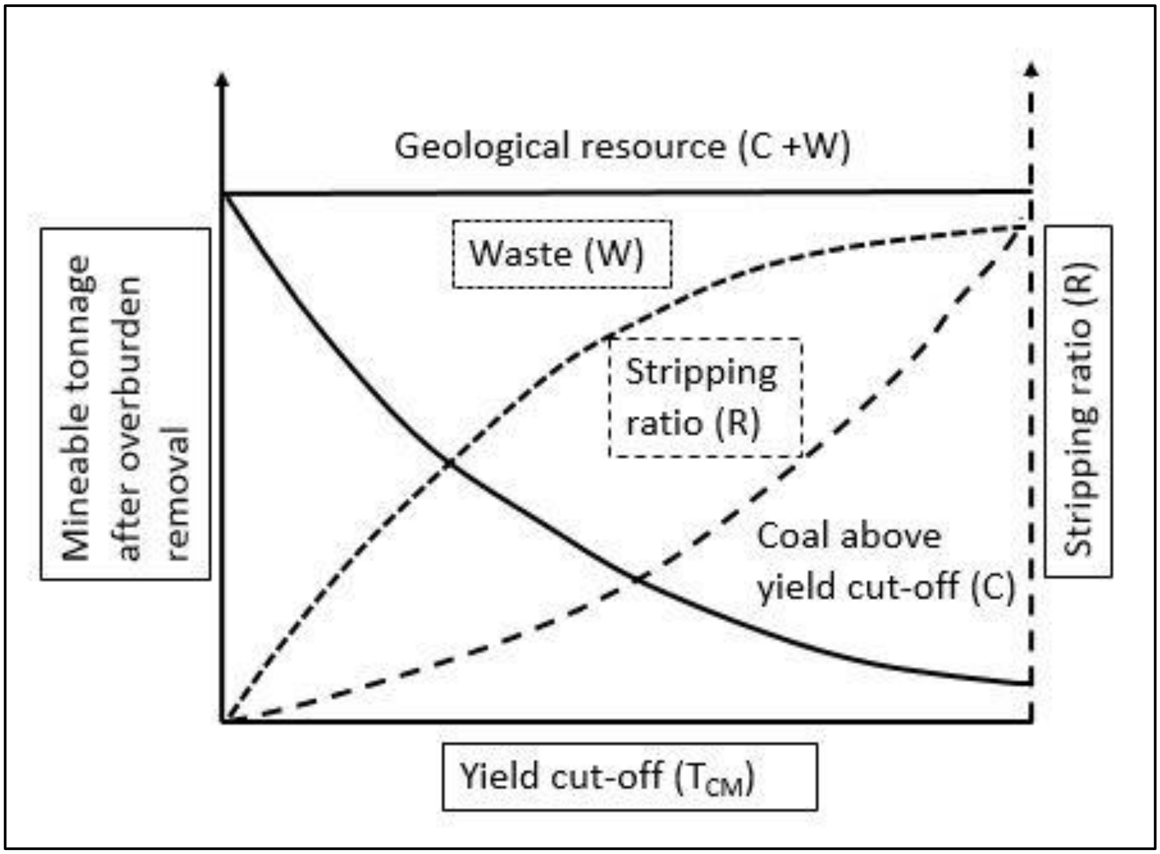

Figure 2.1: Impact of yield cut-offs on waste, the stripping ratio and coal above specification. Adapted from *(Da Gama, 2013)*

Based on an understanding of the relationship illustrated in Figure 2.1, Da Gama (2013) suggested that to maximise profitability on an open-pit operation, one must understand the minimum allowable yield cut-offs and the maximum allowable stripping ratio. In normal operating conditions, the yield cut-off and stripping ratio should be set away from these minimum and maximum numbers such that profit cannot be zero or negative. These costs change in different market conditions, necessitating that these limits are evaluated periodically. The hourly profit function is given by equation 2.1

$$L = PTUV - P(M + ER + B) - F \qquad \text{Equation 2.1}$$

Where:

- L is the hourly profit (R/h)
- T is average grade (yield) of material being mined (%);
- M is the cost of mining per tonne of excavated ore (R/t);
- U is the product recovered from the plant (%);
- V is the selling price of the product per tonne (R/t);
- E is the cost of removing a tonne of waste (R/t);
- R is the instantaneous waste/ore (coal) stripping ratio (t/t);
- B is the cost of processing per tonne of material entering the plant (R/t);
- F is the hourly fixed costs, capital, taxes and other indirect costs (R/h);
- P is the hourly production rate (t/h).

The hourly profit function defines the profit that can be made on an hourly basis during operations. By dividing Equation 2.1 by P, the hourly production rate, the hourly profit function can now be stated on a unit profit basis as opposed to an hourly profit. The unit profit function (L') expresses profit per tonne or per cubic meter of coal. L' is given by equation 2.2.

$$L' = TUV - M - ER - B - {}^{F}/_{P} \qquad \text{Equation 2.2}$$

By making L' equal to zero 0) and stating T as the subject of the formula, it is possible to calculate the minimum cut-off grade (yield cut-off). The derivation of the minimum cut-off grade (yield cut-off) equation is shown step by step in equations 2.3 to 2.7. The formula for the determination of the minimum cut-off grade (yield cut-off) is shown in equation2.8.

$$0 = TUV - M - ER - B - {}^{F}/_{P} \qquad \text{Equation 2.3}$$

$$-TUV = -M - ER - B - {}^{F}/_{P} \qquad \text{Equation 2.4}$$

$$-1(-TUV) = -1(-M - ER - B - {}^{F}/_{P}) \qquad \text{Equation 2.5}$$

$$TUV = M + ER + B + {}^{F}/_{P} \quad \text{Equation 2.6}$$

$$\frac{TUV}{UV} = \frac{M+ER+B+{}^{F}/_{P}}{UV} \quad \text{Equation 2.7}$$

$$T_{CM} = \frac{M+ER+B+{}^{F}/_{P}}{UV} \quad \text{Equation 2.8}$$

Where:

- CM is the minimum cut-off

Using the unit profit function, it also possible to derive the equation to determine the maximum allowable stripping ratio. This is achieved by making L' equal to zero (0) and stating R as the subject of the formula. The derivation of the maximum allowable stripping ratio is shown in equation 2.9 to equation 2.11. The formula used to calculate the maximum allowable stripping ratio is shown in equation 2.12.

$$0 = TUV - M - ER - B - {}^{F}/_{P} \quad \text{Equation 2.9}$$

$$ER = TUV - M - B - {}^{F}/_{P} \quad \text{Equation 2.10}$$

$$\frac{ER}{E} = \frac{TUV-M-B-{}^{F}/_{P}}{E} \quad \text{Equation 2.11}$$

$$R_{max} = \frac{TUV-M-B-{}^{F}/_{P}}{E} \quad \text{Equation 2.12}$$

Where:

- R_{max} is the maximum allowable

Thompson (2005) understood that the stripping of overburden is generally regarded as the most significant cost in surface mining and by extension the profitability of a surface coal mine. He defines a few different stripping ratios that can be determined to calculate profitability. These include the actual stripping ratio, instantaneous stripping ratio, and break-even stripping ratio (BESR). The actual or overall stripping ratio is the total volume of waste that must be removed to access the total reserve of coal. The instantaneous stripping ratio is defined as the actual amount of waste removed in proportion to actual amount of coal recovered for a defined period (Bakhtavar, et al., 2010). Lastly, the BESR is the point at which the total production costs of one unit of coal is equivalent to the revenue received from selling that one unit of coal (Thompson, 2005).

Like Da Gama (2013), Thompson (2015) emphasised the importance of understanding the limits of the stripping ratio when making any economic decision. The stripping ratio of the deposit must below the BESR, otherwise no profit will be realised. The BESR is given by equation 2.13:

$$S_{BESR} = \frac{rF-A}{B} \qquad \text{Equation 2.13}$$

Where:

- r is the sale price of one unit of coal;
- F is the coal yield/ recovery. This is essentially the amount of coal that is eventually sold from what is mined (%);
- A is the unit cost of mining one unit of coal by surface mining; and
- B is the unit cost of mining one unit of waste.

In some instances, as is the case at GCM, multiple seams are mined on a single operation. In operations such as this, it may not necessarily be true that all the seams in the deposit are economically mineable. Thompson (2005) used the example of a deposit that consists of:

- 10m of overburden,
- 1m coal seam (Seam 2),
- 20m of interburden and
- Another 0.5m coal seam (Seam 1).

The overall stripping ratio in this example is calculated to be 20:1. Given that the operation that seeks to exploit this hypothetical resource determines it's BESR to be 25:1, this stripping ratio would be deemed profitable. However, upon closer analysis, the stripping ratio of Seam 2 is 10:1, while the Seam 1 is 40:1. The stripping ratio of Seam 1 is above the operation's determined BESR. This means that while Seam 2 is profitable to strip and mine, Seam 1 is not under the current circumstances. This example is shown in Table 2.2.

Table 2.2: Configuration and stripping ratios of the hypothetical deposit

Mining Units	**Thickness**	**Mining Benches**
	10m	Overburden
	1m	Seam 2
	20m	Interburden
	0.5m	Seam 1

Thompson (2005) further explains that this case can be further complicated by the addition of a third seam above Seam 1. If the configuration of the interburden and the thickness of the new seam were favourable, the mining of Seam 1 may become profitable. It is therefore sometimes necessary to consider more than the stripping ratio to determine profitability. The profit function can assist in evaluating such instances and it is given by equation 2.14.

$$P = (r - O - R - T)F - S'B - A - C - V - D \qquad \text{Equation 2.14}$$

Where:

- r is the sale price of one unit of coal;
- O is the cost of sales and overheads per sale;
- R is royalties per sales unit;
- T is the transportation cost per sales unit;
- F coal yield/recovery;
- S' is the incremental stripping ratio;
- B is the unit cost of mining waste;
- A is the unit cost of mining coal;
- C is the coal treatment cost;
- V is the rehabilitation cost per unit mined;
- D is the administration and management cost.

By rearranging the formula to make F (coal yield) the subject and setting the profit zero (0), it is possible to use this function to determine a minimum yield cut-off as suggested by Da Gama (2005). The resultant formula, which is adapted from Thompson (2005), is shown in equation 2.15.

$$F = \frac{S'B+A+B+C+V+D}{(r-o-R-T)} \qquad \text{Equation 2.15}$$

Using equation 2.15, it is possible to differentiate which portions of Bench 7B are profitable and which are not. The profit function assumes that no unplanned dilution occurs during mining, and as established earlier, the accurate exploitation of Bench 7B is hindered by the machinery used at GCM. It is therefore also necessary to evaluate scenarios where incremental portions Bench 7A and Bench 8 are added to Bench 7B. This is done to analyse the effect of including the waste benches to the Bench 7B RoM feed's product yield, product quality and ultimately profitability.

Thompson (2005) and Da Gama (2013) have introduced the importance of cost considerations in assessing yield-cut offs and by extension of economic viability. Rendu (2014) explains that costs are divided into two categories; fixed costs and variable costs. Fixed costs are those costs that do not change in proportion to the level of activity, whereas variable costs change in relation to the level of activity. Typical examples of each cost category are shown in Table 2.3.

Table 2.3: Examples of fixed and variable cost. Adapted from (Rendu, 2014)

Fixed cost	Variable costs
Capital expenditure	Drilling
Equipment depreciation	Sampling
General administration	Blasting
Property taxes	Loading
Marketing	Crushing
	Concentration
	Shipping

It can be argued that for yield cut-off optimisation, one only need consider variable costs provided that fixed and variable costs are properly defined. Costs incurred in the past that do not change with the level of activity can be considered sunk costs (Rendu, 2014). In the case of GCM, the fixed costs associated with the removal of Bench 7B either as ore or waste, are considered sunk costs. This is because the material must be removed to access Benches 9A, 9B and 11. These benches supply higher value metallurgical coal. Therefore, in any cut-off grade calculation that is conducted, the addition or omission of fixed costs must be considered based on the maturity of the operation and/or solution being evaluated.

2.5 Economic surface mining

There are two assumptions around which economic theory is based. The first is that human needs and wants are unlimited. The second is that society has limited resources with which to cater for these wants and needs. These assumptions are the basis of the economic concept of scarcity. Scarcity requires society to make choices on what needs and wants to satisfy based on the limited resources. This choice is based on an assessment of expected cost versus the potential benefit of the choices (Camus, 2002). The mining of any deposit is reliant on a thorough analysis of costs and benefits to make decisions on exploitation.

Multiple seam mining refers to instances where two or more coal seams are extracted simultaneously from the same pit. Falkie and Porter (1972) based their work on multiple seam operations in Kentucky and Ohio in the United States of America. They proposed a model that would assist in the decision-making process on whether to mine a given coal seam within a multiple seam environment. They recognised that the decision on whether to strip a seam was important to coal miners for two reasons; firstly, it determined whether the company would have the coal reserves to meet future demands. Secondly, it determines if the company could realise the maximum return on investment. The model proposed by Falkie and Porter is divided into four (4) phases;

1. Decision-making;
2. Simulated mining;
3. Cost calculation; and
4. Determination of a discounted cash flow return on investment.

For the purposes of this research project we will focus on the decision-making phase as it relates to the decision that need to be made at GCM regarding the exploitation of Bench 7B. The criteria upon which the decisions are made are divided into three broad categories; physical, chemical and economic. Examples of the three broad categories are summarised in Table 2.4.

Table 2.4: Decision making criteria categories. Adapted from (Falkie & Porter, 1972)

Physical criteria	Chemical criteria	Economic criteria
Ratio of overburden to coal	Yield of coal	Selling price
Ratio of overburden and parting to coal	Quality of coal	Variable operating costs
Thickness of the overburden	Ash content	Transportation cost to market
Parting thickness	Moisture content	Cost of capital
Thickness and variability of coal seams	Sulphur content	Capital expenditure required
Dip of seams	Volatile content	Production rate
Physical continuity or thickness and qualities	Calorific content	
Amount of reserves	Fixed carbon content	
Equipment capacities and capability		
Physical characteristics of the overburden		
Physical characteristics of the coal		

Falkie and Porter (1972) recognised that the most important consideration in the decision-making portion of their model are the physical criteria to be considered. The first to be considered are the thickness of the overburden and coal respectively. These two criteria have a direct impact on the type of machinery used to mine the deposit. The machinery used at GCM are large and have been selected to be flexible enough to cater for the thick benches of the Volksrust Formation coal, which have an average thickness of 16m. Most of the lower coal benches of the Vryheid Formation coal are also thick with average thickness between 4.1m and 7.8m for Benches 6, 9 and 11 as shown in Table 1.2. Bench 7B has an average thickness of 1.5m and does not lend itself for optimal extraction with current machinery. Furthermore, Bench 7B is situated between two (2) waste benches, namely Bench 7A and Bench 8, which both have an average thickness 5.7m and 4.3m respectively. This means that the waste from Bench 7A, must be removed to access Bench 7B. In addition, the waste from Bench 8 must be removed to access the higher value Bench 9 coal.

Falkie and Porter (1972) further recognised that large operations, such as GCM, have contracts that have quality clauses designed around the coal that is available in the deposit. In so doing, the product specifications being delivered to customers allow for the optimal utilization of the coal resource. This fact is supported by the work of Falcon and Ham (1988), who recognised that boilers must be designed to accommodate the characteristics of the coal that will be fed to them as discussed earlier. This makes chemical criteria of less importance when compared to the other two criteria as a limiting factor for economic extraction. However, the chemical criteria do remain important as they form the basis of the customer’s quality penalty and rejection limits for the coal product. This has been discussed in the section on the effect of dilution on coal qualities in the literature review.

With regards to the economic criteria identified by Falkie and Porter (1972), as a mature operation that is close to its customer and has a fixed term supply contract; economic criteria like selling price, capital costs and cost of transportation add little to no effect on profitability as they are either fixed or low. However, the variable costs associated with mining Bench 7B do have an impact on profitability as they are dependant with the level of activity required to exploit Bench 7B. As suggested by Rendu (2014), the determination and optimisation of the Bench 7B yield cut-off will focus on variable costs for this reason.

2.6 Exploratory data analysis

Exploratory data analysis (EDA) is the process of trying to gain an understating of sample data by undertaking statistical computations. In so doing inferences can be made on the characteristics of the data population based on what is observed in the sample data. This is achieved through use of descriptive statistics as well as visual representations of the sample data. (Dohm, 2015). The statistical analysis was sub-divided into three (3) broad categories: the measurements of the central tendencies, the measurements of variability and the description of the underlying distribution.

The aim of measuring the central tendencies of the data, is to see where most of the values within a data set lie. This can be equated to determining what are the “typical” values that can be expected for a variable (Clark & Harper, 2000). The measurements of central tendencies undertaken in this research project included the calculation of the mean, median and mode.

The aim of measuring the variability of our sample data is to see how far the sample population values can differ from the typical value or mean (Clark & Harper, 2000). The measure of variability undertaken for this research project included the determination of the sample data range, variance and standard deviation

Lastly the aim of describing the shape of the underlying sample population distribution, is to see how the sample data is grouped around the mean (Clark & Harper, 2000). The two values calculated to observe the shape of the distribution were the skewness and kurtosis of the population distribution. Kurtosis can be described as the measure of peaked-ness of the population distribution. Skewness is the measure of the level of asymmetry in the sample data (Clark & Harper, 2000).

By under taking EDA, we can determine if the sample data that was collected belongs to one sample population. If this is the case, any calculations conducted on the sample data will be valid for the population and any inferences made about the sample population based on the sample data will be equally valid.

2.7 Concluding remark on literature review

The aim of the chapter was to introduce the literature reviewed in this research project. The concept of coal qualities and their importance to the thermal coal product that GCM produces was discussed first. Thereafter dilution and its impact on coal qualities and yield was discussed. The literature indicates that dilution is the result of multiple factors. The most relevant to the mining of Bench 7B at the GCM operation is inaccurate mining because of the large machinery used to mine the Bench 7B coal. This machinery is more suited to mining the larger coal bench of the Volksrust formation. Dilution has an impact on coal qualities and has the potential to result in the coal product delivered to the customer being either penalised, or rejected if it is outside the agreed upon specification resulting in an impact on profitability. In addition, dilution results in a decrease in the yields realised and therefore impacting profitability as well.

The impact of yield cut-offs and stripping ratio on profitability was also discussed. The literature indicates that for a given coal reserve; the higher the yield cut-off, the higher the stripping ratio as more material will be classified as waste that must be removed. The literature also indicated that the limits of an operations stripping ratio and yield cut-off must be well defined. Operations should exploit the reserve below the stripping ratio limit and above the yield cut-off limit to ensure profitability. A common misconception in surface coal mines is that if the stripping ratio is below the maximum determined level, the mining of coal will be profitable. However, the literature review shows that this is not the case. Instances do exist where more than stripping ratio must be considered. By using a rearranged profitability function, the yield cut-off can be determined. This can be used as an evaluation tool to determine the profitability of mining Bench 7B. In reviewing the literature on yield cut-off optimisation, it can be argued that the addition or omission of certain costs must be carefully considered depending on the maturity of the operation.

The economic considerations when determining the profitability of exploiting a multiple seam deposit were discussed. Based on the work of Falkie and Porter (1972), the most important considerations for economic surface mining were split into three (3) broad categories; physical criteria, chemical criteria and economic criteria. The literature indicated that the most important considerations for economic exploitation at an operation such as GCM are the physical characteristics of the deposit. While the chemical characteristics of the product are important for the beneficiated coal product as they can have a financial impact if they do not meet the customer's specifications. The literature also indicated that variable costs are the most important economic criteria. This is because the other economic criteria have a lesser impact on large operations like GCM. In the next chapter, the methodology applied in investigating this the economic viability of mining Bench 7B will be discussed.

Lastly the aim of the exploratory data analysis through a statistical approach was discussed. The descriptive statistics parameters to be determined as part of this study were outlined and the purpose of determining each of these was also outlined.

3 METHODOLOGY

3.1 Chapter overview

A scientific approach was taken in trying to evaluate the economic viability of mining Bench 7B. In the literature review, it was established that the mining of a coal unit such as Bench 7B is a unique problem with no clearly defined approach to solving it. Instead the possible solution will require a multi-faceted approach which encompasses different aspects of coal mining and processing. In this study the evaluation of profitability is undertaken under fixed assumptions. These include:

- Maximum resource utilisation: It is assumed that if some profit is made, Bench 7B should be mined,
- Equipment availability: It is assumed that the equipment that can be used to mine Bench 7B, specifically the front-end loaders, is available; and
- Plant capacity: It is assumed that the plants used to beneficiate Bench 7B have the capacity to handle any material sent to them in the process of mining Bench 7B. This includes any dilution material that is planned or unplanned.

3.2 Data collection and exploratory data analysis

Mining block data was extracted from the GCM geological model and used as the basis of this project. This data was taken for a five (5) year period of mining from the position of Bench 7B and the data-set used consisted of data from 260 mining blocks. The thickness, relative density (RD), CV, ash, and sulphur quality data pertaining to the Benches 7A, 7B and 8 were analysed statistically to understand their respective characteristics. The understanding of the quality characteristic on Bench 7A and Bench 8 is important as these two benches are the source of the unplanned dilution included in the Bench 7B RoM coal in the current mining scenario.

In conducting exploratory data analysis, the intention is to ensure that the data collected is representative of the project area and belongs to a single population. In so doing inferences about the nature of the resource can be made based on the calculations that were undertaken using the sample data. It is important to note that the EDA was conducted on the raw (un-beneficiated) coal qualities. This was done to investigate the population characteristics before the influence of a beneficiation process. It is assumed that if the sample data belongs to one population, it will behave similarly when beneficiated.

3.3 Yield cut-off determination and dilution scenario testing

The various mining costs and the Eskom coal sale price were obtained from the mine's finance department. This was necessary as the cost and benefits of mining Bench 7B must be understood to determine profitability. The costs used for this project are based on the 2017 budget costs and are in line with the 2016 actual costs. Using these costs, the minimum yield cut-off for the undiluted mining of Bench 7B was determined using equation 2.15. New yield cut-off values were also calculated for undiluted Bench 7B material when beneficiated at 1.8 g/cm^3, 1.9 g/cm^3 and 2.0 g/m^3 respectively.

As part of this study, Bench 7A and Bench 8 were used to dilute Bench 7B in different mining configurations. This was done to determine the impact of the addition of these waste benches on product yield, product quality, and profitability. New yield and yield cut-offs were determined for each of these dilution scenarios at wash densities of 1.8 g/cm^3, 1.9 g/ cm^3 and 2.0 g/cm^3 respectively on a block-by-block basis. For practical analysis and reporting purposes, the resultant average yield cut-off and quality are discussed. In addition, the estimated product tonnes that can be expected from 1000 tonnes of RoM feed will be calculated based on the new yield.

The new yield that results from the dilution of Bench 7B was plotted against the dilution thickness on a line graph. On the same graph, the calculated yield cut-off was also plotted against the dilution thickness. The point at which these two lines meet, would be an indication of where the yield cut-off is reached or even exceeded. It is at this point that the mining of Bench 7B is no longer profitable.

The penalisation and rejection limits for the ash and sulphur qualities for the Eskom power stations are indicated in Table 2.1. The resultant qualities from each dilution scenario were evaluated against the quality specification limits to ensure that they are within specification. In instances where the penalty and rejection quality limits are reached, the minimum yield cut-off was recalculated using an adjusted selling price. Penalties of between 30-50% of the cost of the free-on truck coal are imposed by Eskom on products that are outside of specifications (Steyn &

Minnitt, 2010). For the purposes of the research project, a 50% penalty was applied to the selling price where the coal product qualities exceeded the Eskom specifications. In instances where the rejection limit is reached, the minimum yield cut-off cannot be calculated. This is because the denominator in the equation will be negative and will therefore give unrealistic results.

3.4 Sensitivity analysis

The sensitivity of the mining costs, selling price and stripping ratio were each analysed. Each of these variables were individually increased in increments of 10 %, while the remaining variables in the yield cut-off function were kept constant. The exception to this was the selling price, which was decreased in 10% reductions. The decrease in selling price was done to simulate the same effect that an increase in costs would have on yield cut-offs. The new yield cut-offs obtained from changing the selling price or variable cost was then plotted against the percentage increment by which the variable was changed and the resultant trend was then analysed.

The sensitivity analysis on the impact of the stripping ratio on the yield cut-off was conducted in a similar way. The stripping ratio was increased in 0.5 ratio increments while the remaining parameters within the yield cut-off function were kept constant. The new yield cut-offs obtained from the change in stripping ratio was then plotted against the increased stripping ratio. In this way, it is possible to analyse the impact that a change in stripping ratio had on yield cut-off.

3.5 Concluding remarks on methodology

In this chapter, the methodology applied in evaluating the profitability of mining Bench 7B was discussed. The data collected and the aim of the exploratory data analysis was explained first. The methodology used to calculate the yield cut-off as a measure of profitability was presented next. In addition, the methodology used to evaluate the impact of dilution on yield cut-off and the resultant qualities was also discussed. Lastly, the methodology applied in assessing the sensitivity of the variables used in the calculation of the yield cut-off was discussed. In the next chapter, the results obtained from the methodology described above are discussed.

4 RESULTS AND DISCUSSION

4.1 Chapter overview

In this chapter, the results obtained from the applying the methodology described chapter 3 are discussed. The results are presented in the same sequence and under the same themes described in the methodology. The results of the exploratory data analysis of Bench 7A, Bench 7B and Bench 8 are presented separately. The descriptive statistics and sample population characteristics of the CV, ash, sulphur, yield, RD and bench thickness variables are discussed in detail. For each bench discussed, the impact of the average values presented on mining is outlined.

The yield cut-off of mining Bench 7B without any dilution is then calculated and discussed. Thereafter, the results of the dilution scenarios that were tested as part of the research project are presented and discussed. The results for the dilution scenarios considered are presented in two (2) sections. In the first section, the results that are presented show what effect incrementally diluting Bench 7B with Bench 7A has on product yield, yield cut-off, product qualities and product tonnes. The amount of product (PRD) that can be expected from 1000 tonnes of RoM feed based on the various dilution scenarios will also be determined. These results are discussed for each RD at which the diluted Bench 7B is beneficiated. In the second section, the same data is presented for scenarios where Bench 7B is incrementally diluted with Bench 8.

Lastly, a discussion on the impact of changes in the input costs, selling price and stripping ratio related to the exploitation of Bench 7B is presented. The results of the sensitivity analysis conducted on each of the parameters are shown and discussed.

4.2 Exploratory data analysis results and discussion

4.1.1. Bench 7A

Bench 7A raw ash analysis has a mean of 70.59 %, a median of 70.69 % and Mode of 71.1 %. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The data has a range of 8.4 % with a variance of 1.71 and standard deviation of 1.31%. This indicates little spread in the data. The underlying frequency distribution of the data is slightly positively skewed and having a platykurtic shape. The histogram showing the shape of the distribution is shown in *Figure 4.1*.

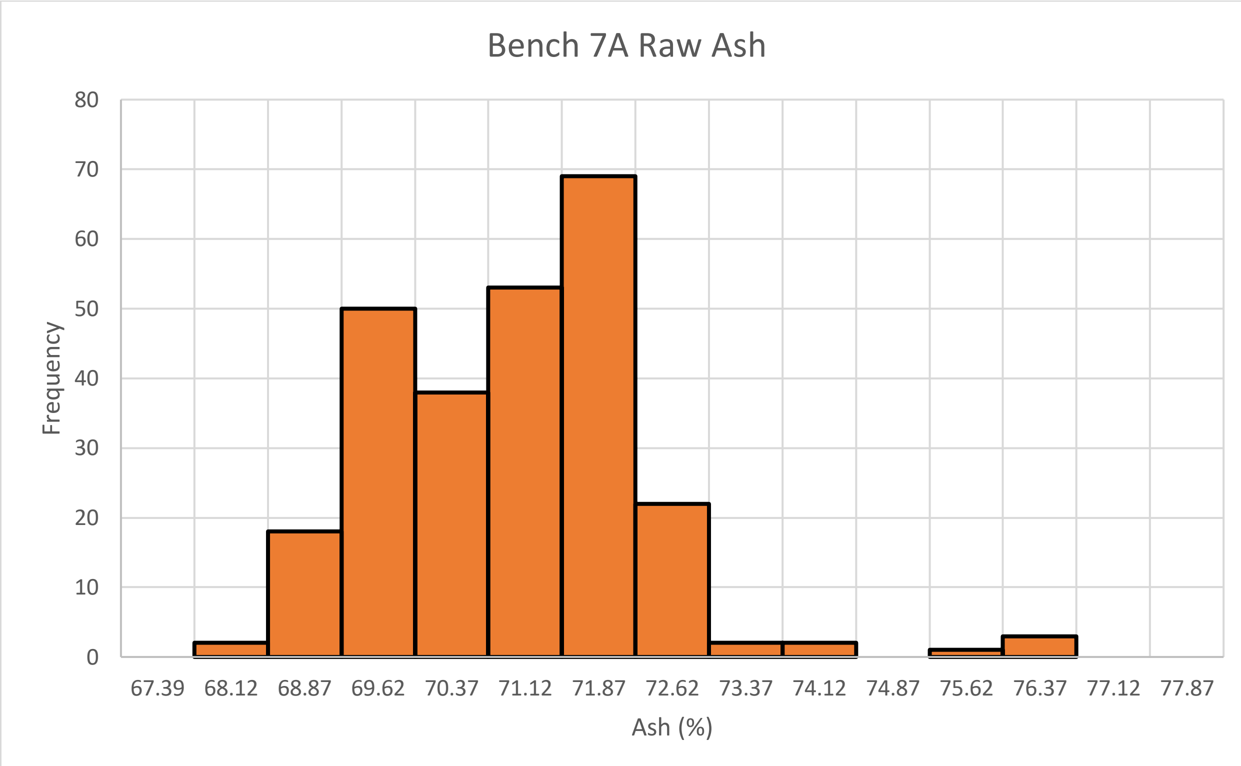

Figure 4.1: Bench 7A raw ash histogram

The results indicate that the raw ash sample data for Bench 7A belongs to a single data population. It is therefore possible to use this data to make inferences about the sample population. A high average raw ash value of 70.59% is more than double the rejection limits for Eskom power station which is 35%. This means this bench is unsuitable for power station coal usage in its raw form. Furthermore, the inclusion of any material from Bench 7A to the Bench 7B RoM coal would result in an increase in the ash values that would be expected from the Bench 7B coal.

The raw CV analysis has mean of 8.99 MJ/Kg, a median of 9.0 MJ/Kg and a mode of 8.66 MJ/Kg. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The raw CV variable has a range of 2.82 MJ/Kg with a variance of 0.19 and standard deviation of 0.44 MJ/Kg. This shows little spread in the data. The underlying population distribution is slightly negatively skewed and can be described as having a platykurtic shape. The histogram that illustrates the shape of the underlying distribution is shown in Figure 4.2.

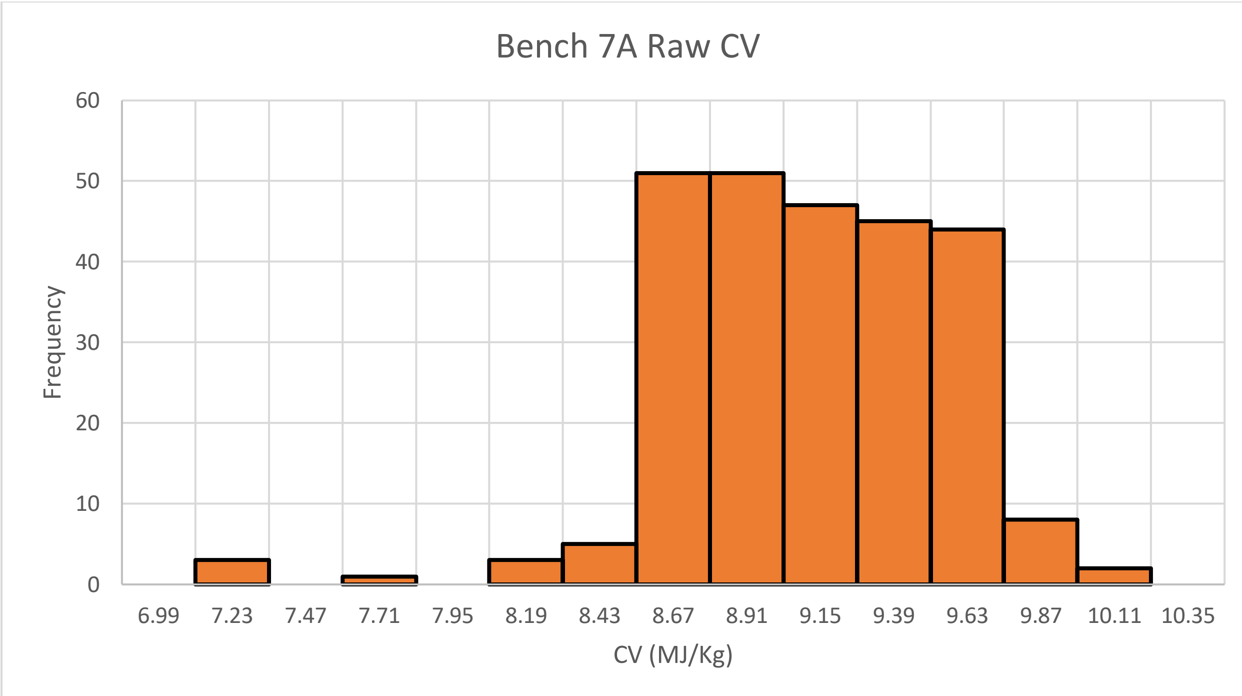

Figure 4.2: Bench 7A raw CV histogram

The EDA results for the raw CV data obtained for Bench 7A indicates that the data belong to one population. It is therefore acceptable to make inferences on the population based on the sample data. The average raw CV value for Bench 7A is 8.99 MJ/ Kg. This is below the Eskom specifications of 20 MJ/ Kg as required for use in power station. This means that Bench 7A is not suitable for power station feed in its raw form. Furthermore, the addition of any Bench 7A material to the Bench 7B RoM coal would result in a decrease in the in the CV values that would be expected from Bench 7B.

The raw Bench 7A material has a mean sulphur of 0.35 %, a median of 0.30 % and a mode of 0.21 %. The mean is approximately equal to the median and they are both greater than the mode. This is typical of a log-normal type distribution. The Bench 7A raw sulphur data has a range of 1.05% with a variance of 0.03 and standard deviation of 0.18%. This indicates that there is little variability in the data. The underlying population distribution is positively skewed and has a platykurtic shape. The histogram that indicates the shape of the underlying distribution is shown in Figure 4.3.

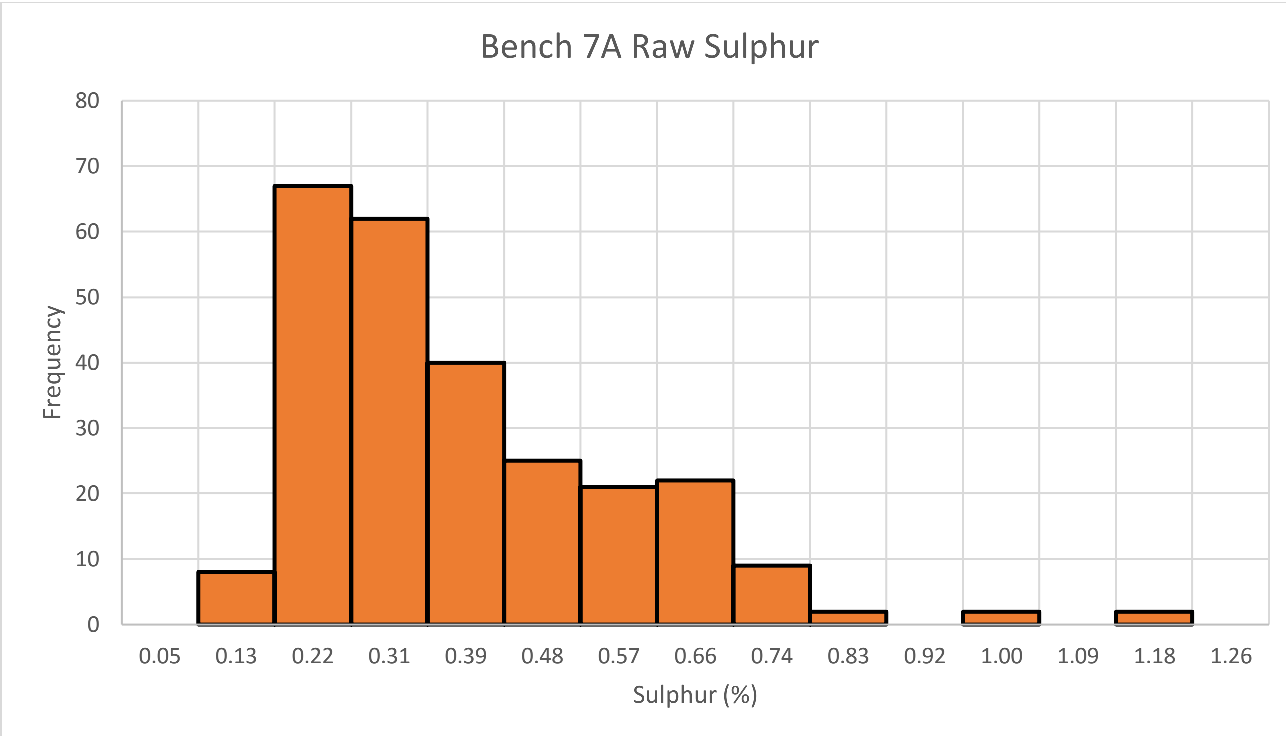

Figure 4.3: Bench 7A raw sulphur histogram

EDA of the raw sulphur data obtained from Bench 7A indicate that the sulphur data belongs to one data population. It is therefore appropriate to make inferences about the population based on the sample data. The average raw sulphur content of Bench 7A is 0.35%, which is below the Eskom rejection limit of 2.0% for the power stations. These results indicate that the raw Bench 7A material would not contribute negatively to sulphur sensitivity of the power station. In addition, the inclusion of any Bench 7A material to the Bench 7B coal would not impact the sulphur qualities negatively.

Bench 7A has a mean thickness of 5.38m with a median and mode of 5.31m and 5.27m respectively. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. Although the range of the thickness data is 1.59m, a variance of 0.11 and a standard deviation of 0.33m indicates little variability. The Bench 7A thickness data has an underlying population distribution that is positively skewed and has a platykurtic shape.

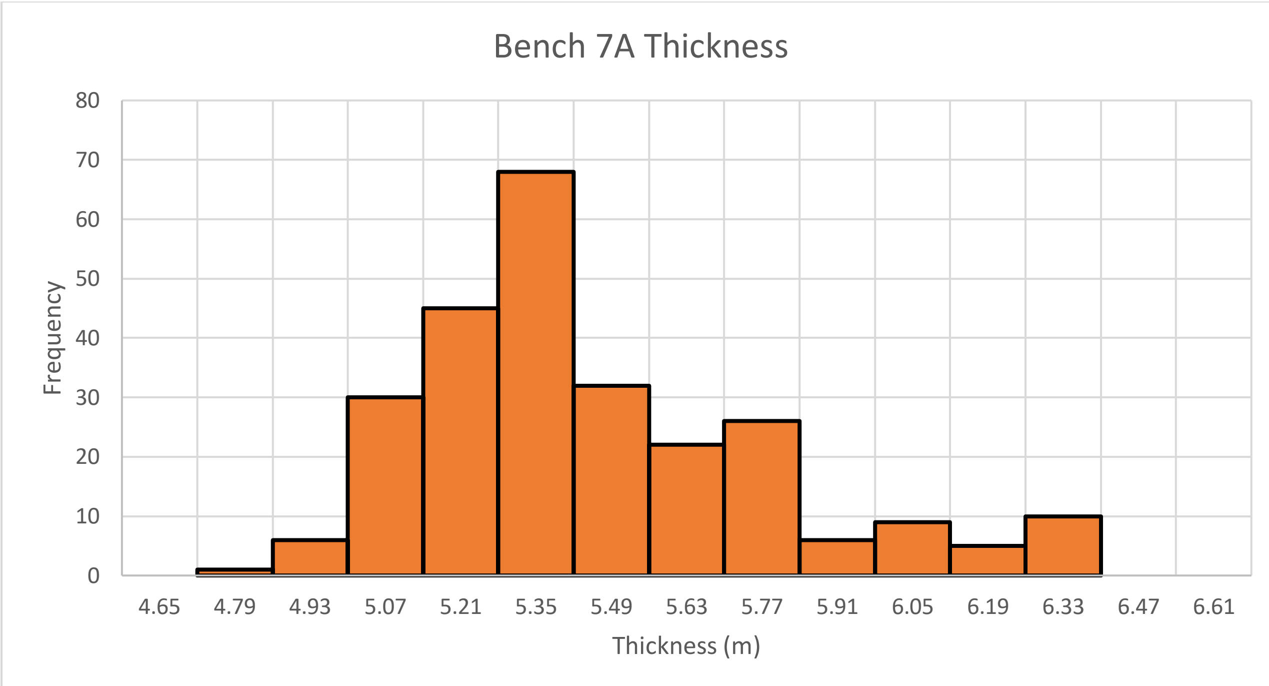

Figure 4.4: Bench 7A thickness histogram

The results of the EDA conducted on the thickness of Bench 7A indicate that the thicknesses of Bench 7A obtained from the sample data all belong to one population. It is therefore acceptable to make inferences about the population based on the sample data.

Bench 7A has a mean RD of 2.19 g/cm^3 with a median and mode of 2.19 g/cm^3 and 2.18 g/cm^3 respectively. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The data has a range of 0.16g/cm^3, a variance of 0.006 and a standard deviation of 0.02g/cm^2. This shows variability that is almost negligible. The shape of the underlying population distribution can be described as leptokurtic and is positively skewed. The histogram that illustrates the shape of the sample population distribution is shown in Figure 4.5.

The results of the EDA conducted on the Bench 7A RDs indicate that the sample data belongs to one population. It is therefore acceptable to make inferences about the population based on the sample data. The average RD of Bench 7A is 2.19 g/cm^3, which is typical of waste rock that should not be added to coal for beneficiation.

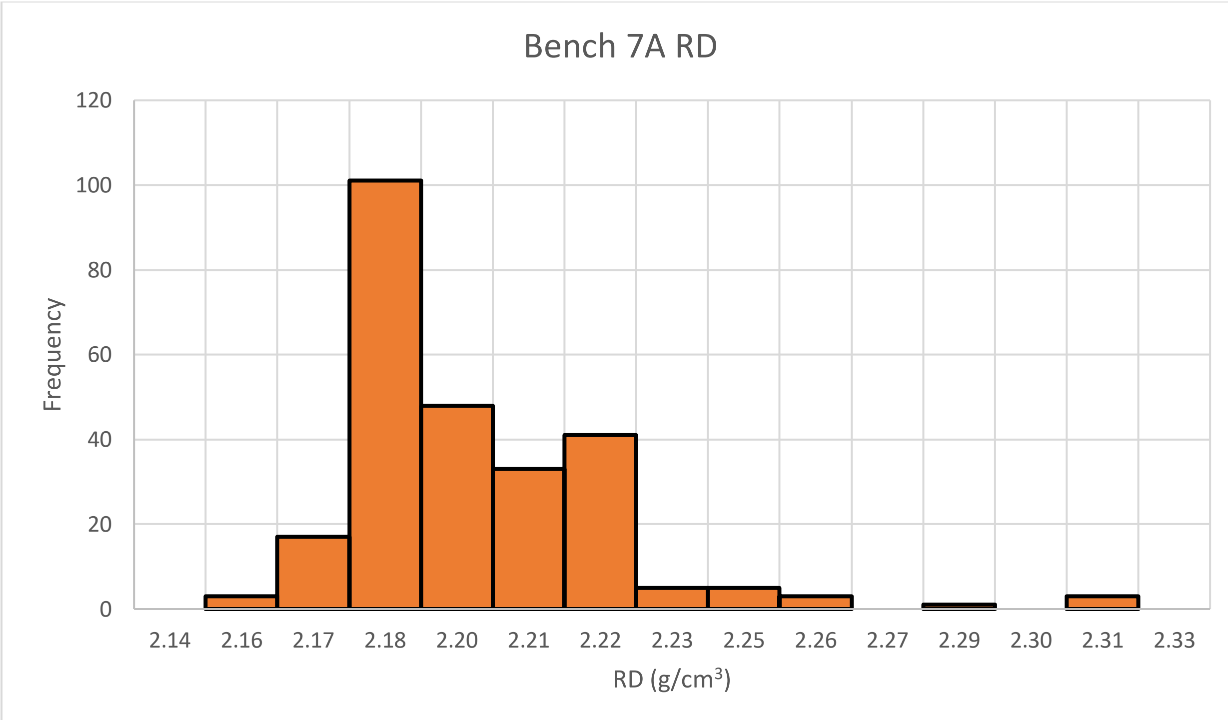

Figure 4.5: Bench 7A raw RD histogram

Table 4.1 is a summary of the descriptive statistics for Bench 7A sample data as described above. A cumulative wash table that is representative of the beneficiation of Bench 7A is included in Table 4.2. In addition to the variables discussed as part of the EDA, the fixed carbon (FC), moisture (MO) and volatile (VOL) content are also included in the cumulative wash table. The cumulative wash table indicates that Bench 7A has little carbonaceous material in it. This is evidenced by the low yields that are realised below a density of less than or equal to 1.8 g/cm^3 where carbonaceous material is typically washed. Bench 7B is typically washed at densities between 1.8 g/cm^3 and 2.0 g/cm^3. Table 4.2 indicates that yields of 7.28% and 14.64% respectively are obtained when washing the Bench 7A materials at these densities. It is noteworthy that the qualities obtained when Bench 7A is washed at a density of 1.8 g/cm^3 meet the specifications of Eskom.

Table 4.1: Summary of the descriptive statistics for Bench 7A

Variable	Mean	Median	Mode	Range	Variance	Standard Deviation	Kurtosis	Skewness
Ash	70.59	70.69	71.1	8.4	1.71	1.31	2.33	0.76
CV	8.99	9.00	8.66	2.82	0.19	0.44	2.42	-0.83
Sulphur	0.35	0.30	0.21	1.05	0.03	0.18	2.46	1.37
Thickness	5.38	5.31	5.27	1.59	0.11	0.33	0.41	0.91
RD	2.19	2.19	2.18	0.16	0.006	0.02	5.80	1.75

Table 4.2: Cumulative wash table for Bench 7A

Bench 7A	RD (g/cm^3)	ASH (%)	CV (MJ/Kg)	FC (%)	MO (%)	SU (%)	VOL (%)	YLD (%)
Float	1.50	12.92	28.86	53.95	2.15	0.59	30.98	1.10
Float	1.55	15.18	28.05	52.56	2.12	0.56	30.15	1.40
Float	1.60	17.36	27.27	51.21	2.09	0.54	29.34	1.70
Float	1.70	24.87	24.60	47.22	2.02	0.47	25.90	3.15
Float	1.80	34.11	21.39	41.79	1.88	0.39	22.22	7.28
Float	1.90	40.92	19.03	37.23	1.79	0.34	20.06	14.64
Float	2.00	45.42	17.43	33.98	1.79	0.32	18.81	22.11
Float	2.10	48.99	16.16	31.29	1.81	0.30	17.91	28.73
Float	2.20	54.93	14.08	26.59	1.84	0.27	16.65	40.20
Raw	2.19	70.60	8.99	14.04	1.47	0.35	13.90	100.00

4.1.2. Bench 7B

The raw ash analysis has a mean of 43.32 %, a median of 43.1 % and Mode of 41.14 %. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The data has a range of 10.79 % with a variance of 3.66 and standard deviation of 1.91%. This indicates a greater spread in the data than the raw ash from Bench 7A. The variability is still low however. The underlying distribution of the population is slightly positively skewed and has a platykurtic shape. The histogram that illustrates the sample population distribution of the Bench 7B ash variable is included in Figure 4.6.

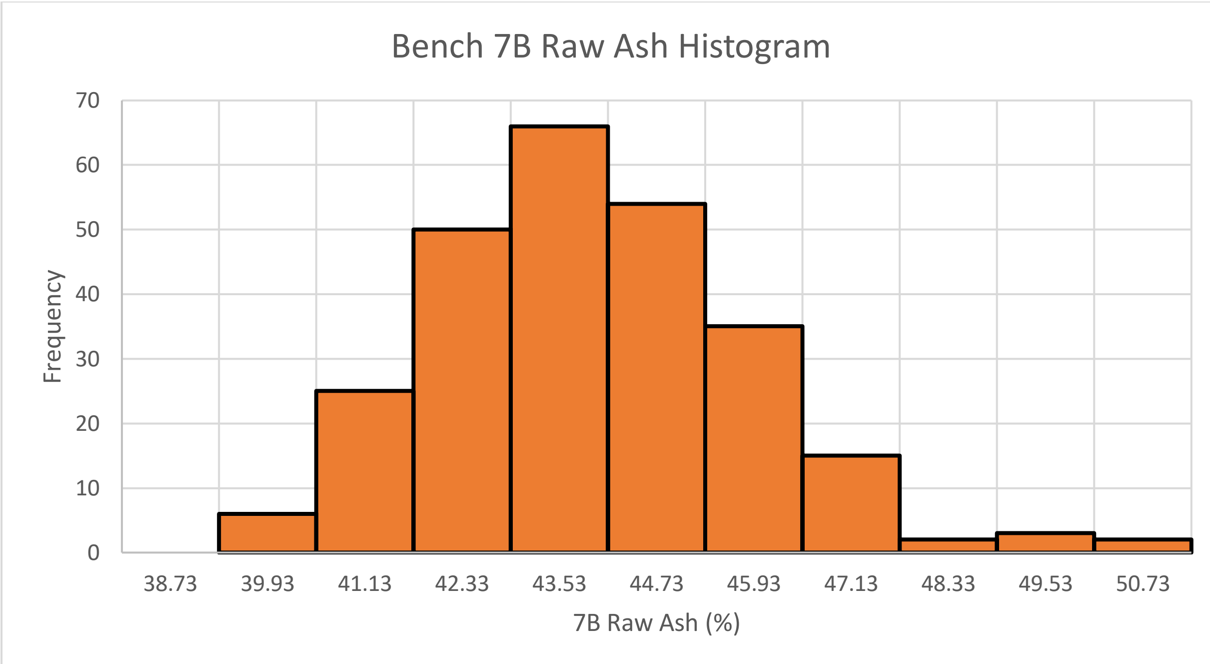

Figure 4.6: Bench 7B raw ash histogram

The results of the EDA indicate that the raw ash sample data for Bench 7B belongs to a single data population. It is therefore possible to use this data to make inferences about the sample population. The average raw ash content of Bench 7B is 43.32% which is approximately 8% higher than the rejection limit for Eskom power stations of 35%. This means this bench is unsuitable for power station coal usage in its raw form. In addition, the inclusion of Bench 7A material to the Bench 7B coal with increase the ash content even more.

The raw CV analysis has mean of 18.28 MJ/Kg, a median of 18.33 MJ/Kg and a mode of 17.85 MJ/Kg. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The raw CV variable has a range of 3.93 MJ/Kg with a variance of 0.41 and standard deviation of 0.64 MJ/Kg. This indicates that there is little spread in the data. The underlying distribution is slightly negatively skewed and can be described as having a platykurtic shape. The histogram that illustrates the sample population distribution of the Bench 7B CV variable is included in Figure 4.7.

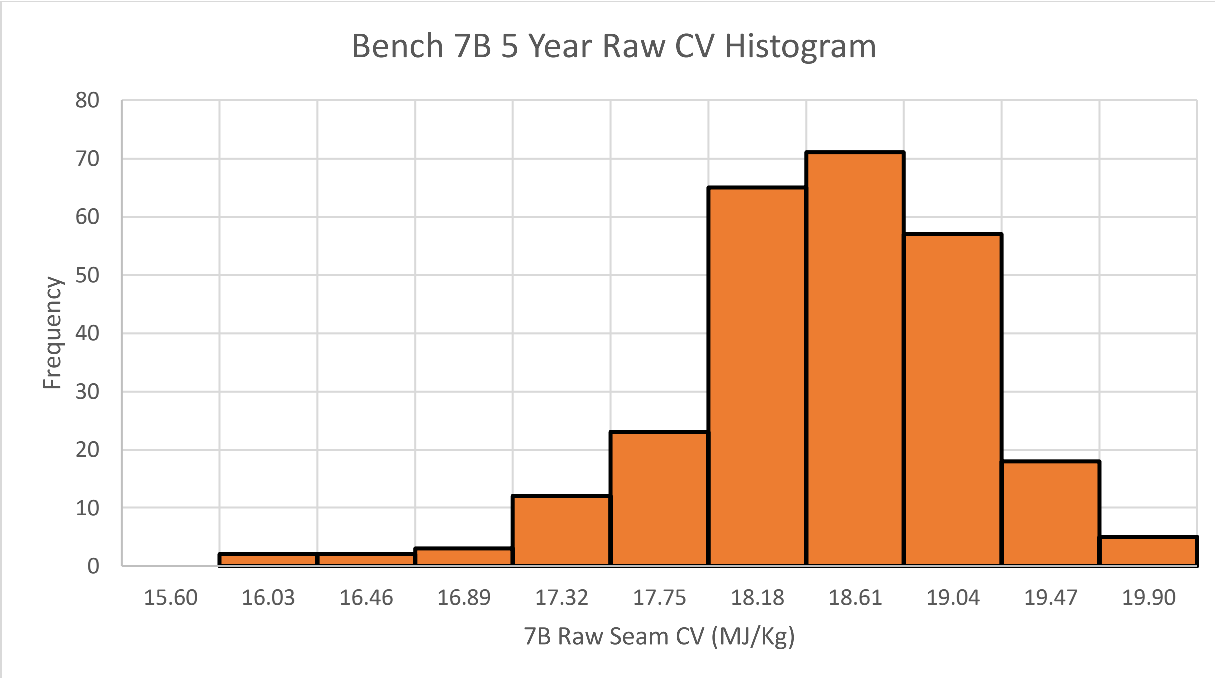

Figure 4.7: Bench 7B raw CV histogram

The EDA results for the raw CV data obtained for Bench 7B indicates that the data belongs to one population. It is therefore acceptable to make inferences on the population based on the sample data. The average raw CV value for Bench 7B is 18.28 MJ/ Kg. This is 1.72 MJ/kg below the Eskom specifications of 20 MJ/ Kg as required for use in the power stations. The results indicate that Bench 7B is not suitable for power station feed in its raw form. Furthermore, the addition of any Bench 7A material to the Bench 7B RoM coal would result in a further decrease in the in the CV values that would be expected from Bench 7B.

The raw coal obtained from Bench 7B has a mean sulphur of 3.26 %, a median of 3.24% and a mode of 2.71%. The mean is approximately equal to the median are both greater than the mode. This is typical of a log-normal type distribution. Although the Bench 7B raw sulphur data has a range of 3.54%, a variance of 0.56 and standard deviation of 0.75% indicate that there is little variability in the data. The underlying distribution is roughly symmetrical and has a platykurtic shape. The histogram that illustrates the sample population distribution of the Bench 7B sulphur variable is included in Figure 4.8.

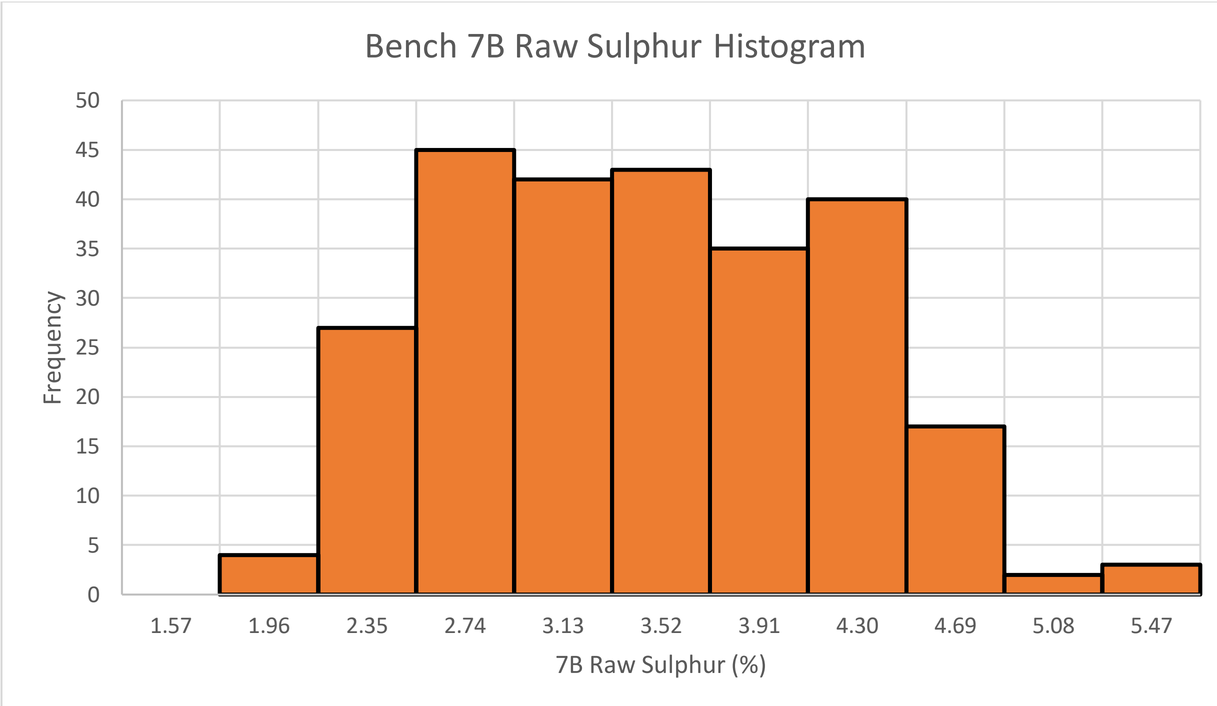

Figure 4.8: Bench 7B raw sulphur histogram

EDA of the raw sulphur data obtained from Bench 7B indicate that the sulphur data belongs to one data population. It is therefore appropriate to make inferences about the population based on the sample data. The average raw sulphur content of Bench 7B is 3.26%, which is above the Eskom rejection limit of 2.0% for the power stations. These results indicate that the coal obtained from Bench 7B is not suitable for power station feed in its raw form.

Bench 7B has a mean thickness of 1.39m with a median and mode of 1.38m and 1.38m respectively. The mean is approximately equal to the median which is approximately equal to the mode, this is typical of a normal type distribution. The data has a large range of 1.17m. However, a variance of 0.023 and standard deviation of 0.15m indicate low variability. The Bench 7B thickness data is has an underlying distribution that is positively skewed and has a leptokurtic shape. The histogram that illustrates the sample population distribution of the Bench 7B thickness variable is included in Figure 4.9.

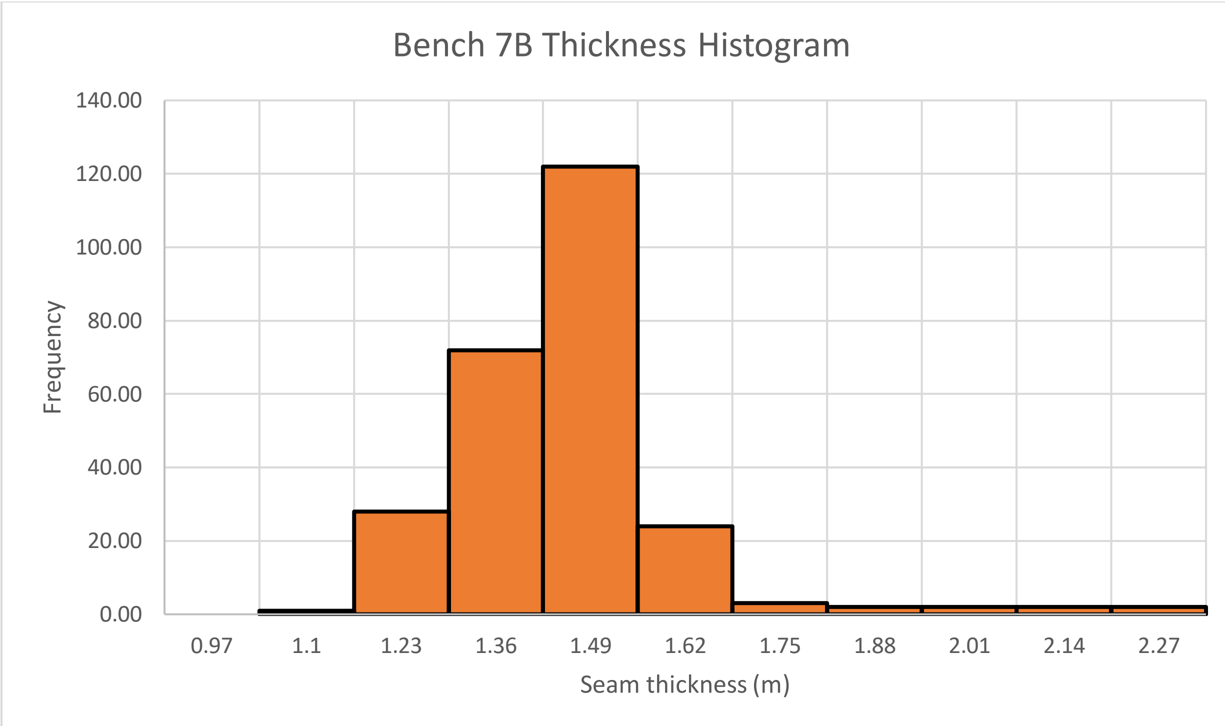

Figure 4.9: Bench 7B thickness histogram

The results of the EDA conducted on the thickness of Bench 7B indicate that the result obtained from the sample data all belong to one population. It is therefore acceptable to make inferences about the population based on the sample data. The EDA also confirms that Bench 7B is a relatively thin bench when compared to the other benches mined at GCM. Exploiting such a thin bench with the equipment currently used at the mine is not ideal and is likely to result in the dilution of Bench 7B when using the current mining method.

Bench 7B has a mean RD of 1.83 g/cm^3 with a median and mode of 1.84 g/cm^3 and 1.84 g/cm^3 respectively. The mean is approximately equal to the median which is approximately equal to the mode, this is typical of a normal type distribution. The variability in the Bench 7B RD data is low, this is indicated by a range of 0.17g/cm^3, and a variance of 0.0009 and a standard deviation of 0.03g/cm^3. The shape of the underlying distribution can be described as platykurtic and is roughly symmetrical. The histogram that illustrates the sample population distribution of the Bench 7B thickness variable is included in Figure 4.10.

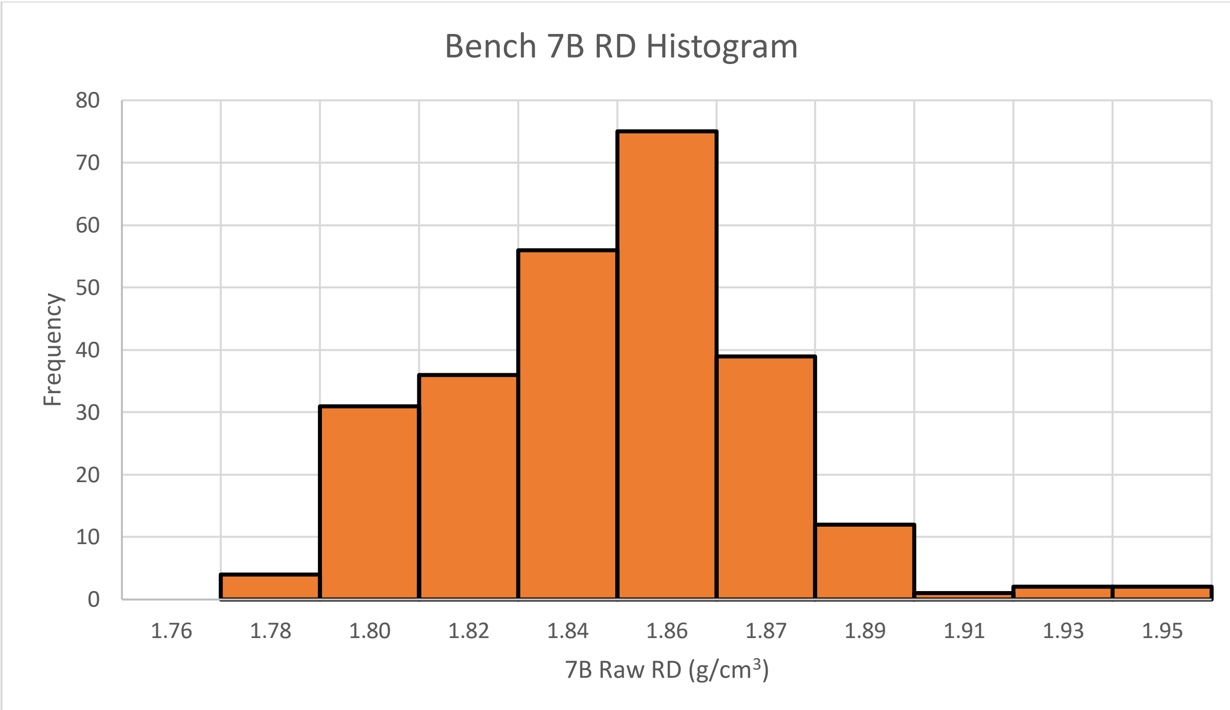

Figure 4.10: Bench 7B RD histogram

The results of the EDA conducted on the Bench 7B RDs indicate that the sample data belongs to one population. It is therefore acceptable to make inferences about the population based on the sample data. The average RD of Bench 7B is 1.84 g/cm^3, which is typical of lower quality coal which has a higher density.

The descriptive statistics that pertain to Bench 7B as presented above are summarised in Table 4.3. A cumulative wash table that is representative of the beneficiation of Bench 7B is presented in

Table 4.4. The cumulative wash table indicates that at wash densities of 1.8 g/cm^3, 1.9 g/cm^3 and 2.0 g/cm^3, the yield of Bench 7B is 51.95%, 61.96% and 68.62% respectively. These yields are also illustrated when inspecting the cumulative washability curve for Bench 7B shown in Figure 4.11. The resultant ash, CV and sulphur qualities obtained at wash RD's of 1.8 g/cm^3 and 1.9 g/cm^3 are all acceptable for use in the Eskom power stations. At a wash RD of 2.0 g/cm^3 the resultant ash is 33.09%. This is above the Eskom limit and is likely to result in penalisation, but not rejection.

Table 4.3: Summary of the descriptive statistics for Bench 7B

Variable	Mean	Median	Mode	Range	Variance	Standard Deviation	Kurtosis	Skewness
Ash	43.32	43.1	41.14	10.79	3.66	1.91	0.68	0.55
CV	18.28	18.33	17.85	3.93	0.41	0.64	1.27	-0.64
Sulphur	3.26	3.24	2.71	3.54	0.56	0.75	-0.76	0.22
Thickness	1.39	1.38	1.38	1.17	0.023	0.15	8.99	2.15
RD	1.83	1.84	1.84	0.17	0.0009	0.03	0.41	0.27

Table 4.4: Cumulative wash table for Bench 7B

Bench 7B	RD (g/cm^3)	ASH (%)	CV (MJ/ Kg)	FC (%)	MO (%)	SU (%)	VOL (%)	YLD (%)
Float	1.50	13.94	28.67	58.63	2.11	0.67	25.33	10.43
Float	1.55	16.51	27.74	57.05	2.08	0.62	24.37	16.13
Float	1.60	18.97	26.86	55.53	2.04	0.56	23.45	21.65
Float	1.70	24.28	24.97	51.82	1.96	0.57	21.94	36.78
Float	1.80	28.44	23.51	48.56	1.88	0.58	21.12	51.95
Float	1.90	31.11	22.57	46.34	1.83	0.64	20.71	61.96
Float	2.00	33.09	21.87	44.65	1.80	0.69	20.46	68.62
Float	2.10	34.80	21.27	43.18	1.77	0.74	20.25	73.64
Float	2.20	36.86	20.54	41.43	1.74	0.79	19.96	79.15
Raw	1.83	43.35	18.27	35.55	1.66	3.26	19.45	100.00

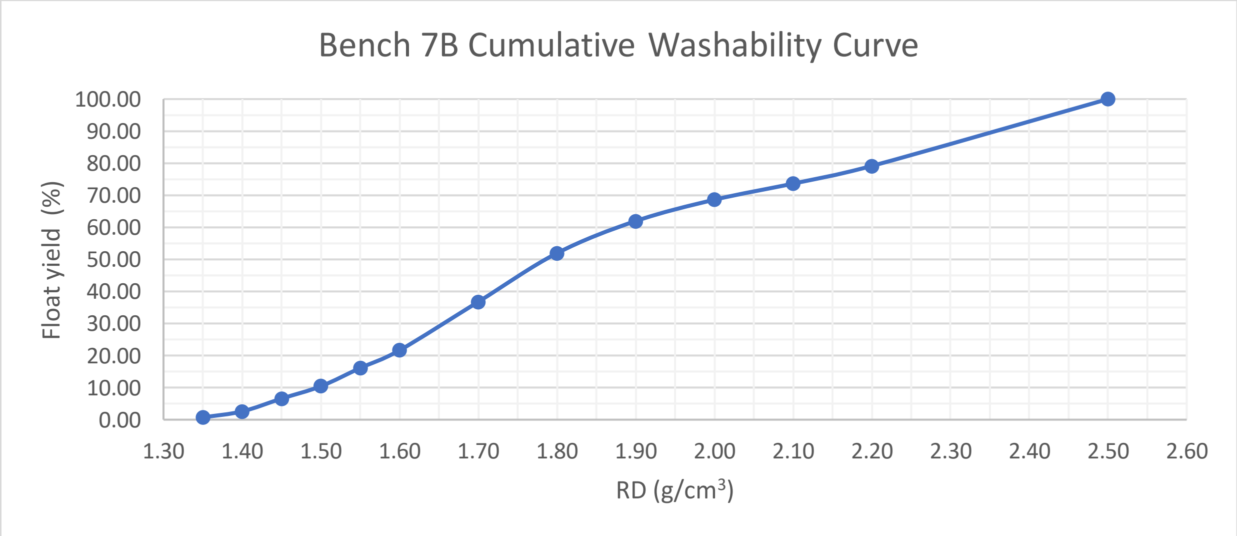

Figure 4.11: Cumulative washability curve for Bench 7B

4.1.3. Bench 8

The raw ash analysis for Bench 8 has a mean of 83.35 %, a median of 83.49 % and Mode of 82.83 %. The mean is approximately equal to the median and they are both greater than the mode. This is typical of a log-normal type distribution. The data has a range of 5.64 % with a variance of 0.97 and standard deviation of 0.99%. This indicates little variability in the data. The underlying distribution of the population is negatively skewed and has a platykurtic shape. The histogram that illustrates the sample population distribution of Bench 8 raw ash is included in Figure 4.12.

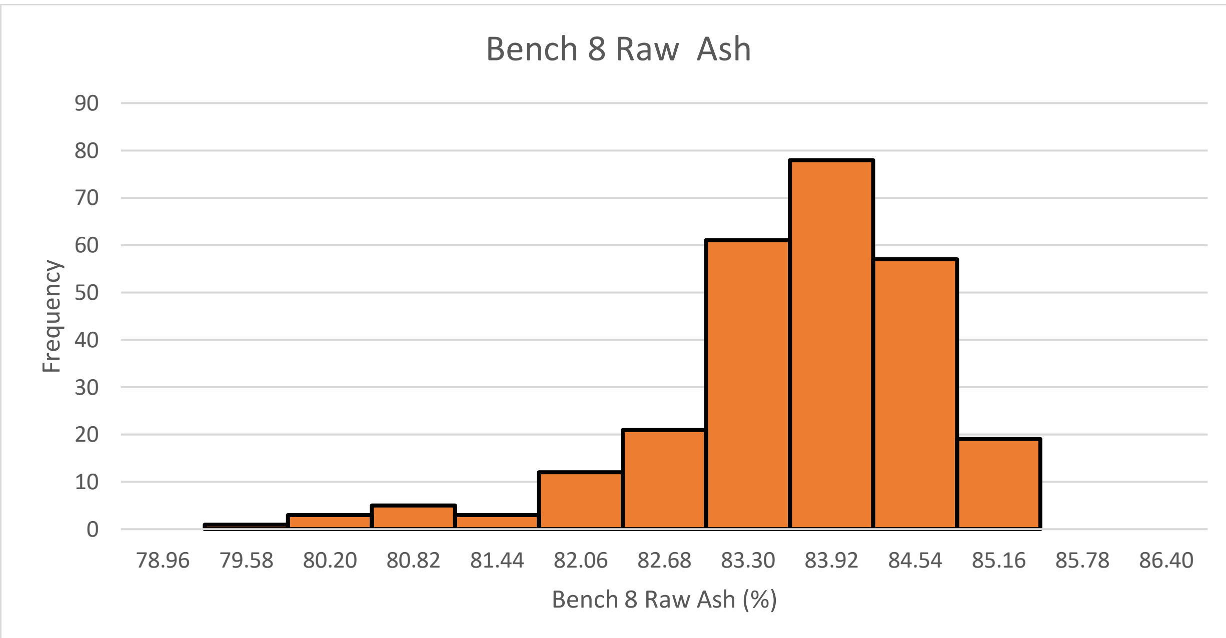

Figure 4.12: Bench 8 raw ash histogram

The results of the EDA conducted on the Bench 8 raw ash analysis indicate that the results obtained from the sample data all belong to one population. It is therefore acceptable to make inferences about the population based on the sample data. The average raw ash value for Bench 8 is 83.35% which is higher than the Eskom power station rejection limit of 35%. These results indicate that Bench 8 is not suitable for power station feed in its raw form. The raw ash content of Bench 8 is also higher than the same variable for Bench 7A. This means that the inclusion of Bench 8 material would have a more negative impact on Bench 7B ash qualities than the addition Bench 7A material during mining.

The raw CV analysis has mean of 5.04 MJ/Kg, a median of 5.03 MJ/Kg and a mode of 5.09 MJ/Kg. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. The raw CV variable has a range of 1.81 MJ/Kg with a variance of 0.09 and standard deviation of 0.30 MJ/Kg. This shows very little spread in the data. The underlying distribution is negatively skewed and can be described as having a platykurtic shape. The histogram that illustrates the Bench 8 raw CV sample distribution is included in Figure 4.13.

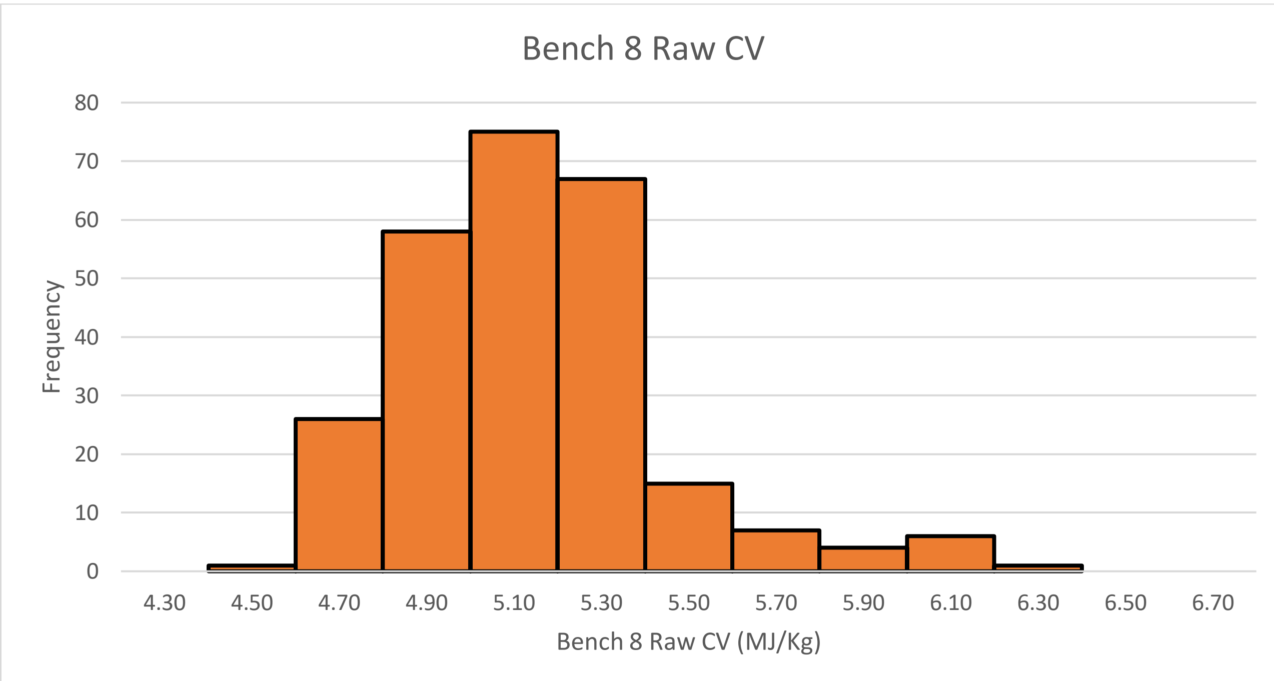

Figure 4.13: Bench 8 raw CV histogram

The EDA results for the raw CV data obtained for Bench 8 indicates that the sample data belongs to one population. It is therefore acceptable to make inferences about the population based on the sample data. The average raw CV value for Bench 8 is 5.04 MJ/ Kg. This is below the Eskom specifications of 20 MJ/ Kg as required for use in the power stations. The results indicate that the raw Bench 8 material is not suitable for use in the power station feed. Furthermore, the addition of any Bench 8 material to the Bench 7B RoM coal would result in a decrease in the CV values that would be expected from Bench 7B. The raw CV values obtained from Bench 8 are lower than those obtained from Bench 7A. This indicates that the addition of Bench 8 material to Bench 7B would be more detrimental to the expected CV values than the addition of Bench 7A material.

The raw coal has a mean sulphur of 0.16 %, a median of 0.13% and a mode of 0.04 %. The mean is approximately equal to the median and they are both greater than the mode. This is typical of a log-normal type distribution. The Bench 8 raw sulphur data has a range of 1.15 % with a variance of 0.03 and standard deviation of 0.16 %. Although the data has a high range of 1.15%, the variance of 0.03 and standard deviation on 0.16% indicate that there is little variability in the data. The underlying distribution is positively skewed and has a leptokurtic shape. The histogram that illustrate the sample population distribution is included in Figure 4.14.

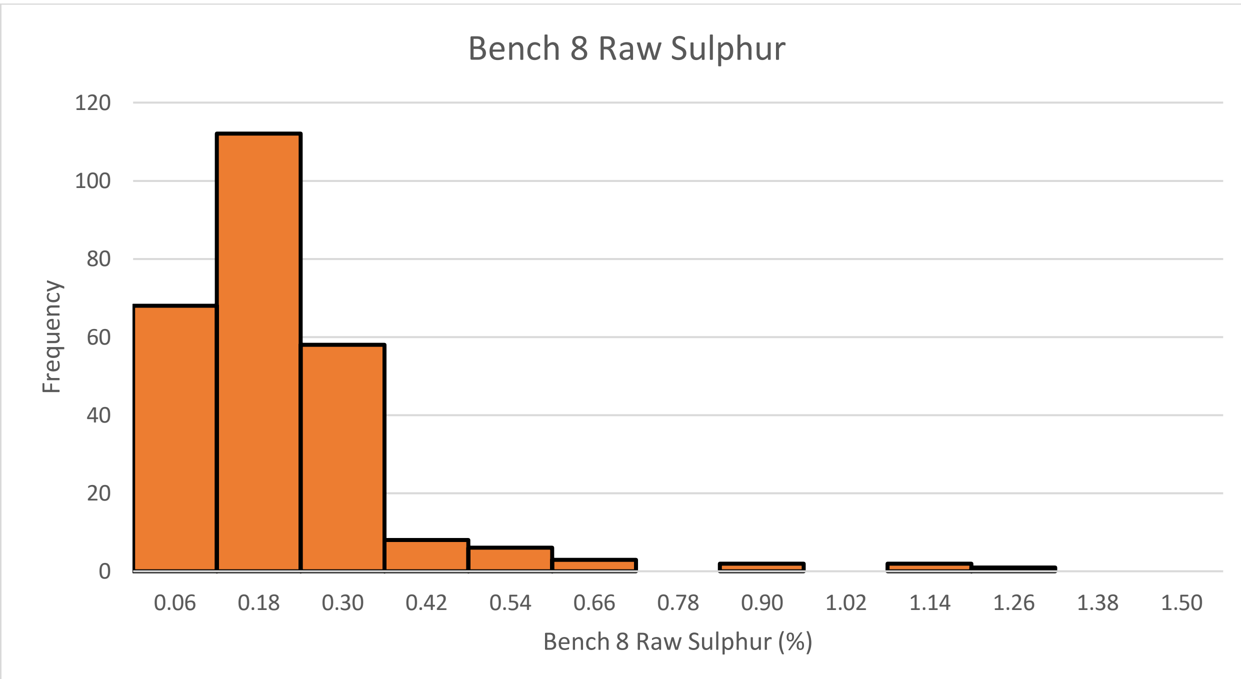

Figure 4.14: Bench 8 raw sulphur histogram

EDA of the raw sulphur data obtained from Bench 8 indicate that the sulphur data belongs to one data population. It is therefore appropriate to make inferences about the population based on the sample data. The average raw sulphur content of Bench 7B is 0.16%, which is below the Eskom rejection limit of 2.0% for the power stations. These results indicate that the material obtained from Bench 8 would not negatively affect the sulphur sensitivity of the power station in its raw form. The results also indicated that, like Bench 7A, the addition of any Bench 8 material to Bench 7B would not negatively affect its sulphur content.

Bench 8 has a mean thickness of 3.46m with a median and mode of 3.48m and 3.89m respectively. The mean is approximately equal to the median which is approximately equal to the mode. This is typical of a normal type distribution. There is very little variability in the thickness data. This is indicated by a range of 1.11 m, a variance of 0.11 and a standard deviation of 0.33 m. The Bench 8 thickness data has an underlying distribution that is roughly symmetrical and has a platykurtic shape. The histogram that illustrates distribution of the sample population is included in Figure 4.15.

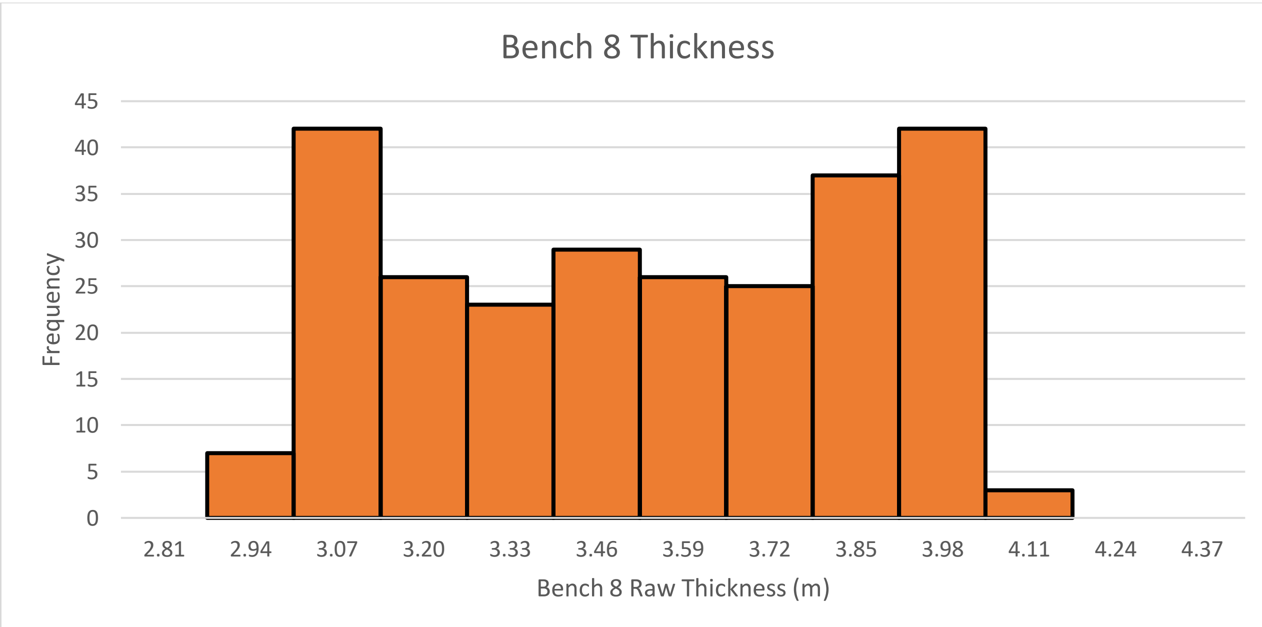

Figure 4.15: Bench 8 thickness histogram

The results of the EDA conducted on the thickness of Bench 8 indicate that the result obtained from the sample data all belong to one population. It is therefore acceptable to make inferences about the population based on the sample data.

Bench 8 has a mean RD of 2.49 g/cm^3 with a median and mode which both have a value of 2.5 g/cm^3. The mean is approximately equal to the median which is equal to the mode. This is typical of a normal type distribution. The variance in the Bench 8 RD data is nearly negligible. This is indicated by a range of 0.17 g/cm^3, a variance of 0.001 and a standard deviation of 0.033 g/cm^3. The shape of the underlying distribution can be described as platykurtic and is negatively skewed.

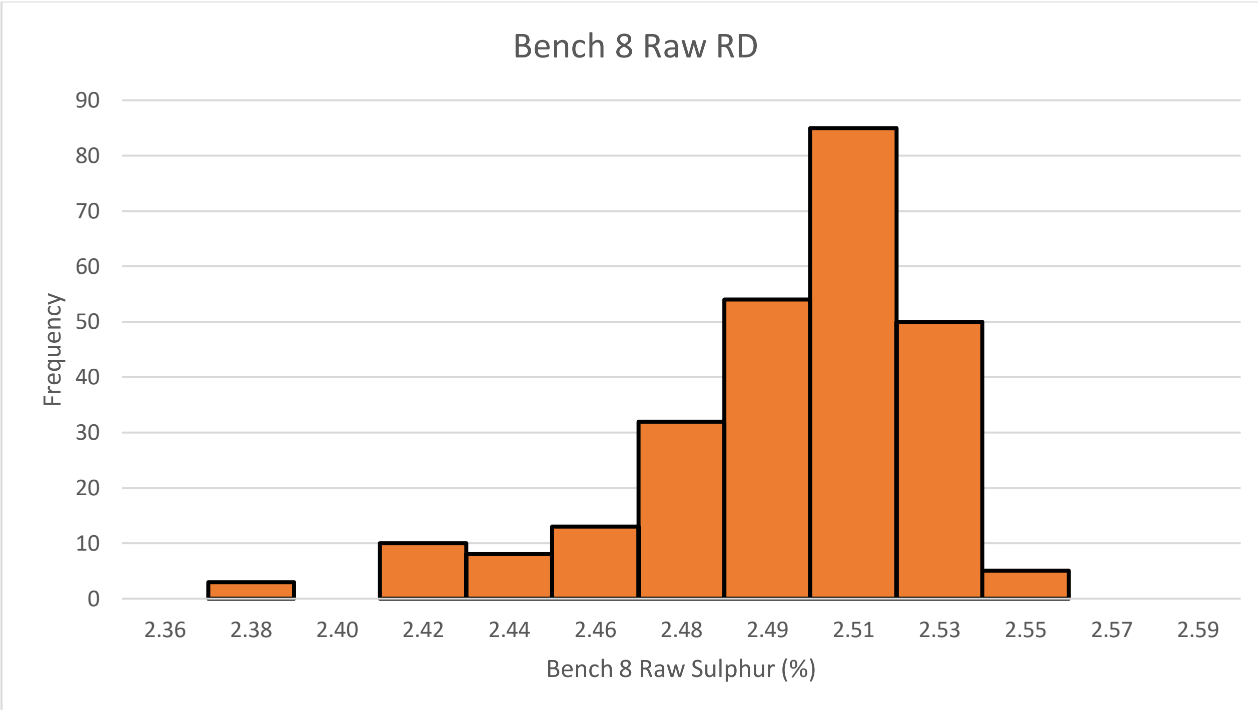

Figure 4.16: Bench 8 RD histogram

The results of the EDA conducted on the Bench 8 RD data indicate that the sample data belongs to one population. It is therefore acceptable to make inferences about the population based on the sample data. The average RD of Bench 7B is 2.49 g/cm^3, this high RD value is typical of waste rock.

The Bench 8 descriptive statistics described above are summarised in Table 4.5. A cumulative wash table that represents the beneficiation of Bench 8 is also included in Table 4.6.

Table 4.5: Summary of the descriptive statistics for Bench 8

Variable	Mean	Median	Mode	Range	Variance	Standard Deviation	Kurtosis	Skewness
Ash	83.35	83.49	82.83	5.64	0.97	0.99	2.40	-1.24
CV	5.04	5.03	5.09	1.81	0.09	0.30	2.01	1.07
Sulphur	0.16	0.13	0.04	1.15	0.03	0.16	14.95	3.30
Thickness	3.46	3.48	3.89	1.11	0.11	0.33	-1.38	-0.070
RD	2.49	2.50	2.50	0.17	0.001	0.033	1.28	-1.13

Table 4.6: Cumulative wash table for Bench 8

Bench 8	RD (g/cm^3)	ASH (%)	CV (MJ/Kg)	FC (%)	MO (%)	SU (%)	VO (%)	YLD (%)
Float	1.50	15.07	27.97	56.50	2.34	0.55	26.08	0.06
Float	1.55	17.37	27.23	56.01	2.27	0.52	24.36	0.10
Float	1.60	20.16	26.21	54.57	2.26	0.49	23.02	0.13
Float	1.70	26.17	24.06	50.41	2.20	0.50	21.22	0.27
Float	1.80	33.68	21.40	44.66	2.12	0.54	19.54	0.61
Float	1.90	39.98	19.14	39.71	2.12	0.54	18.19	1.15
Float	2.00	45.36	17.31	35.39	2.01	0.42	17.22	1.92
Float	2.10	51.13	15.31	30.71	1.99	0.42	16.17	3.00
Float	2.20	57.28	13.21	25.41	1.96	0.34	15.36	4.77
Raw	2.49	83.34	5.04	2.63	0.91	0.17	13.12	100.00

When Bench 8 is washed at a RD of 1.8 g/cm^3, all the expected quality values obtained, except for ash, are acceptable for use in the power station. The ash value is 33.68% which is below the rejection limit of 35%, but is likely to result in penalties as it is above the acceptable limit of 33% as shown in Table 2.1. The expected yield is however negligible at 0.61%. In addition, the expected yield value from Bench 8 at this beneficiation RD is lower than the yield of Bench 7A when beneficiated at the same RD.

4.3 Yield cut-off determination

Using the yield cut-off formula, defined in Equation 2.5, it is possible to calculate a minimum yield cut-off for Bench 7B. This is defined as the minimum yield above which the mining of Bench 7B is profitable. The costs used for the calculation of the minimum yield cut-off were obtained from the GCM finance department. These costs were based on the 2017 budget figures and are summarised in Table 4.7. It must be noted that the costs presented here have be factorised as the information is confidential. The answers obtained are however proportional and reflective of the GCM scenario.

The cost of mining and stripping are shown to be equal in Table 4.7. Due to fact that GCM mines multiple benches that are both coal and waste concurrently, there is no segregation of costs between those associated with coal mining and those associated with waste removal. Instead, a cost of material removal per tonne is provided. This is based on the total cost of material removal from the pit, and the total amount of material moved.

Table 4.7 further indicates that the cost of rehabilitation, like the cost of conveying product to the power station, is low. This is because both are associated with the cost of transporting material via a conveyor belt as opposed to the more expensive cost associated with trucking material to the required destination.

Table 4.7: Input costs for exploitation of Bench 7B

Equation prefix	Item	Price
A	Cost of stripping	R 17.40/ tonne
B	Cost of mining	R 17.40/ tonne
C	Cost of processing	R 15.80/ tonne
V	Cost of rehabilitation	R 0.85/ tonne
D	Administration and management	R 0.00
r	Sale price	R 450.00/ tonne
O	Cost of sales overheads	R 0.00
R	Royalties per sales unit	R 31.50 (7% of Sale price)
T	Cost of conveying product to the power stations	R 1.94/ tonne

The costs of general overheads, administration and cost of sales were set as zero (0). This is because these costs can be considered as sunk as they must be incurred to access the higher value Bench 9 and Bench 11 coal. Furthermore, as established by the work of Rendu (2014) and Falkie and Porter (1972), the variable costs are a more important consideration in the context of GCM. The fees charges for royalties are variable and calculated using a formula. The fees charges for royalties are variable and calculated using a formula provided by National Treasury. The formula considers Earnings Before Interest and Tax (EBIT), gross sales as well as a constant of 9 for unrefined minerals which includes coal (National Treasury Department, 2008). The National Treasury Department further states that a maximum royalty rate of seven percent (7%) is used for unrefined mineral. For this reason, the royalty rate used in the calculation of the minimum cut-off yield is 7% of the sale price.

The average stripping ratio for the 5-year mining window considered for this project was calculated to be 4.67:1. Substituting the stripping ratio and the costs obtained from the GCM finance department into equation 2.15, the resultant calculation is shown below in equation 4.1. The yield cut-off determined in equation 4.1 and the quality specifications shown in Table 2.1, are the base against which all calculated yield cut-offs and resultant diluted qualities are compared.

$$F = \frac{(4.67 \times R\ 17.40) + R\ 17.40 + R\ 15.80 + R\ 0.85 + R\ 0}{(R\ 450 - R\ 0 - R\ 31.50 - R\ 1.94)} = 27.68\ \% \qquad \text{Equation 4.1}$$

The result of equation 4.1 determines that the yield cut-off of the bench is 27.68%. When Bench 7B is mined without any dilution and beneficiated at wash RDs of 1.8 g/cm^3, 1.9g/cm^3 and 2.0 g/cm^3 the yields obtained are 51.95%, 61.96% and 68.62% respectively. This is shown in the cumulative table included as Table 4.4. These values are all above the yield cut-off which is the minimum measure for profitability. This means that Bench 7B is profitable to mine in its undiluted state. This is provided that the resultant products do meet product specifications.

As suggested by Da Gama (2013), using the yield cut-off function, it is possible to determine the minimum yield at which it is no longer profitable to mine Bench 7B. When evaluating the beneficiated product, both diluted and undiluted, the yield cut-offs obtained will be the minimum against which the product yield will be compared. When considering an appropriate solution, it is important that the yield achieved is above this minimum yield cut-off to ensure profitability.

4.4 Dilution scenarios and yield cut-off

When Bench 7B is diluted with incremental amounts of Bench 7A a new yield and new product qualities must be calculated for the diluted bench. As discussed in the literature review section of this project report, an increase in dilution will have a concurrent decrease in the yield obtained. In addition, this dilution will have an impact on the resultant qualities of the diluted bench. This impact on the qualities can result in the penalisation or rejection of the coal product. In cases where the penalisation limit is reached, the expected revenue will be less thus increasing the minimum yield cut-off required for profitable mining.

When Bench 7B is diluted with Bench 7A, there we will be less Bench 7A to remove as waste. Furthermore, there will be an increase in the amount of material to be mined as coal. The decreased amount of material classified as waste and the increase in the amount of material classified as coal, influences the yield cut-off calculation. Thus, a new yield cut-off must also be determined for every dilution scenario. The amount of product (PRD) that can be expected from 1000 tonnes of RoM feed based on the various dilution scenarios will also be determined. This is calculated based on both the yield that will be expected and the yield cut-off at the specified dilution scenario.

For each RD at which the diluted coal will be beneficiated, the recalculated yield and yield cut-off are plotted against the amount of dilution included. When illustrated graphically, it may be possible to observe trends. Furthermore, it may be possible for a trend line to be fitted onto the plotted data points and to obtain a R^2 value for the trendline. The R^2 value is called the coefficient of determination. It is obtained by multiplying the coefficient of correlation (R) by itself and is a measure of how well a fitted trendline describes the relationship (Clark & Harper, 2000). The closer an R^2 value is to one (1) the better the correlation. In addition, an equation that describes this trendline can also be obtained. The equation obtained can be used for estimation purposes. By substituting in a known dilution thickness into the equation that gives the trend line, the new yield or yield cut-off can be predicted. Alternatively, by substituting in a known yield or yield cut-off, an estimated dilution thickness can be obtained. The results obtained and the trends observed are discussed below.

4.4.1. Bench 7A and Bench 7B

For a wash RD of 1.8 g/cm^3; the resultant product yield, yield cut-off, product qualities and expected product tonnes (based on 1000 tonnes of RoM feed) are summarised in Table 4.8. When Bench 7B is diluted with Bench 7A and beneficiated at a wash density of 1.8 g/cm^3, there is no effect on the quality of the product for Eskom coal usage. All qualities obtained from the diluted bench scenarios are within the product specification ranges as summarised in Table 2.1.

The fitted trend line that describes the relationship between a change in yield as Bench 7B is diluted with incremental amounts of Bench 7A has a R^2 value of 0.99, and is defined by a fifth-order polynomial that is given by Equation 4.2. An R^2 value of 0.99 indicates that the trend line describes the relationship between yield and dilution thickness well. This relationship is illustrated graphically in Figure 4.17. The fitted trend that describes the relationship between a change in yield cut-off as bench 7B is diluted with incremental amounts of Bench 7A is linear and is given by Equation 4.3, and has a R^2 value of 0.96. This R^2 value of 0.96 indicates a good correlation between the data points. This relationship is also illustrated in Figure 4.17.

Table 4.8: Qualities resulting from the dilution Bench 7A with Bench 7B and washing at a RD 1.8 g/ cm^3 wash

1.8 WASH	ASH (%)	CV (MJ/Kg)	SU (%)	YLD (%)	DILUTION (m)	YCO (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	28.44	23.51	0.58	51.95	0	27.68	520	277
B7B +B7A 0.1	28.52	23.48	0.58	48.42	0.10	31.50	484	315
B7B +B7A 0.2	28.59	23.46	0.58	45.37	0.20	31.14	454	311
B7B +B7A 0.3	28.65	23.43	0.58	42.75	0.30	30.78	427	308
B7B +B7A 0.4	28.72	23.41	0.58	40.46	0.40	30.41	405	304
B7B +B7A 0.5	28.78	23.39	0.57	38.45	0.50	30.05	385	300
B7B +B7A 0.6	28.84	23.36	0.57	36.68	0.60	29.69	367	297
B7B +B7A 0.7	28.90	23.34	0.57	35.09	0.70	29.32	351	293
B7B +B7A 0.8	28.96	23.32	0.57	33.67	0.80	28.96	337	290
B7B +B7A 0.9	29.02	23.30	0.57	32.39	0.90	28.59	324	286
B7B +B7A 1	29.07	23.28	0.56	31.22	1.00	28.23	312	282
B7B +B7A 1.5	29.33	23.18	0.55	26.72	1.50	26.41	267	264
B7B +B7A 2	29.57	23.09	0.55	23.65	2.00	24.59	236	246
B7B +B7A 2.5	29.78	23.01	0.54	21.41	2.50	22.78	214	228
B7B +B7A 3.0	29.97	22.94	0.53	19.72	3.00	20.96	197	210
B7B +B7A 3.5	30.15	22.87	0.53	18.38	3.50	19.14	184	191
B7B +B7A 4	30.31	22.81	0.52	17.31	4.00	17.32	173	173
B7B +B7A 4.5	30.44	22.76	0.52	16.42	4.50	15.50	164	155

At a wash density of 1.8 g/cm^3, Bench 7B can be diluted with up to approximately 1.5m of Bench 7A material. The resultant mining bench thickness at this level of dilution is approximately 2.89 m.` The yield cut-off is reached when 1.6 m of Bench 7A material is added to Bench 7B. This is the point as which zero profit is made. It must be noted that although this level of dilution is theoretically possible, it is the maximum level. As established by of Da Gama (2013), it is important to understand the limits of both stripping ratio and yield cut-offs to stay as far away from these limits as possible.

Figure 4.17 illustrates that between dilution thicknesses of 1.6 m and 3.9 m, the expected diluted yields are below the diluted yield cut-offs. It is therefore unprofitable to mine and beneficiate Bench 7B at an RD of 1.8 g/cm^3 with that amount of Bench 7A. This is because diluting Bench 7B with 1.6 m to 3.9 m of Bench 7A material, results in increased processing costs that are higher than the expected revenue.

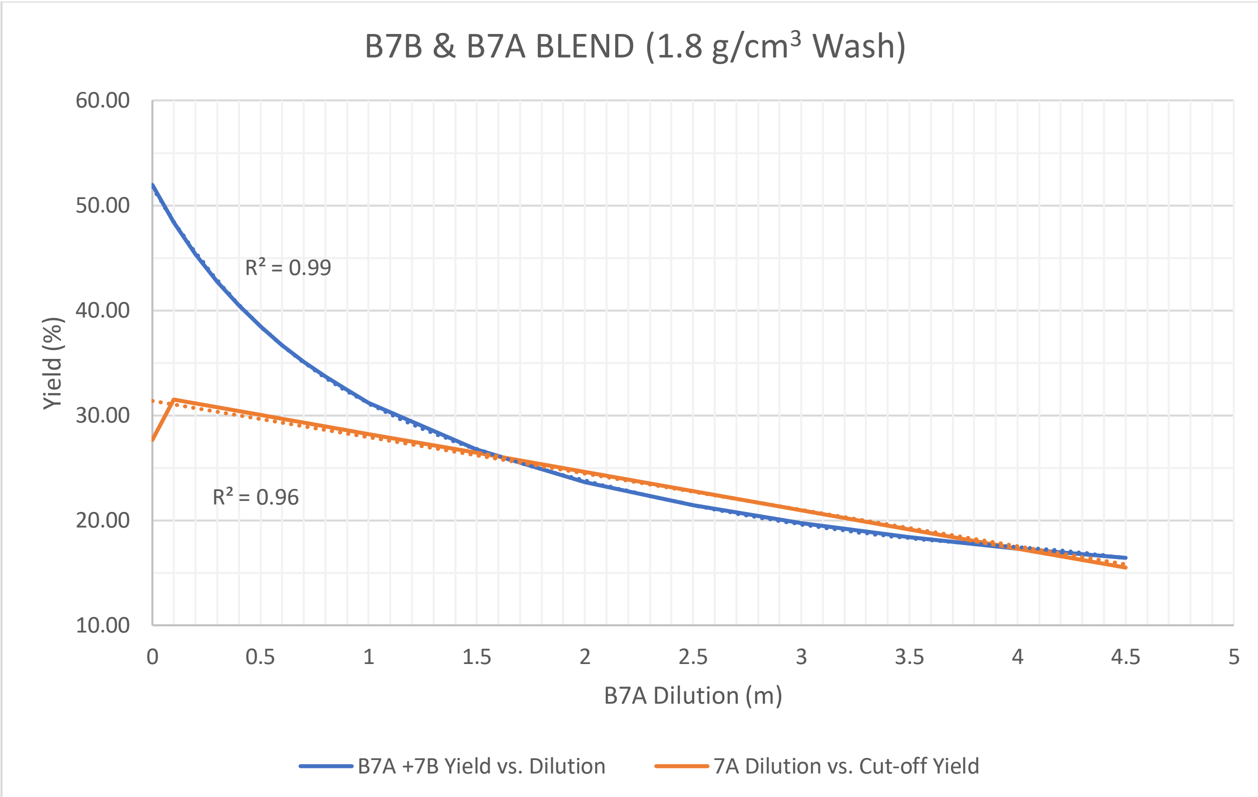

Figure 4.17: Resultant yield and yield cut-off when Bench 7B diluted with Bench 7A at 1.8g/ cm^3 wash

$$y = -0.096x^5 + 1.34x^4 - 7.30x^3 + 20.64x^2 - 35.21x + 51.77 \qquad \text{Equation 4.2}$$

$$y = -3.46x + 31.37 \qquad \text{Equation 4.3}$$

When Bench 7B is diluted with more than 3.9 m of Bench 7A material, it is again theoretically profitable to mine the diluted Bench 7B. This is because the increased dilution results in a lower stripping ratio, and thus lowers the stripping costs being realised. This in-turn re-establishes profitability. It must be noted that this profitability at these levels of dilution is marginal, as it is accompanied by an increase in processing costs as more Bench 7A is being taken to the plant for processing whilst realising low yields. This is illustrated in Figure 4.17 as the lines that represent the relationship between yield and dilution thickness, as well as yield cut-off and dilution thickness are close to each other at dilution thicknesses above 3.9 m.

For a wash RD of 1.9 g/cm^3; the resultant product yield, yield cut-off, product qualities and expected product tonnes are summarised in Table 4.9.

Table 4.9: Qualities resulting from diluting Bench 7B with Bench 7A and washing at a RD of 1.9 g/ cm^3

1.9 WASH	ASH (%)	CV (MJ/Kg)	SU (%)	YLD (%)	DILUTION (m)	YCO (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	31.11	22.57	0.64	61.96	0	27.68	620	277
B7B +B7A 0.1	31.31	22.50	0.64	58.23	0.10	31.50	582	315
B7B +B7A 0.2	31.50	22.43	0.63	55.00	0.20	31.14	550	311
B7B +B7A 0.3	31.69	22.36	0.63	52.22	0.30	30.78	522	308
B7B +B7A 0.4	31.86	22.30	0.62	49.80	0.40	30.41	498	304
B7B +B7A 0.5	32.03	22.24	0.61	47.68	0.50	30.05	477	300
B7B +B7A 0.6	32.20	22.18	0.61	45.79	0.60	29.69	458	297
B7B +B7A 0.7	32.35	22.12	0.60	44.12	0.70	29.32	441	293
B7B +B7A 0.8	32.50	22.07	0.60	42.61	0.80	28.96	426	290
B7B +B7A 0.9	32.65	22.01	0.60	41.25	0.90	28.59	412	286
B7B +B7A 1	32.79	21.96	0.59	40.02	1.00	28.23	400	282
B7B +B7A 1.5	33.43	21.73	0.57	35.25	1.50	53.07	352	531
B7B +B7A 2	33.97	21.54	0.56	31.99	2.00	49.42	320	494
B7B +B7A 2.5	34.43	21.37	0.54	29.62	2.50	45.76	296	458
B7B +B7A 3	34.84	21.22	0.53	27.82	3.00	42.11	278	421
B7B +B7A 3.5	35.20	21.09	0.51	26.41	3.50	N/A	264	N/A
B7B +B7A 4	35.52	20.98	0.51	25.27	4.00	N/A	253	N/A
B7B +B7A 4.5	35.77	20.89	0.50	24.33	4.50	N/A	243	N/A

When Bench 7B is diluted with more than 1 m of Bench 7A, the recalculated qualities indicate that the ash content of the resultant product exceeds the specification for Eskom power stations. The coal produced at these levels of dilution is likely to have penalties imposed upon it, thus decreasing expected revenue and impacting profitability. When Bench 7B is diluted with more than 3 m of Bench 7A material, the ash rejection limit for Eskom power station is reached and the coal will not be accepted for use at the power station. The carbonaceous nature of the shale layers found in Bench 7A, as well as the presence of coal stringers in the bench means that some yield is realised even though it is considered waste. At a wash density of 1.9 g/cm^3 some of the more carbonaceous material in Bench 7A will report to the product fraction. This means this material will contribute to the resultant qualities for the diluted bench and result in an increase the ash content.

The line that describes the relationship between a change in yield and dilution thickness as Bench 7B is diluted with incremental amounts of Bench 7A is shown in Figure 4.18. The trend line fitted to this relationship and is defined by a 5th order polynomial equation that is shown in Equation 4.4. This line has a R^2 value of 0.99 which indicates that the fitted trend line accurately describes the relationship between the change in dilution thickness and yield at a beneficiation RD of 1.9g/cm^3.

The line that illustrates the change in yield cut-off as Bench 7B is diluted with incremental amounts of Bench 7A is described by a 6th polynomial that is shown in Equation 4.5. This line has an R^2 value of 0.94 which indicates that it describes the relationship accurately.

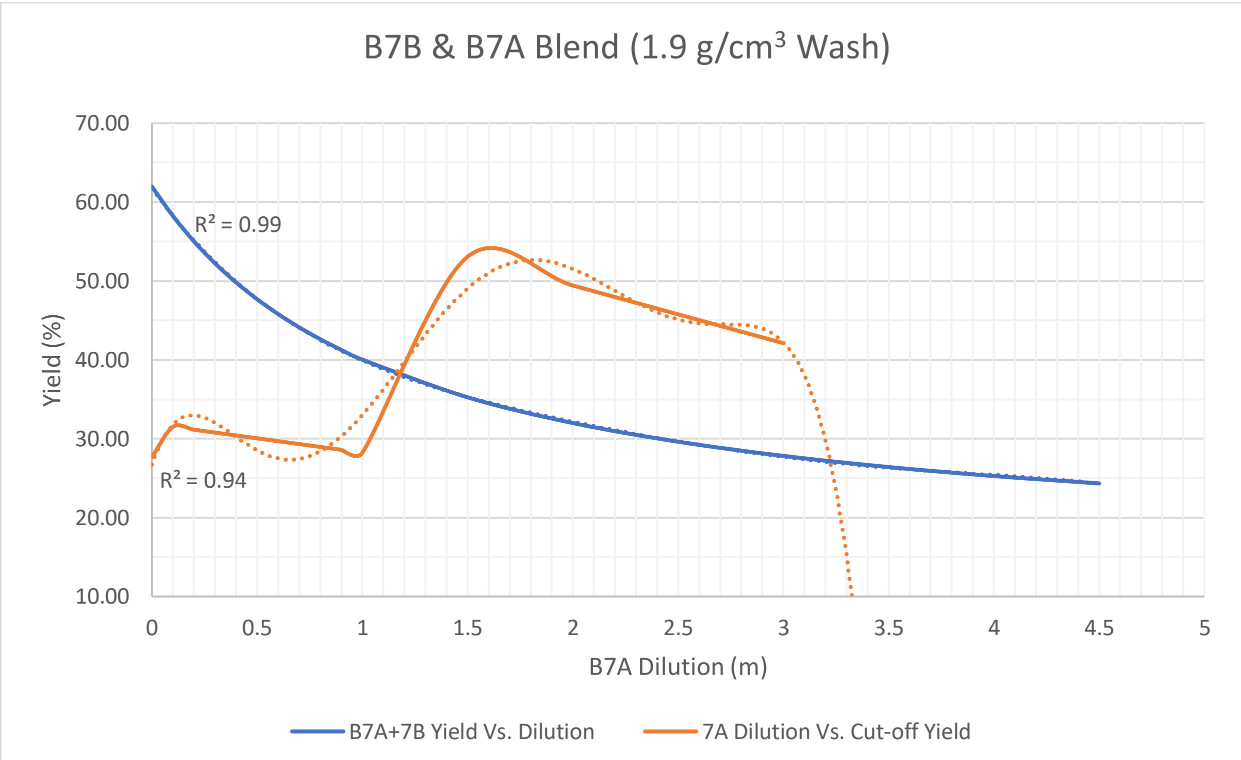

Figure 4.18: Resultant yield and yield cut-off when Bench 7B is diluted with Bench 7A and washed at 1.9 g/ cm^3

$$y = -0.10x^5 + 1.41x^4 - 7.71x^3 + 21.81x^2 - 37.27x + 61.77 \qquad \text{Equation 4.4}$$

$$y = -7.59x^6 + 73.83x^5 - 268.5x^4 + 441.23x^3 - 310.44x^2 + 77.82x + 26.68 \qquad \text{Equation 4.5}$$

When considering the dilution of Bench 7B with Bench 7A and beneficiating the resultant blend at a RD of 1.9 g/cm^3, the yield cut-off is reached when approximately 1.2m of Bench 7A is added to Bench 7B. This is the direct result of the penalties that would imposed on the coal product due to the resultant ash qualities. The imposition of penalties would result in a decrease in the selling price, thus increasing the minimum yield cut-off. When more than 3 m of Bench 7A material is added to Bench 7B, the resultant ash quality of the coal product reaches the rejection limit. At this point, a minimum yield-cut-off cannot exist as the coal product realised would not be bought by Eskom. Therefore, a maximum of 1.2 m of Bench 7A dilution material is viable for profitable mining. This level of dilution would result in a 2.49 m mining bench.

For a wash RD of 2.0 g/cm^3 the resultant product yield, yield cut-off, product qualities and expected product tonnes are summarised in Table 4.10.

Table 4.10*:* Qualities resulting from diluting Bench 7B with Bench 7A and washing at a RD of 2.0 g/ cm^3

2.0 WASH	ASH (%)	CV (MJ/Kg)	SU (%)	YLD (%)	DILUTION (m)	YCO (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	33.09	21.87	0.69	68.62	0	55.61	687	556
B7B +B7A 0.1	33.43	21.75	0.68	64.96	0.10	63.30	650	633
B7B +B7A 0.2	33.74	21.64	0.67	61.79	0.20	62.57	618	626
B7B +B7A 0.3	34.05	21.53	0.66	59.05	0.30	61.84	591	618
B7B +B7A 0.4	34.33	21.42	0.65	56.68	0.40	61.11	567	611
B7B +B7A 0.5	34.61	21.33	0.64	54.59	0.50	60.38	546	604
B7B +B7A 0.6	34.86	21.23	0.64	52.74	0.60	59.65	527	596
B7B +B7A 0.7	35.11	21.14	0.63	51.09	0.70	N/A	511	N/A
B7B +B7A 0.8	35.35	21.06	0.62	49.61	0.80	N/A	496	N/A
B7B +B7A 0.9	35.57	20.98	0.61	48.27	0.90	N/A	483	N/A
B7B +B7A 1	35.78	20.90	0.61	47.06	1.00	N/A	471	N/A
B7B +B7A 1.5	36.73	20.56	0.58	42.37	1.50	N/A	424	N/A
B7B +B7A 2	37.50	20.28	0.55	39.17	2.00	N/A	392	N/A
B7B +B7A 2.5	38.15	20.05	0.54	36.84	2.50	N/A	368	N/A
B7B +B7A 3.0	38.70	19.85	0.52	35.07	3.00	N/A	351	N/A
B7B +B7A 3.5	39.17	19.69	0.50	33.68	3.50	N/A	337	N/A
B7B +B7A 4	39.58	19.54	0.49	32.56	4.00	N/A	326	N/A
B7B +B7A 4.5	39.89	19.42	0.48	31.64	4.50	N/A	316	N/A

Table 4.10 shows that when beneficiating Bench 7B at a wash RD of 2.0 g/cm^3, even with no dilution included, the ash variable of the resultant product is 33.09%. This is marginally above the Eskom ash limit. This would mean that penalties would be imposed on this product. As a result, the price realised for the coal is lower and the minimum yield cut-off for the undiluted Bench 7B increases from 27.68% to 55.61 % for this beneficiation RD. When 0.7m of Bench 7A is included with the Bench 7B RoM material, the resultant ash quality is 35.11%. This is above the Eskom rejection limit and would not realise any revenue. For this reason, the minimum yield cut-off does not exist at this level of dilution and beyond.

At a wash RD of 2.0g/cm^3 it is theoretically possible to dilute Bench 7B with 0.1m of Bench 7A. This would result in a mining bench that is 1.49 m thick. Even at this level of dilution however, the resultant product would have penalties imposed upon it, thus decreasing profitability. The yield cut-off is reached when 0.2 m of Bench 7A is added to Bench 7B. Beyond this point, it is no longer profitable to mine the resultant bench. The fitted trend that describes the relationship between a change in yield as Bench 7B is diluted with Bench 7A at different increments is defined by a 5th order polynomial equation that is shown in Equation 4.6 and has a R^2 value of 0.99. The R^2 value of 0.99 indicates that the fitted trend line describes the relationship between the dilution thickness and the change in yield at a beneficiation RD of 2.0 g/cm^3 well. The line that illustrates the change in yield cut-off as Bench 7B is diluted with Bench 7A is described by Equation 4.7 and is defined by a 5th order polynomial. The graph that represent the relationship between product yield and dilution thickness, as well as yield cut-off and dilution thickness are shown in Figure 4.19.

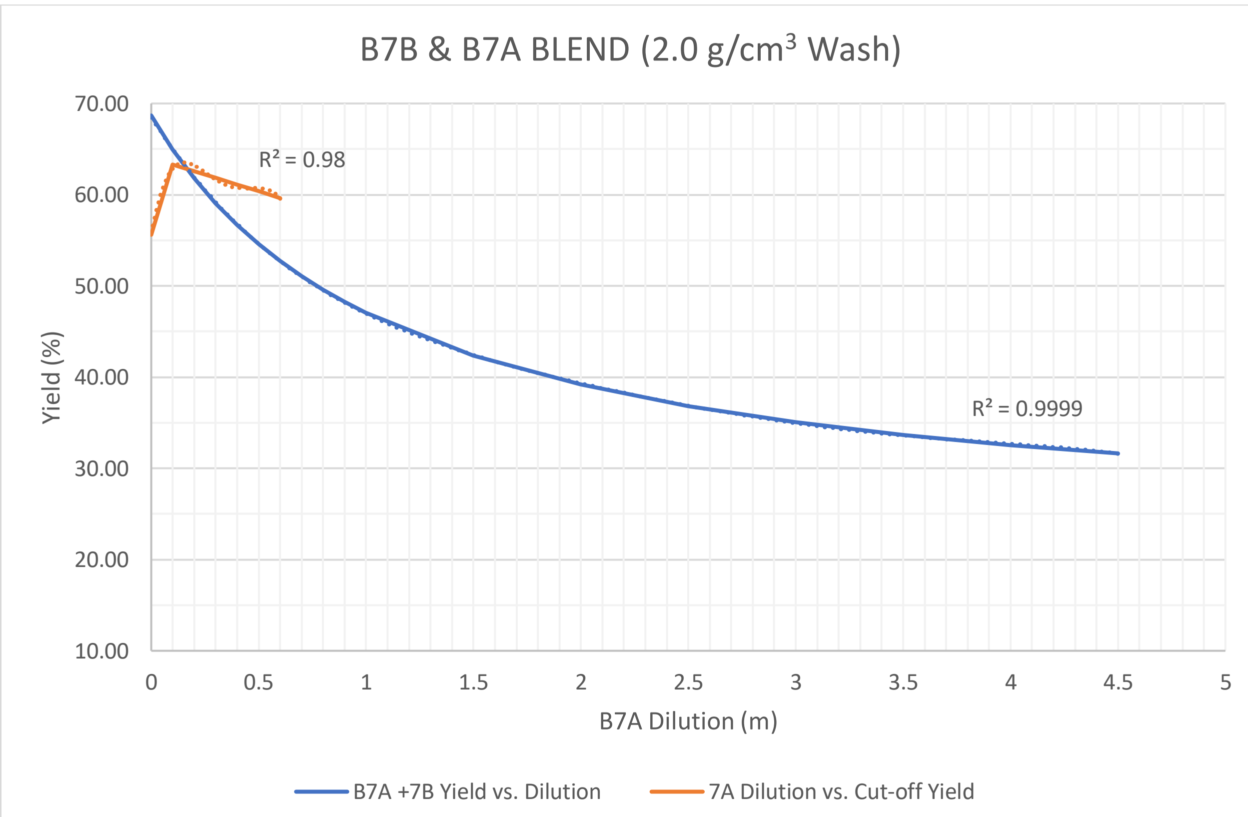

Figure 4.19: Resultant yield and yield cut-off when Bench 7B is diluted with Bench 7A and washed at 2.0 g/ cm^3

$y = 0.47x^5 - 5.52x^4 + 22.45x^3 + 35.111x^2 - 6.58x + 58.51$ Equation 4.6

$y = -957.17x^4 + 1382.6x^3 - 685.97x^2 + 127x + 55.72$ Equation 4.7

The results illustrated in Figure 4.19 and Table 4.10 indicate the beneficiation of Bench 7B at an RD of 2.0 g/cm^3 is not advisable as the resultant qualities are above Eskom specification limits. The inclusion of any dilution material worsens the situation.

4.4.2. Bench 7B and Bench 8 dilution scenarios and yield cut-off

For a wash RD of 1.8 g/cm^3; the resultant product yield, yield cut-off, product qualities and expected product tonnes obtained from diluting Bench 7B with incremental amounts of Bench 8 are summarised in

Table 4.11. When beneficiating Bench 7B diluted with Bench 8 at a wash density of 1.8 g/cm^3, there is no effect on the quality of the product for Eskom coal usage. All qualities obtained from the diluted bench scenarios are within the product specification ranges as summarised in Table 2.1.

Table 4.11: Qualities resulting from diluting Bench 7B with Bench 8 and washing at a RD of 1.8 g/ cm^3

1.8 WASH	ASH (%)	CV (MJ/Kg)	SUL (%)	YLD (%)	DILUTION (m)	COY (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	28.44	23.51	0.58	51.95	0	27.68	520	277
B7B+ B8 0.1	28.46	23.51	0.58	47.37	0.10	30.10	474	301
B7B+ B8 0.2	28.46	23.50	0.58	43.52	0.20	28.62	435	286
B7B+ B8 0.3	28.47	23.50	0.58	40.25	0.30	27.38	403	274
B7B+ B8 0.4	28.47	23.50	0.58	37.45	0.40	26.31	374	263
B7B+ B8 0.5	28.48	23.50	0.58	35.02	0.50	25.39	350	254
B7B+ B8 0.6	28.49	23.49	0.58	32.89	0.60	24.58	329	246
B7B+ B8 0.7	28.49	23.49	0.58	31.01	0.70	23.86	310	239
B7B+ B8 0.8	28.50	23.49	0.58	29.34	0.80	23.23	293	232
B7B+ B8 0.9	28.50	23.49	0.58	27.84	0.90	22.66	278	227
B7B+ B8 1	28.51	23.48	0.58	26.49	1.00	22.15	265	221
B7B+ B8 1.5	28.54	23.47	0.58	21.36	1.50	20.20	214	202
B7B+ B8 2	28.57	23.46	0.58	17.93	2.00	18.90	179	189
B7B+ B8 2.5	28.60	23.45	0.58	15.47	2.50	17.97	155	180
B7B+ B8 3	28.63	23.44	0.58	13.55	3.00	17.27	135	173

At a wash density of 1.8 g/cm^3 it is theoretically possible to dilute Bench 7B with up to approximately 1.6 m of Bench 8. The resultant mining bench for this level of dilution would be 2.99 m. The fitted trend line that describes the relationship between a change in yield when incrementally diluting Bench 7B with Bench 8 is given by a 5th order polynomial shown in Equation 4.8. This trend line has a R^2 value of 1 which is indicative of an excellent correlation. The trend that describes the relationship between a change in yield cut-off as Bench 7B is incrementally diluted with Bench 8 is defined by a second order polynomial shown in Equation

4.9. This trend has an R^2 value of 0.97 which is indicative of a good correlation. These trends are illustrated in Figure 4.20.

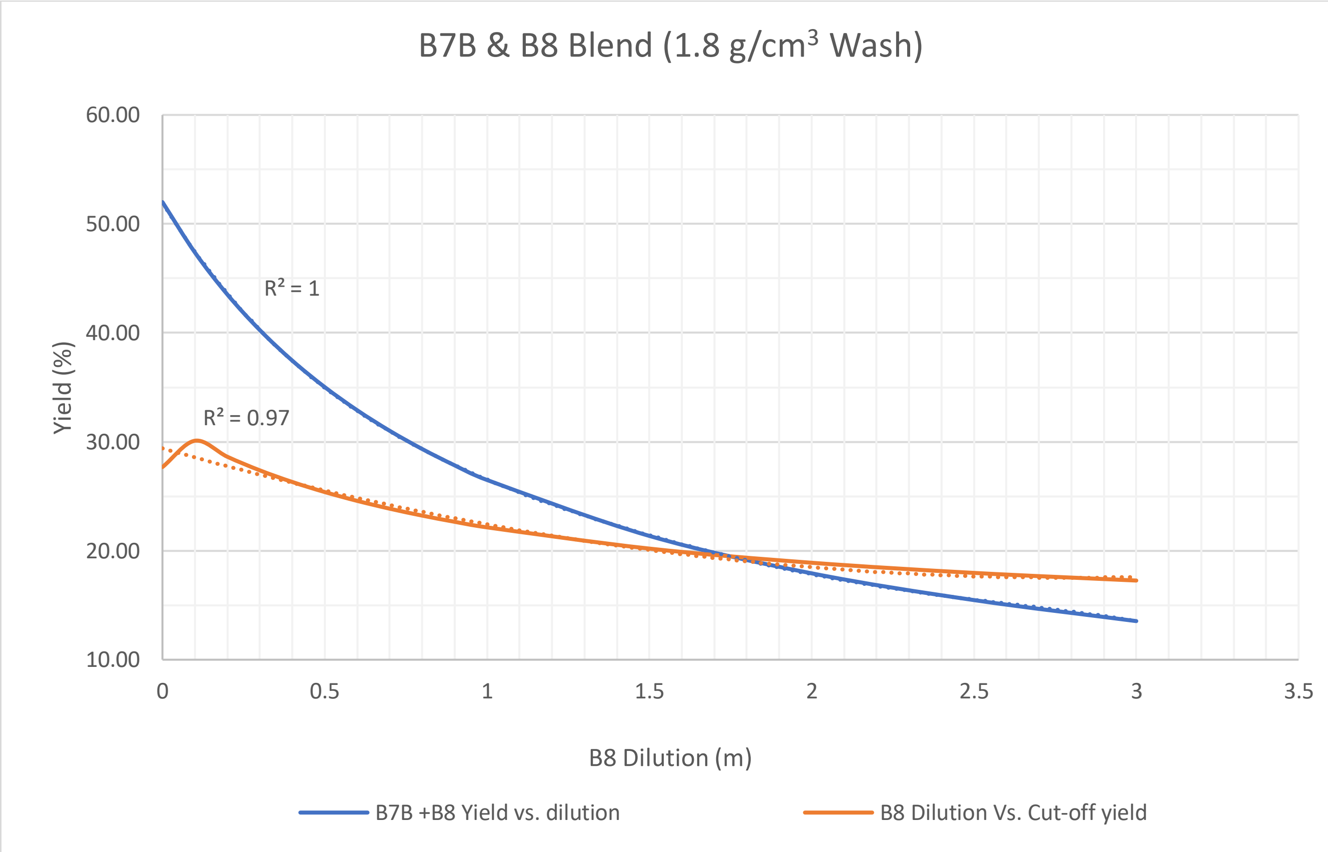

Figure 4.20: Resultant yields and yield cut-off when Bench 7B diluted with Bench 8 and washed at 1.8 g/ cm^3

$y = -0.53x^5 + 4.96x^4 - 18.49x^3 + 37.07x^2 - 48.40x + 51.92$ Equation 4.8

$y = 1.51x^2 - 8.51x + 29.40$ Equation 4.9

When 1.7 m of Bench 8 is added to Bench 7B the yield cut-off is reached. Beyond this level of dilution, it is no longer profitable to mine Bench 7B. Even though the qualities are all within specification, the costs associated with mining and processing the diluted material are higher than the expected revenue.

For a wash RD of 1.9 g/cm^3; the resultant yield, yield cut-off, product qualities and expected product tonnes obtained from diluting Bench 7B with incremental amounts of Bench 8 are summarised in Table 4.12. In all scenarios evaluated, the resultant qualities are acceptable for use in the Eskom power stations.

Table 4.12: Qualities resulting from diluting Bench 7B with Bench 8 and washing at a RD of 1.9 g/ cm^3

1.9 WASH	ASH (%)	CV (MJ/Kg)	SU (%)	YLD (%)	DILUTION (m)	COY (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	31.12	22.57	0.64	62.03	0	27.68	620	277
B7B+ B8 0.1	31.13	22.56	0.64	56.54	0.10	30.10	565	301
B7B+ B8 0.2	31.15	22.56	0.64	51.97	0.20	28.62	520	286
B7B+ B8 0.3	31.16	22.55	0.64	48.11	0.30	27.38	481	274
B7B+ B8 0.4	31.18	22.54	0.64	44.79	0.40	26.31	448	263
B7B+ B8 0.5	31.19	22.54	0.64	41.91	0.50	25.39	419	254
B7B+ B8 0.6	31.21	22.53	0.64	39.39	0.60	24.58	394	246
B7B+ B8 0.7	31.22	22.53	0.64	37.16	0.70	23.86	372	239
B7B+ B8 0.8	31.24	22.52	0.64	35.18	0.80	23.23	352	232
B7B+ B8 0.9	31.26	22.51	0.64	33.40	0.90	22.66	334	227
B7B+ B8 1	31.27	22.51	0.64	31.81	1.00	22.15	318	221
B7B+ B8 1.5	31.35	22.48	0.64	25.72	1.50	20.20	257	202
B7B+ B8 2	31.42	22.45	0.64	21.66	2.00	18.90	217	189
B7B+ B8 2.5	31.49	22.42	0.64	18.75	2.50	17.97	187	180
B7B+ B8 3	31.56	22.40	0.64	16.56	3.00	17.27	166	173

At this wash density, it is theoretically possible to dilute Bench 7B with 2.6 m of Bench 8. The resultant bench at this level of dilution is 3.99m. The fitted trend that describes the change in yield when diluting Bench 7B with incremental amounts of Bench 8 is given by the fifth order polynomial shown in Equation 4.8. The trend line has a R^2 value of 1 which is indicative of an excellent correlation. The trend that describes the change in yield as Bench 7B is diluted with Bench 8 is illustrated in a second order polynomial shown in Equation 4.9. This trend has an R^2 value of 0.97 which is indicative of a good correlation. The relationship between a change in yield, yield cut-off and dilution is shown in Figure 4.21

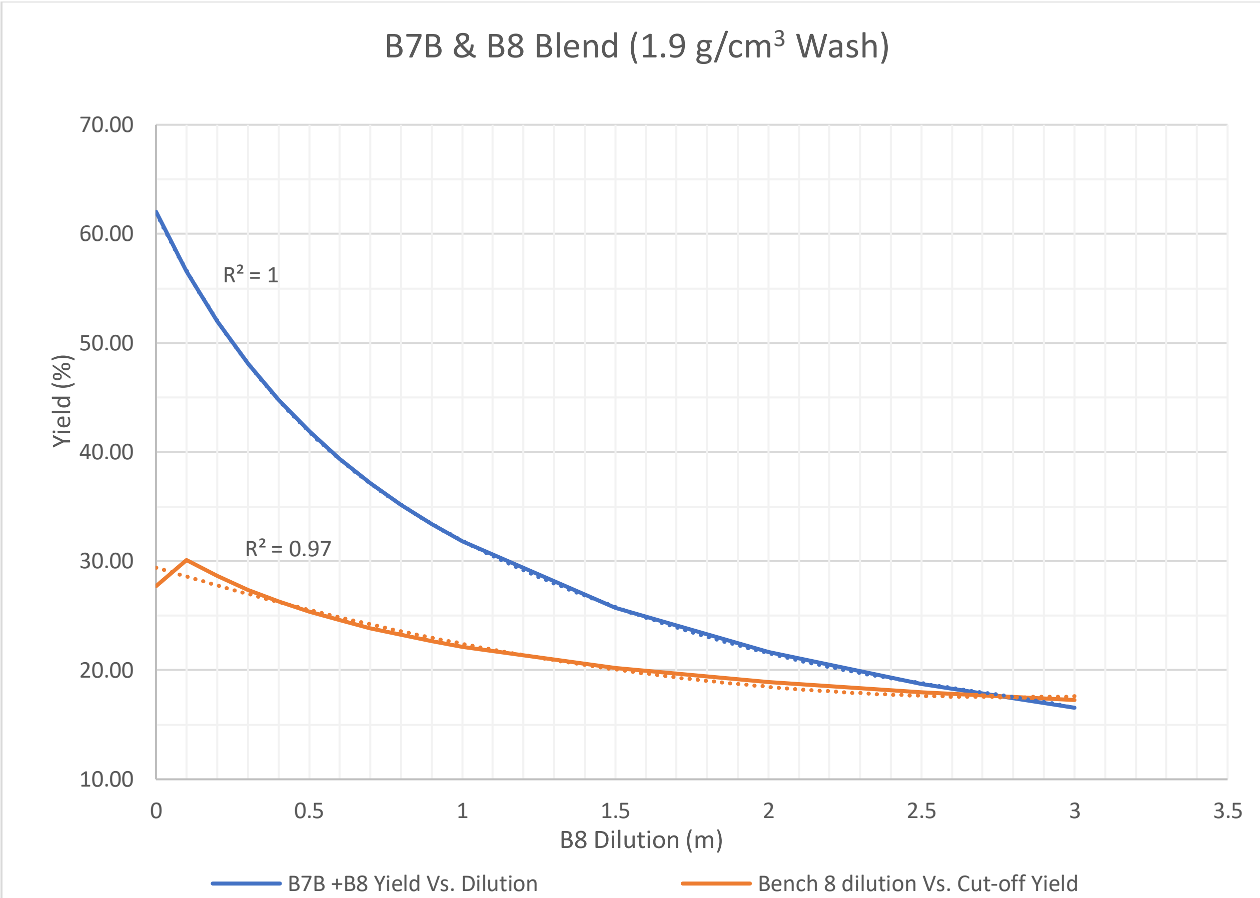

Figure 4.21: Resultant yield and yield cut-off when Bench 7B diluted with Bench 8 and washed at 1.9 g/cm^3

$$y = -0.6219x^5 + 5.8216x^4 - 21.793x^3 + 43.814x^2 - 57.318x + 61.934 \qquad \text{Equation 4.10}$$

At a dilution thickness of 2.7 m the yield cut-off is reached. Although the resultant qualities are unaffected by the inclusion of Bench 8 at this wash RD, the yield obtained beyond a dilution thickness of 2.7 m make it unprofitable to mine and process the material.

For a wash RD of 2.0 g/cm^3; the resultant yield, yield cut-off, product qualities and product tonnes obtained from diluting Bench 7B with incremental amounts of Bench 8 are summarised in Table 4.13 . At this wash RD all the scenarios evaluated indicate that the ash variable is above the Eskom power station limit of 33%, even when Bench 7B is mined without any dilution. This is likely to result in penalties and thus effect profitability. For this reason, the minimum yield cut-off for the undiluted Bench 7B increases from 27.68% to 55.61 % for this beneficiation RD. None of the resultant qualities reached the rejection limit in any of the dilution scenarios considered.

Table 4.13: Qualities resulting from diluting Bench 7B with Bench 8 and washing at a RD of 2.0 g/cm^3

2.0 WASH	ASH (%)	CV (MJ/Kg)	SUL (%)	YLD (%)	DILUTION (m)	YCO (%)	PRD (t) at YLD	PRD (t) at YCO
B7B	33.09	21.87	0.69	68.69	0	55.61	687	556
B7B+ B8 0.1	33.12	21.86	0.69	62.67	0.10	60.47	627	605
B7B+ B8 0.2	33.15	21.85	0.69	57.66	0.20	57.52	577	575
B7B+ B8 0.3	33.19	21.84	0.69	53.41	0.30	55.02	534	550
B7B+ B8 0.4	33.22	21.82	0.69	49.77	0.40	52.87	498	529
B7B+ B8 0.5	33.25	21.81	0.69	46.61	0.50	51.01	466	510
B7B+ B8 0.6	33.28	21.80	0.69	43.85	0.60	49.39	438	494
B7B+ B8 0.7	33.32	21.79	0.69	41.40	0.70	47.95	414	479
B7B+ B8 0.8	33.35	21.78	0.69	39.23	0.80	46.67	392	467
B7B+ B8 0.9	33.38	21.76	0.69	37.28	0.90	45.53	373	455
B7B+ B8 1	33.41	21.75	0.68	35.53	1.00	44.50	355	445
B7B+ B8 1.5	33.56	21.70	0.68	28.86	1.50	40.59	289	406
B7B+ B8 2	33.71	21.64	0.68	24.40	2.00	37.97	244	380
B7B+ B8 2.5	33.85	21.59	0.68	21.21	2.50	36.10	212	361
B7B+ B8 3	33.99	21.54	0.67	18.78	3.00	34.70	188	347

At this wash density, it is theoretically possible to dilute Bench 7B with 0.1 m. The resultant bench has a thickness of approximately 1.49 m. The relationship between yield and dilution thickness is shown Figure 4.22. The fitted trend that describes the change in yield when diluting Bench 7B with incremental amounts of Bench 8 is given by the fifth order polynomial shown in Equation 4.11. The trend line has a R^2 value of 1 which is indicative of an excellent correlation. The trend that describes the change in yield as Bench 7B is diluted with Bench 8 is also illustrated in Figure 4.22. This trend can be described by the sixth order polynomial shown in Equation 4.12. The trend has an R^2 value of 0.99 which is indicative of a good correlation.

At a dilution thickness of 0.2m the yield cut-off is reached. At this wash RD all the resultant qualities, diluted and undiluted, are below the rejection limit but are above the Eskom specification. This will result in the product incurring penalties thus decreasing the expected revenue. This decrease in expected revenue will result in an increase in the yield cut-off. It is therefore not advisable to beneficiate Bench 7B at this was RD.

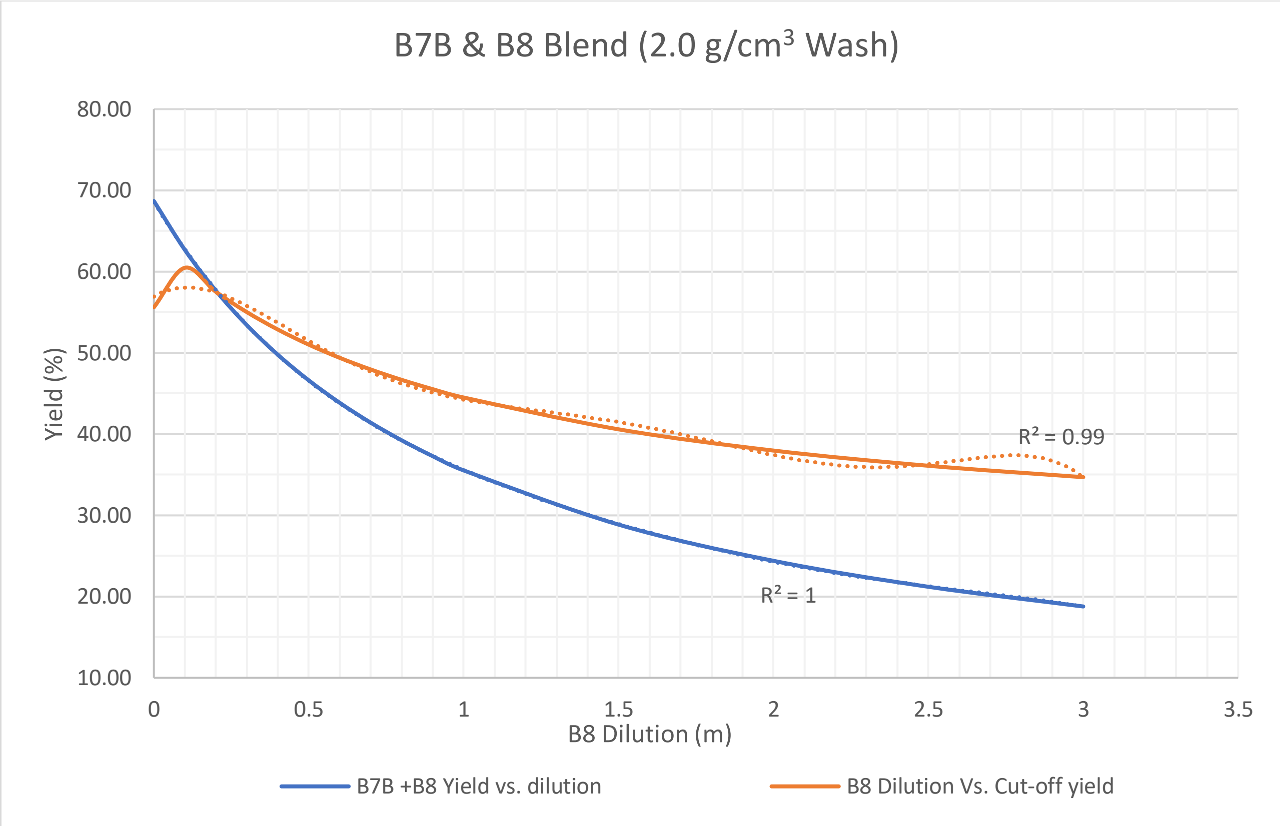

Figure 4.22: Resultant yield and yield cut-off when Bench 7B diluted with Bench 8 and washed at 2.0 g/cm^3

$y = -0.69x^5 + 6.40x^4 - 23.94x^3 + 48.13x^2 - 62.89x + 68.59$ Equation 4.11

$y = -3.51x^6 + 31.20x^5 - 111.9x^4 + 182.32x^3 - 134.86x^2 + 23.11x + 56.91$ Equation 4.12

Due to the non-carbonaceous nature of Bench 8, all the material added to Bench 7B will report to waste whether it is washed at a density of 1.8 g/cm^3, 1.9 g/cm^3 or 2.0 g/cm^3. This means the qualities of the resultant product remain largely unaffected by the addition of Bench 8 material. Rather, they are affected by the inherent qualities of Bench 7B at the wash RD. The biggest impact of mixing Bench 8 with Bench 7B and beneficiating the resultant bench at these RDs, is the amount of material the plants will have to handle in processing and the associated costs thereof.

4.5 Sensitivity analysis

Figure 4.23 illustrates the sensitivity of yield cut-off as result of a decrease in the selling price. The selling price of the coal product has the biggest impact on the yield cut-off, as a decrease in this parameter results in the biggest increase in the yield cut-off. The trend that describes the change in yield cut-off as the selling price decreases is given by the third order polynomial described by equation 4.13. The R^2 value of this trend is 0.99 which is indicative of a good correlation.

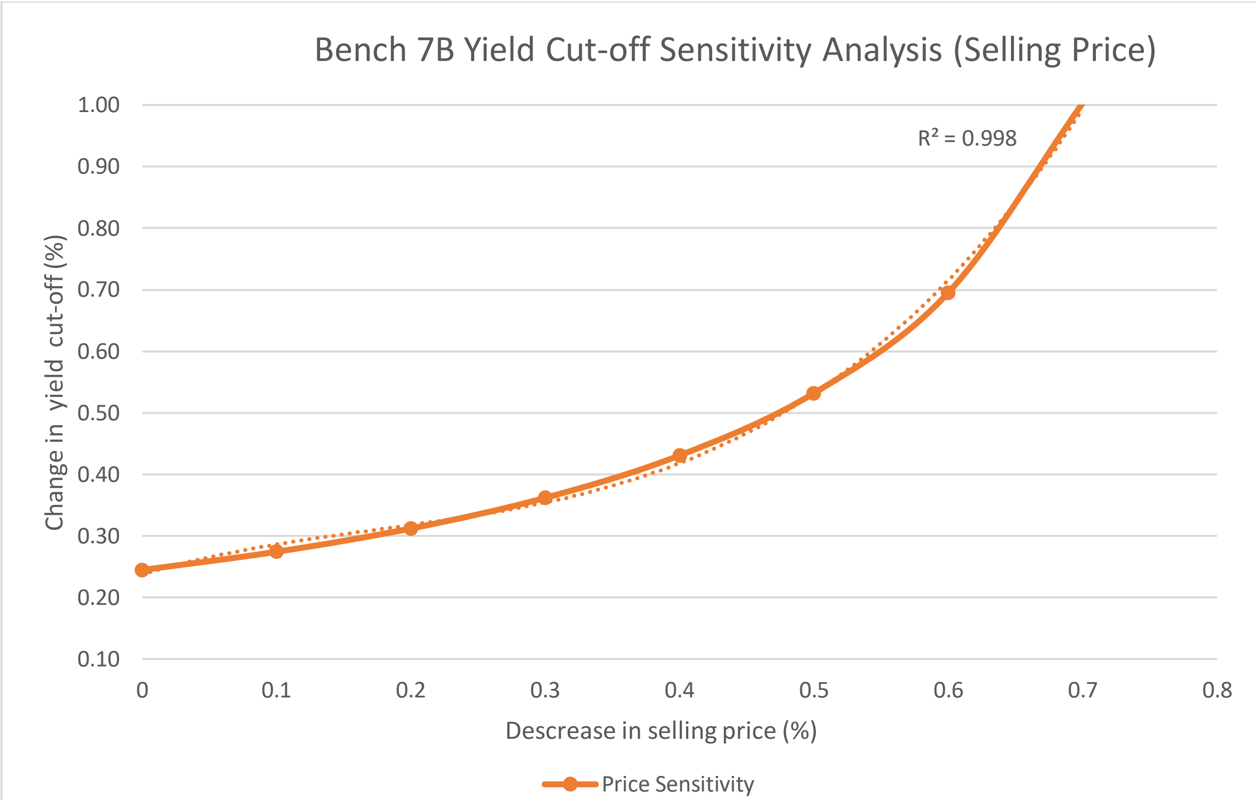

Figure 4.23: The impact of an increase in selling price on the yield cut-off

$$y = 3.67x^3 - 1.96x^2 + 0.65x + 0.24 \qquad \text{Equation 4.13}$$

The mining cost, which is the same as the cost of removing waste, has the second biggest impact of yield cut-off. An increase in this cost results in an increase in the yield cut-off. This relationship between yield-cut off and a change in mining costs follows a linear trend which is described by equation 4.14. The R^2 value of this trend is 1 which is indicative of an excellent correlation. The processing costs are the third most sensitive, while rehabilitation costs and transport costs appear to be the least sensitive and follow linear trends that are similar. The sensitivity of all the cost parameters on the yield cut-off are shown in Figure 4.24.

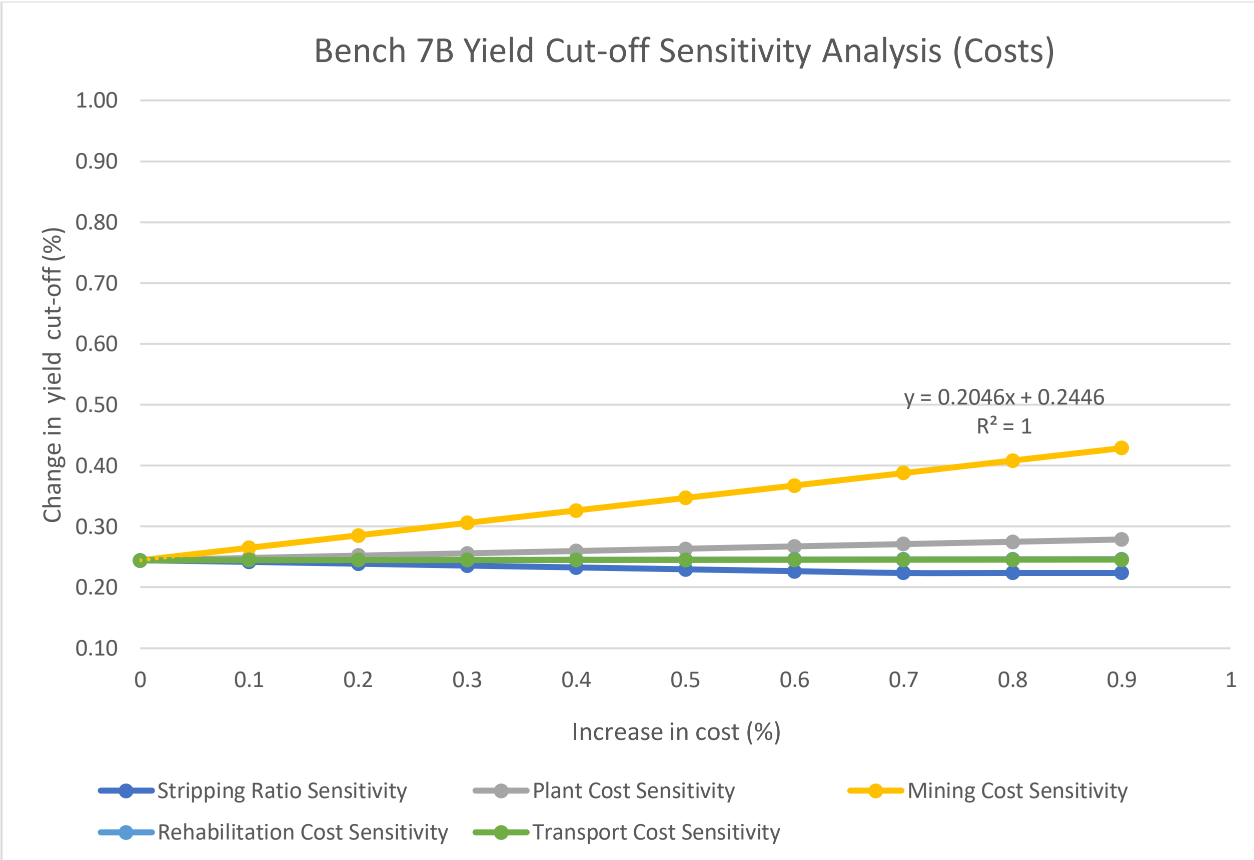

Figure 4.24: The impact of a decrease in costs on the yield cut-off

$y = 0.20x + 0.24$ Equation 4.14

The sensitivity analysis of the cost variables and selling price used in the yield cut-off function indicates that all the cost related parameters follow the same trend. An increase in the cost parameters results in a complementary increase in the yield cut-off. A decrease in the selling price used in the yield cut-off function has the same effect. The severity of the increase does however vary from variable to variable.

The relationship between the stripping ratio and its impact on yield cut off displays a linear trend. As the stripping ratio increases, there is an increase in the yield cut-off as well. The fitted trend line that describes the relationship between yield cut-off and stripping ratio is given by the equation 4.15 and has a R^2 value of 1. The R^2 value of 1 is indicative of an excellent correlation. The relationship between stripping ratio and yield cut-off is illustrated in Figure 4.25.

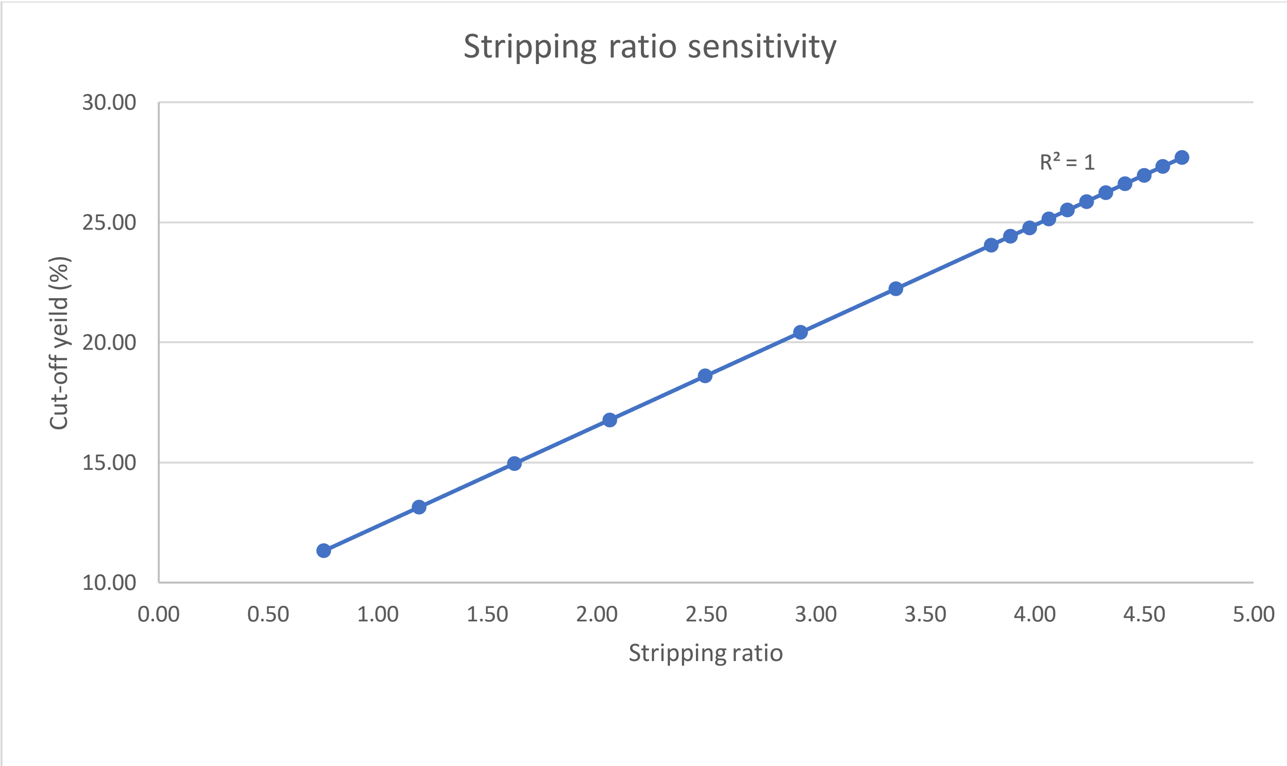

Figure 4.25: The impact of an increase in stripping ratio on the yield cut-off

$y = 4.18x + 8.17$ Equation 4.15

The results indicate that the higher the stripping ratio, the higher the yield cut-off required to make mining Bench 7B profitable. It is therefore possible for Bench 7B to become profitable at higher levels of dilution with Bench 7A. This is because as more material from Bench 7A is used to dilute Bench 7B, there is less material to remove to access Bench 7B. This in turn decreases the yield cut-off by decreasing the stripping ratio. It must again be noted though, that this increased level of dilution has a direct impact on qualities as well as the amount of addition material that the plants will have to handle. Furthermore, dilution will have an overall effect of profitability as the yield realised will also decrease.

4.6 Concluding remarks on results and discussion

In this chapter, the results obtained by applying the methodology proposed for this research project were presented. Firstly, the results of the EDA were presented. All the sample data obtained from the different benches were found to be representative of each sample population. The EDA also revealed that in its raw form Bench 7B did not have CV or ash qualities acceptable for power station feed. The raw sulphur qualities were however acceptable for power station feed. Furthermore, the addition of either Bench 7A or Bench 8 as dilution material would negatively affect the Bench 7B qualities. The Bench 7A and Bench 8 CV and ash qualities were not suitable for power station feed in their raw form either as these are waste benches. Like Bench 7B, Bench 7A and Bench 8 have acceptable raw sulphur qualities for power station feed. The cumulative wash tables presented as part of the EDA showed that Bench 7B has yields 51.95, 62.03% and 68.69% at beneficiation RDs of 1.8 g/cm^3, 1.9 g/cm^3 and 2.0 g/cm^3 respectively. These RDs are representative of how the Bench 7B material is currently processed. The expected product qualities for Bench 7B beneficiated at 1.8 and 1.9 g/cm^3 are acceptable for use in the Eskom power stations. At a wash RD of 2.0 g/cm^3 resultant the ash variable for Bench 7B is 33.09%. This is marginally above the Eskom specification. Although this product would not be rejected, it may have penalties imposed upon it.

At RDs of 1.8 g/cm^3 1.9 g/cm^3 and 2.0 g/cm^3, Bench 7A realises yields of 7.28%, 14.64% and 22.11%. At the same wash densities Bench 8 realises yields of 0.61%, 1.15% and 1.92% respectively. These results show that Bench 7A has more carbonaceous material within it which could contribute to the overall product. However, the cumulative wash table also indicate that both Bench 7A and Bench 8 have ash values above 33% at all the wash RD considered. This means that they do not meet the Eskom specifications as shown in Table 2.1. They will also negatively impact overall product qualities when included with Bench 7B.

The calculation of the minimum yield cut-off for the profitable mining of Bench 7B was also included in this chapter. When exploited without dilution, it was determined that the point at which zero profit is made, is when the yield from Bench 7B reaches 25.74%. The resultant yield of Bench 7B when mined without any dilution and beneficiated at a RD 1.8 g/cm^3 is 51.95%. At a wash RD of 1.9 g/cm^3 the undiluted bench has a resultant yield of 62.03%, while a yield of 68.69% is achieved when Bench 7B is washed at 2.0 g/cm^3. These results are all above the minimum yield cut-off. This means that from a yield perspective, it is profitable to mine Bench 7B without any dilution.

By plotting the recalculated yield cut-offs and diluted yields against the dilutions thickness, it was possible to observe trends in the data. By fitting regression lines to the observed data points, it was also possible to describe the relationship between the yield cut-off and dilution thickness.

Furthermore, it was also possible to describe the relationship between diluted yield and the dilution thickness. These relationships can be expressed as equations which can be used for prediction purposes. R^2 values were obtained for the fitted regression lines and all the R^2 values calculated for the overserved trends in this study were greater than 0.94. This indicates that the trend lines accurately describe the relationships investigated and that the trend lines accurately account for the variability in the observed data points. This was true for the dilution of Bench 7B with Bench 7A and when Bench 7B was diluted with Bench 8.

The results indicate that relationship between yield and dilution thickness changes depending on two factors; the density at which the feed is beneficiated and the density of the material used to dilute Bench 7B. Depending on these factors, the additional material will either contribute to the overall product yield or simply washed out as discard. The more material that reports to discard as a proportion of the total feed, the lower the product yield. This lower yield and higher processing cost due to the additional feed will have an impact on profitability.

In the scenarios where Bench 7B is diluted with Bench 7A, some Bench 7A material does contribute to the product. The amount of Bench 7A material that will be included in the product will be dependent on the wash density at which it is beneficiated. This changes the relationship between yield and dilution thickness. In addition, because some of the Bench 7A material will contribute to the product, there is a notable change in qualities that must be considered.

When Bench 7B is diluted with Bench 8, regardless of the density at which the diluted bench is beneficiated, most of the Bench 8 material will report to discard as opposed to the product. This is because Bench 8 is far less carbonaceous and the material within it is of a higher density than the wash densities considered. This results in the changes in yield between the wash densities considered being less prominent. The change in the product qualities is also negligible with the resultant product qualities being like those achieved when beneficiating undiluted Bench 7B material.

The price obtained for the coal has the largest impact on yield cut-off. The sensitivity analysis indicates that mining costs have a second largest impact on the yield cut-off, while plant cost have the third largest impact. Furthermore, while the change in the selling price has an exponential impact on the yield cut-off, the cost variables all have a linear impact. As GCM has fixed term supply contracts with the power stations it supplies, the selling price is not an immediate need for concern.

Lastly, the research has indicated that the variables that are inputs to the yield cut-off function all impact profitability differently. These are the selling price, stripping ratio, cost of waste removal, cost of mining, cost of rehabilitation and the cost of conveying product to the power station. The sensitivity analysis indicated that the magnitude of the impact of each variable cost on the yield cut-off is in line with the magnitude of the cost. The bigger the variable cost per tonne, the bigger the impact of yield cut-off will be. The material used to dilute Bench 7B is more abrasive than clean coal. With increased wear and tear there may be an increase in processing costs thereby increasing the impact of these costs on the yield cut-off. The impact of the abrasiveness of the dilution material on the plant components, and thus wear and tear, is beyond the scope of this research project and is therefore not discussed further.

Stripping ratios also have an effect that can be directly correlated to profitability. There is a linear relationship between the change in the stripping ratio and the yield cut-off. An increase in the stripping ratio results in a complementary increase in the yield cut-off.

In the next chapter, the conclusions that can be drawn from the results discussed above will be presented. In addition, some recommendations on future work that be conducted to support the findings of this research project are also presented.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The mining of Bench 7B without any dilution is profitable. This is despite that fact that it is made up of lower quality coal when compared to the rest of the GCM resources and reserves. When beneficiated between 1.8 g/cm^3, 1.9 g/cm^3 the product meets the Eskom quality requirements. Bench 7B has a yield cut-off of 27.68%, but achieves yields of 52%, 62.03% and 68.69% when beneficiated at 1.8 g/cm^3, 1.9 g/cm^3 and 2.0g/cm^3 respectively.

Bench 7B is a relatively thin bench that is surrounded by thicker waste material from Bench 7A and Bench 8. However, when diluted with certain amounts of material from Bench 7A and 8 it still meets Eskom's quality requirements. This dilution does however affect profitability as it decreases the yield realised. The research has proven that it is possible to estimate the yield cut-off for Bench 7B when mined on its own and when diluted with various thicknesses of Bench 7A or Bench 8 at RDs between 1.8 g/cm^3 and 1.9g/cm^3 respectively. This exercise can be repeated at multiple densities to indicated what level of dilution can be tolerated.

The literature indicates that with an increase in dilution, there will be a decrease in the yield. This decrease in yield has a negative impact on profitability. These observations were confirmed by the results of the dilution scenarios that were tested i.e. when Bench 7B is diluted with either Bench 7A or Bench 8 at GCM, there is decrease in the yield. This in turn has an impact on profitability as the lower the yield, the less material that will be sold to Eskom as a product.

In addition, the test results confirmed that as dilution increases, there is also a negative impact on the resultant product qualities. This was more notable in the dilution scenarios where Bench 7A is used to dilute Bench 7B. This is because at RDs between 1.8 g/cm^3 and 2.0g/cm^3 Bench 7A contributes to the product that is realised during beneficiation. This is limited by the dilution thickness and the Eskom's quality requirements. However, when Bench 7B is diluted with material from Bench 8, at RDs between 1.8 g/cm^3 and 2.0g/cm^3 there is minimal addition to product because Bench 8 is of a poorer quality.

Qualities also have an impact on profitability as they can result in the penalisation or rejection of products that are delivered to the customer. If the qualities do not meet the Eskom qualities outlined in Table 2.1, they can be rejected. This means that there will be no revenue realised and therefore mining will be done at a loss.

When mining, the impact on qualities must be considered in conjunction with yield cut-off. This is illustrated in Table 4.10 where Bench 7B is diluted with Bench 7A and beneficiated at a RD of 2.0 g/cm^3. Although the resultant yield for the different dilution scenarios is above the yield cut-off, the resultant ash qualities exceed Eskom's quality requirements of 33%. The coal product will incur penalties, thus decreasing the expected revenue. In addition, incurring penalties can result in an increase in the required the minimum yield cut-off. This is illustrated in the research by the results obtained when Bench 7B is beneficiated at a RD of 2.0 g/cm^3.

The selling price of the coal product is the most sensitive to change as it has an exponential impact on the yield cut-off. A decrease in the expected selling price has an exponential impact on the price realised. The exponential impact of the selling price on the yield cut-off is also seen in the Figure 4.18. The impact of penalties on a product that does not meet Eskom specifications results in a sudden increase in the required minimum yield cut-off. The variable costs and stripping ratios have linear relationships with the yield cut-off and their impacts vary in magnitude based on the unit cost per tonne. It was observed that the higher the variable cost, the bigger the impact.

5.2 Recommendations

Although Bench 7B only makes up 3% of the total mine reserve, it is still a viable and available source of coal. It is therefore recommended that the mining of Bench 7B should be undertaken by GCM as it is profitable. This should, however, be executed under the following conditions:

- The research has shown that Bench 7B can handle some dilution. However, this dilution has a negative impact on product yield, product qualities and thus profitability. Therefore, the mining of Bench 7B should be conducted with little to no dilution at all.
- Bench 7B should be beneficiated at a wash RD below 2.0 g/cm^3. At this wash RD, the ash variable is marginally above the Eskom limit and would likely result in penalisation or rejection. At a wash RD of 1.9 g/cm^3 a product yield of 62.03% is achieved. This is well above a yield cut-off of 27.68%. The resultant product will also be of sufficient quality to meet Eskom's requirements.

Depending on the long-term exploitation strategy of the mine with regards to coal requirements, reserve utilisation philosophy, target profit margins, plant capacity and equipment allocation more dilution can be accommodated. However, any change must consider all these factors.

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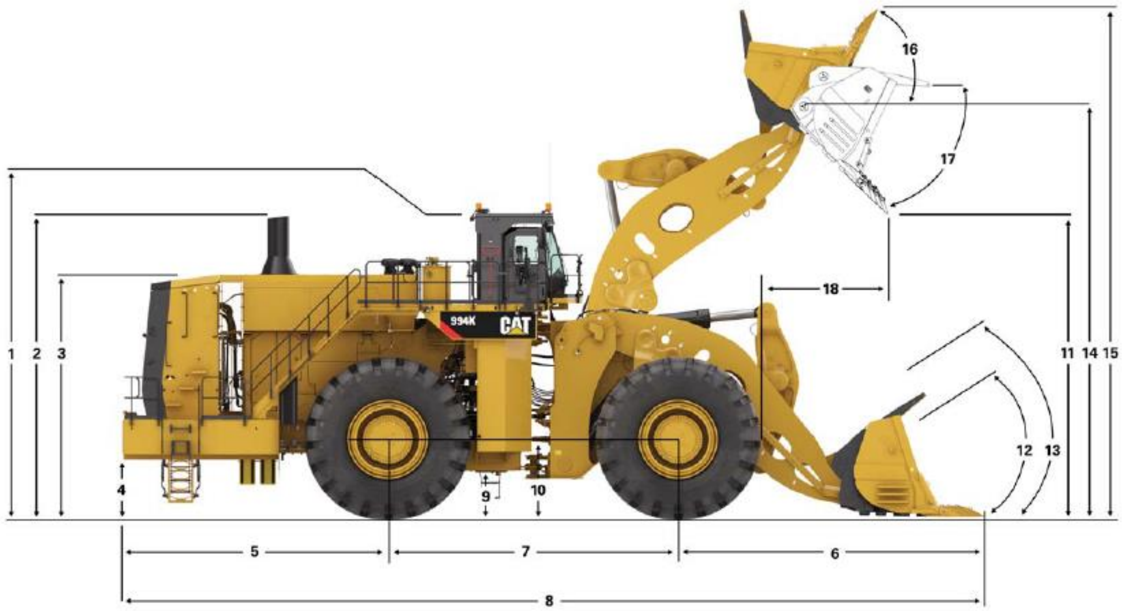
7 APPENDIX

7.1 APPENDIX 1: Dimensions of the Caterpillar 994 series front end loader



	Standard Lift		High Lift	
1 Ground to Top of ROPS	7118.5 mm	23.4 ft	7118.5 mm	23.4 ft
2 Ground to Top of Exhaust Stacks	7067 mm	23.2 ft	7067 mm	23.2 ft
3 Ground to Top of Hood	5682 mm	18.6 ft	5682 mm	18.6 ft
4 Ground to Bumper Clearance	1355 mm	4.4 ft	1355 mm	4.4 ft
5 Rear Axle Center Line to Bumper	6205 mm	20.4 ft	6205 mm	20.4 ft
6 Front Axle Center Line to Bucket Tip	6503 mm	21.3 ft	7097 mm	23.3 ft
7 Wheel Base	6800 mm	22.3 ft	6800 mm	22.3 ft
8 Maximum Overall Length	17 860 mm	58.6 ft	18 454 mm	60.5 ft
9 Ground to Lower Hitch Clearance	898 mm	2.9 ft	898 mm	2.9 ft
10 Ground to Center of Axles	1820 mm	6.0 ft	1820 mm	6.0 ft
11 Clearance at Maximum Lift	6167 mm	20.2 ft	7095 mm	23.3 ft
12 Rack Back Angle at Ground Level	39.7 degrees		45.0 degrees	
13 Rack Back Angle at Carry	47.7 degrees		53.7 degrees	
14 B-Pin Height at Maximum Lift	8790 mm	28.8 ft	9647 mm	31.7 ft
15 Maximum Overall Height, Bucket Raised	11 771 mm	38.6 ft	12 545 mm	41.2 ft
16 Rack Angle at Maximum Lift	59.5 degrees		59.4 degrees	
17 Dump Angle at Maximum Lift	–50.0 degrees		–50.0 degrees	
18 Reach at Maximum Lift	2821 mm	9.3 ft	2688 mm	8.8 ft

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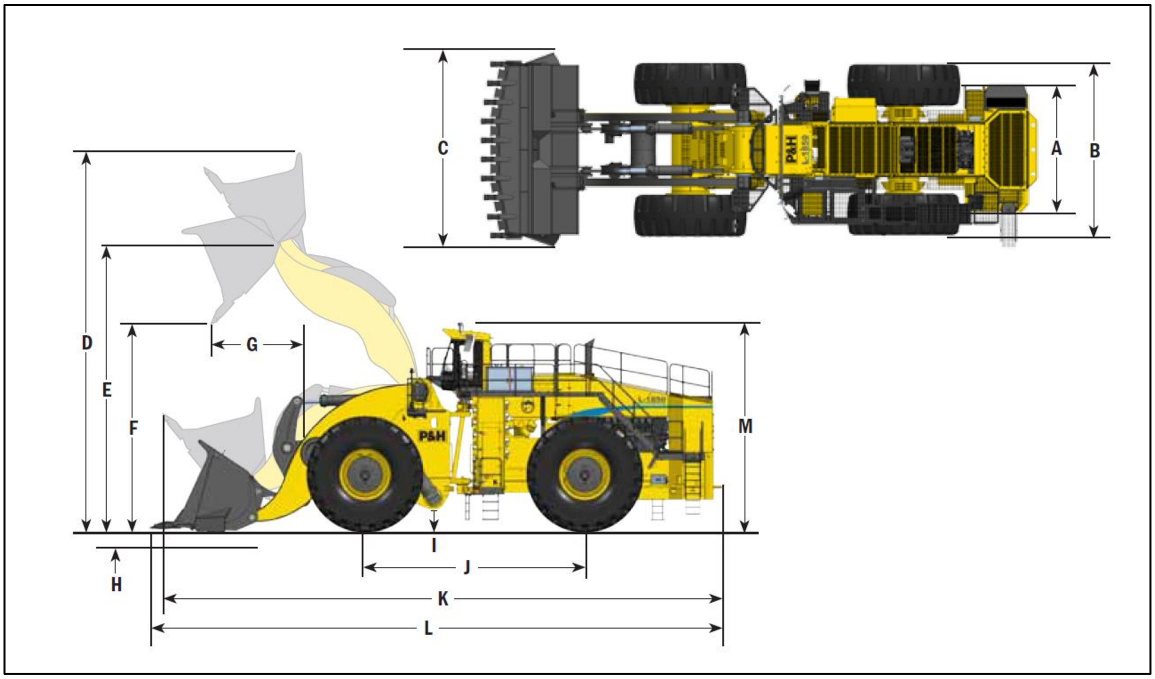
7.2 APPENDIX 2: Komatsu P&H Le Tourneau series from end loader (Komatsu Mining Corporation, 2018)



7.3 APPENDIX 3: Dimensions of the Komatsu P&H Le Tourneau series front end loader (Komatsu Mining Corporation, 2018)

Overall Dimensions

		Standard Lift		High Lift	
A	Tread	15 ft 0 in	4.57 m	15 ft 0 in	4.57 m
B	Width Outside Tires	19 ft 10 in	6.04 m	19 ft 10 in	6.04 m
C1	Rock Bucket Without Deflectors	21 ft 0 in	6.40 m	21 ft 0 in	6.40 m
C2	Rock Bucket With Deflectors	22 ft 0 in	6.71 m	22 ft 0 in	6.71 m
C3	Coal Bucket	24 ft 5 in	7.44 m	24 ft 5 in	7.44 m
D	Height Bucket Fully Raised	41 ft 3 in	12.57 m	42 ft 5 in	12.93 m
E	Hinge – Pin Height	30 ft 10 in	9.40 m	32 ft 6 in	9.91 m
F	Dump Clearance	22 ft 5 in	6.83 m	24 ft 3 in	7.39 m
G	Reach at Full Lift	10 ft 7 in	3.23 m	10 ft 7 in	3.23 m
H	Digging Depth	0 ft 6 in	0.15 m	0 ft 6 in	0.15 m
I	Ground Clearance	2 ft 3 in	0.69 m	2 ft 3 in	0.69 m
J	Wheelbase	24 ft 6 in	7.47 m	24 ft 6 in	7.47 m
K	Overall Length Carry Position	61 ft 4 in	18.69 m	62 ft 6 in	19.06 m
L	Overall Length Bucket Down	62 ft 6 in	18.90 m	63 ft 5 in	19.30 m
M	Height Over Cab	22 ft 1 in	6.73 m	22 ft 1 in	6.73 m

** All dimensions are based on standard tires and standard rock bucket with GET unless otherwise noted.*

7.4 APPENDIX 4: The dimensions of the buckets used on the GCM front end loaders

Dimensions	994	LeTourneau
Width	6.57 m	7.27 m
Height	2.29 m	2.30 m
Depth	1.60 m	2.00 m