Improving Rock Fragmentation at the Ahafo Gold Mine Site

Enhancing Improvements in Production Efficiency and Reducing Operational Costs Through Drill & Blast Pattern Optimization

by

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Abstract

An efficient production is essential for an economic continuation of most gold mining companies, due to a moderate gold price and a competitive market. Recently, the Ahafo South Mining operations owned by the Newmont Mining Corporation and located on a Proterozoic gold belt in the south west of Ghana, indicated that the cost of production must be reduced in order to viably continue the mining operations. For this research, the Ahafo South Mine Site was used as a case study. A site visit of 90 days provided insight in where the efficiency of productivity could possible be improved. During this visit, historical production- and financial data [2014-2016] were gathered from a diverse group of engineers on site. Several audits were conducted to form a solid hypothesis with regards to the optimization of rock fragmentation. The hypothesis of this research states that improved rock fragmentation will result in a reduction of operational costs and delays along with an increase in crusher- and mill throughput.

This case study was used to investigate the effect of a varying fragmentation on shovel loading time and crusher- and mill performance. The financial impact of a potential blast pattern change was also investigated. After a statistical analysis of the available data on post-blast fragmentation, it was observed that the desired run of mine (ROM) P80 target of 350 mm is rarely met. It was concluded that the ”Kuz-Ram” model used to predict the fragment size distribution is incorrectly applied, which resulted in a planned blast design that produces a coarse fragmentation with an excessive presence of boulders. This is referred to as ”bad fragmentation” and proved to contribute significantly to redundant wear-and-tear of mining equipment, delays at the shovel loading operations and the primary crushing station. A correlation between fragmentation and loading time was found after a statistical analysis on the daily average loading time of three Liebherr 9400 shovels. It was concluded that the shovels are only able to produce at the desired rate of 2.4 minutes per truck load when the fragmentation of the ROM meets the P80 target. The Six Sigma principle Define, Measure, Analyse, Improve, Control (DMAIC) was applied to define an accepted interval range of shovel loading time variation (2.4 m. $\pm$ 20 s.). This so called target interval was generally not achieved by the shovels. All three shovels show an increase in average loading time during period where the ROM fragmentation was coarser.

Data generated by a VisioRock^{TM} camera showed, in combination with the throughput of the mills, that an appropriate fragmentation is crucial for an efficient milling process. A detailed analysis of the available data, categorized in ”periods of high interest”, demonstrated that the power consumption of the mills significantly increased when the feed consisted of relatively coarse fragments. It was observed that the post-crushed fragmentation was more coarse when a high fraction of the feed originated directly from the pit. This observation proved that the primary crusher is not able to eliminate all boulder related issues prior to the crushing operations as a result of inadequately planned blasts. Due to inaccurate or unreliable data on mill feed, it was concluded that a full mine to mill survey is required to obtain data needed for an accurate optimization of mill performance.

Newmont Ghana Gold Limited (NGGL) stated that at least 2.3M US$ has been saved on a yearly basis since 2015, as a result of the reduction of explosives used through a blast pattern widening. The cost impact analysis showed that it is uneconomical to save costs on explosives by widening the blast pattern, due to the potential downstream effects when the fragment size distribution is affected. The financial data was inconsistent and it is therefore recommended to conduct a detailed analysis to provide insight in the actual overall (financial) benefits of a blast pattern optimization. It is recommended to investigate both ”double-benching” and the purchase of a continuous surveying camera system. Another recommendation is to narrow the blast pattern down to 3.5 m. by 4 m. so that fragmentation related issues are avoided which are currently to be expected for the continuing production in the Subika- and Awonsu Pit.

K.T. van der Waal
Delft, December 2017

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Introduction

1.1. An Introduction to the Ahafo Gold Mine Case

The excavation of ore- and waste material in an open pit mining environment is usually done by digging, ripping or blasting, depending on the characteristics of the material. There are several operational factors that affect the productivity for each of these excavation methods. Diggability is a common issue in cases where rock is not properly blasted, since the digging or loading operations are designed for a specific range and distribution of material sizes which is commonly referred to as fragmentation. There should be a compromise between the amount of explosives used for blasting and the accepted range of fragment sizes of the material, since the amount of explosive used contributes significantly to the cost of production. The size range of the blasted material determines a substantial percentage of the downstream production costs. The Ahafo Gold Mine Site (Fig. 1.1) is used as a case study to gain insight in this matter.

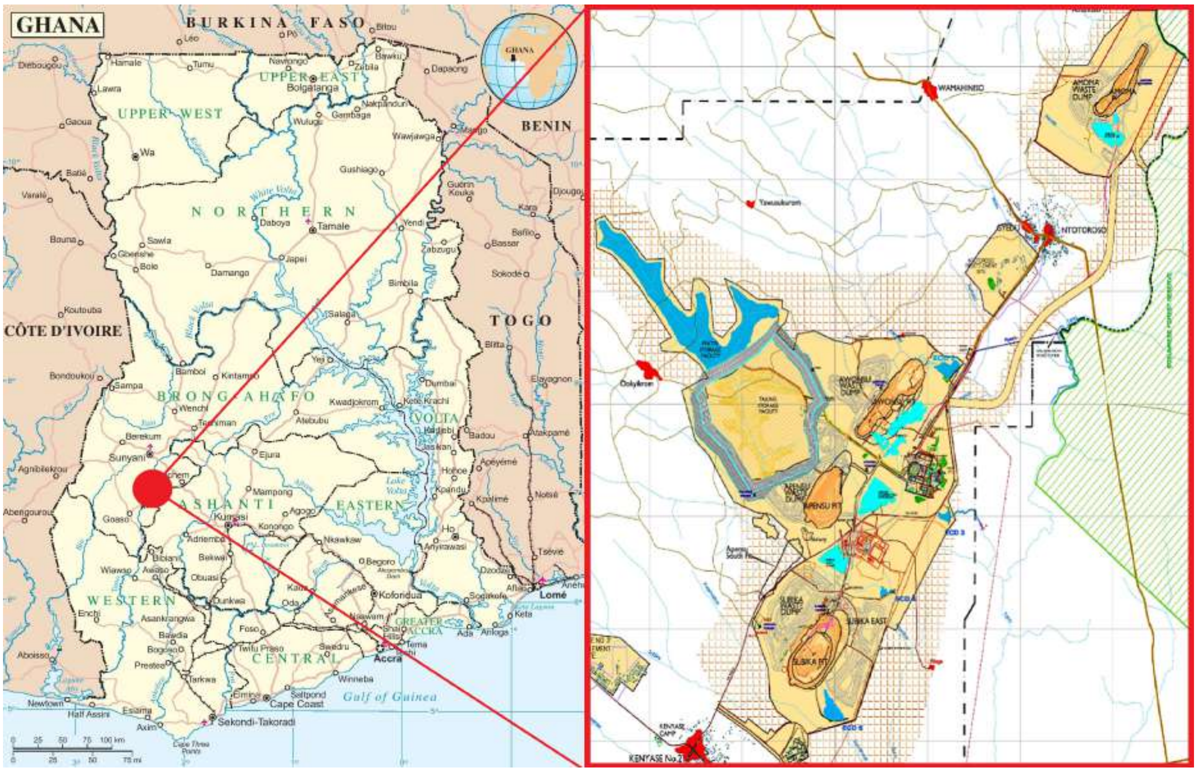


Figure 1.1: Location of the Ahafo Mine site (left) and the Layout of Ahafo South (right)

1.2. The Ahafo Gold Mine site

Newmont's fully owned Ahafo Gold Mine is located approximately 300 kilometres North-West of Accra, the capital city of Ghana, in the Brong Ahafo region (Fig. 1.1, left). The Ahafo Mining Lease, owned by Newmont Ghana Gold Limited (NGGL), consists of two primary ore zones; Ahafo South and Ahafo North. Commercial production began in 2006 at Ahafo South and this ore zone currently produces 350,000 ounces of gold per year, where Ahafo North is currently in the phase of exploration. Four pits have been developed at Ahafo South over the years named; Subika, Apensu, Awonsu and Amoma (Figure 1.1, right). The latter three lie in the same deposit, which strikes from South-West to North-East. Subika is the biggest pit and lies within a parallel deposit. Due to a lasting moderate gold price, the necessity of operational cost reduction became clear. The initial goal of this thesis (Appendix A) was to *"Assess the possibilities for mine optimization, productivity improvement and cost reduction in the Ahafo Gold Mine (Ghana) in order to maximize the success of the Ahafo project".*

1.2.1. Geology of the Ahafo South Mine Site

The Ahafo consession is located in the south west of Ghana, within the "Sefwi Gold Belt". This area represents one of the most significant Proterozoic gold belts in the world [1]. The geology in this area is dominated by the early Proterozoic Birimian Supergroup, which consists of both sedimentary and volcanic rock. Various granitoid intrusions are also present. This supergroup is characterized by mafic volcanic belts that strike north east, which are separated from intervening sedimentary basins by major faults [16]. The gold mineralization is hosted by a shear zone associated with granetoid intrusions, where hydrothermal fluids circulated into these zones during metamorphism phases. These fluids generally originate from magmatic intrusions. The mineralization is associated with major north east striking graphitic, chloritic and serictic fault zones varying between five to forty meters. Alterations such as silica, albite, carbonate and sulphides are commonly present. The mined out Apensu pit had a total of 25,3 Mt of ore with an average grade of 3.0 gram gold per tonne. The Awonsu pit (currently not in operation) is estimated at a total of 44,8 Mt of ore at an average grade of 1.38 gram gold per tonne. The Amoma pit will be mined out by the end of 2017 and has by that time produced 13 Mt of gold ore at 1.45 gram per tonne. The Subika pit has an estimated average gold grade of 2.2 gram per tonne with a total estimated 76.3 Mt of ore (pers.com; 03-2017).

1.2.2. The Impact of the Gold Price

Fig. 1.2 shows the variation of the gold price. The years 2011 and 2012 were exceptional good years for gold companies, however the gold price descended during the successive years. Several economically operational decisions were made by NGGL at the time when it was generally thought that the gold price would keep going up, resulting currently in a challenging time where all possible cost reductions have to be investigated.

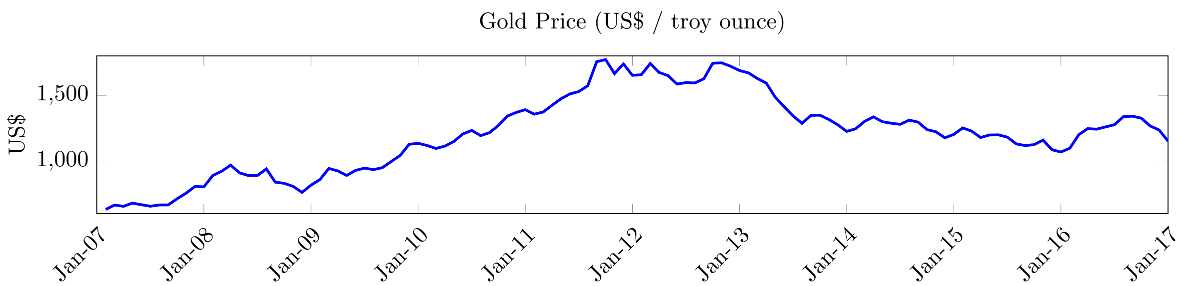


Figure 1.2: Gold Price Variation [13] Throughout the Ahafo South operational Years

Currently the Ahafo South management is cautiously tracking the gold price since it is not economical at this market price to proceed to the next phases of the Subika and Awonsu pit, which means that the proceedings have been put to a halt. Once the gold price increases to a point where the costs per produced ounce of gold are outweighed by the revenue. The development of the last phases of these pits will commence. Until that time, Ahafo South will depend on the Subika underground project. The underground mining activities are however not considered for this thesis.

1.2.3. Site Visit at Ahafo South

During the site visit (7 March 2017- 30 May 2017) an extensive training programme (Appendix B) was followed in order to get a holistic understanding of the Ahafo South Mine site. This training was used, in combination with several audits and interviews with a variety of employees and contractors, to decide on a thesis topic. Fig. 1.3 shows two pictures that were taken during the site visit. Many employees were approached to discuss the efficiency of the Ahafo Mine. Fig. 1.3a captures one of the blasting crews where Fig. 1.3b was taken in the view point that looks over the Subika pit.

(a) (b)

Figure 1.3: Group Picture During a Run Along with a Blasting Crew (a) and Discussion with a Blast Supervisor (b)

In addition to spending time on site, a significant part of the time was used to get to know the community. It was assumed that familiarizing with the country and culture of the workers would significantly contribute to get an understanding of the operational procedures. Fig. 1.4 shows two pictures that demonstrate a contrast between the activities that were undertaken during the visit. Fig. 1.4a shows a pose in front of an explosive carrying vehicle in the morning, where Fig. 1.4b displays an afternoon activity where a local school of the community was visited.

(a) (b)

Figure 1.4: A Picture of a Vehicle used to Transport Explosives (a) and a Group Picture with some Children of the Local Community (b)

A ”Lean Six Sigma” course was followed on site which helped to develop and define a project that would comply with these requirements. The basic deliverables that go along with the start of a Six Sigma project are attached in the appendices C to G.

1.3. Problem Statement

Currently, the Ahafo Gold mining operations are experiencing difficulties in meeting production targets. It was stated (pers.com; 03-2017) by the primary mine advisor that significant production delays have been occurring over the past year as a result of poorly planned blasts, resulting in an excessive presence of large boulders, which is referred to as ”bad fragmentation”. Many boulders are said to be present in the muck since the mining department of Ahafo South had decided to widen the drill & blast pattern in the fourth quarter of 2015 in order to save on production costs. These boulders cannot be properly loaded or hauled, meaning production targets are hardly met. The other issue is that boulders cannot be processed by the main crusher, meaning an available rock breaker is a necessity. The presence of boulder is however so big, that boulders are stored on special ”boulder stockpiles” (Fig. 1.5b), resulting in gold being stored away. It is estimated by the Ahafo South mining department that the boulder stockpile increased with 26,000 tonnes during 2016. The maintenance manager stated (pers.com; 04-2017) that his team has been experiencing excessive equipment damage (Fig. 1.5a), due to negligence of shovel operators with regard to boulders in the muck. Boulders always contribute to a disproportionate wear and tear on the mining equipment and it is therefore essential that the shovels are delicately operated.

(a) (b)

Figure 1.5: Boulder Incident (March 2017) with Haul Truck (a) and me with a Fraction of the 2016 Boulder Stockpile (b)

Audits were conducted with shovel and truck operators in order to confirm and compare the statements. It can be concluded from these audits that the current fragmentation related conditions are far from ideal. Several haul truck operators mentioned (pers.com; 04-2017) that the impact of boulders hitting the body occasionally results in back and neck pains. It should be noted that this can also be the result of careless operators, but that a better fragmentation would reduce the amount of these incidents drastically due to a ”smooth” muck flow onto the body. shovel operators indicated (pers.com; 04-2017) that the excessive presence of boulders makes it unrealistic to achieve the loading target of 2.4 minutes because of inefficient loading or hang-ups when opening the bucket. This target was suggested by the primary operator trainer (pers.com; 04-2017). Both the shovel and haul truck operators stated that a wide and irregular distribution of fragment sizes obstructs them from improving their equipment operating skills. Each particular size distribution requires a specific loading and hauling strategy in order to maximize the moved tonnes per hour. Operators will adapt faster to new circumstances once their experience increases, however they need to start over each time the mining department decides on implementing new strategies. A thesis topic was defined around this fragmentation related problem (Section 1.4). The search for a topic related to cost reduction and productivity improvement was included in the research. After a month of conducting audits and interviews, the topic ”Fragmentation Optimization” was chosen with the full support of the Ahafo South management (pers.com; 04-2017).

1.4. Thesis Goal & Objectives

The goal, research questions, hypothesis and objectives of the thesis are summarized below:

- **Goal**
  - ***Reduce the cost of production of Newmont's Ahafo mining operations by improving SAG & Ball mill throughput and reducing shovel loading time through blast pattern and rock fragmentation optimization.***
- **Hypothesis**
  - *An improved rock fragmentation with less variation will reduce shovel loading delays, eliminate secondary breaking, crusher delays and improve SAG&Ball mill throughput, resulting in cost reduction of Newmont's Ahafo mining operations.*

In order to test this hypothesis, three research questions were defined:

- ***1. How does rock fragmentation relate to the variation in shovel loading time?***
- ***2. How does rock fragmentation relate to crusher and mill throughput?***
- ***3. What is the financial impact of blast pattern change?***

The research questions were answered through respectively completing the following objectives:

- **Objective 1 - Analyse and Improve Shovel Loading Time:**
  1. *Reduce the variation of shovel loading time by finding- and eliminating root causes through a systematic statistical analysis of daily average shovel loading times and moved tonnes per classified ore block.*
  2. *Link rock fragmentation variation to shovel loading time- and moved tonnage variation. The impact of fragmentation distribution on shovel loading efficiency will be demonstrated.*
- **Objective 2 - Analyse and Improve Crusher and SAG&Ball Mill Throughput:**
  1. *Analyse the variation in- and relation between crusher- and mill feed, power consumption and throughput.*
  2. *Recommend a model that predicts power usage- and throughput of both the crusher and the SAG&Ball mill based on historical data.*
- **Objective 3 - Investigate the Cost Impact of Blast Pattern and Rock Fragmentation Optimization:**
  1. *Analyse the current cost of the mine to mill process flow on monthly basis.*
  2. *Recommend an optimal blast pattern design based on historical production figures.*

1.4.1. Assumptions

Several assumptions have been made in order to achieve the objectives as defined above:

- *The Ahafo Mining- and Processing offices are able to provide historical high quality/density data to conduct a statistical analysis on productivity performances.*
- *The rock parameters and ratings used to predict fragmentation in the Kuz-Ram model reflect the actual rock properties.*
- *By focussing only on shovel and fragmentation KPI's, other factors that might have an impact on the mining productivity are filtered out.*
- *The production efficiency of all shifts and crews is equal.*
- *Besides inflation (US$) and change in explosive products, no significant price changes have taken place in other productions steps between 2014 and 2016.*

1.4.2. Scope

Historical performance-, production- and financial data [01-01-2014 - 31-12-2016] formed the basis of the research. Some data from 2013 was also available, which helped to recognize and verify possible (historical) trends. Daily performance and production averages were used to analyse variation as a result of mining muck blasted by different blast pattern sizes. Only muck that has been fed directly to the crusher was analysed to improve the throughput model, in order avoid introducing uncertainties with regards to stockpile characteristics. Monthly cost figures were used to investigate the variation in cost per mined ton of ore. An overview of the obtained data can be found below:

- **Pattern Characteristics - Pattern Size, Powder Factor, Fragmentation Size Distribution**
- **Shovel Feed - Block(s) per day**
- **Shovel Status - Ready/Standby/Delay/Maintenance**
- **Shovel Loading Time/Tonnage - Hourly average per day**
- **Crusher Feed - Daily Blend by Pit**
- **Crusher Throughput & Delays - Size Distribution of Crushed Material per Day**
- **Crusher Power Consumption**
- **SAG & Ball Mill Throughput - Dry Tonnes per Day**
- **SAG & Ball Mill Power Consumption**
- **Cost of Operation - Drilling & Blasting/Loading & Hauling/Crusher & SAG- & Ball Mill Costs on Monthly Basis**

Table 1.1 summarizes the scope of the thesis in key words. In order to be of relevance for future production, all data related to retired equipment and mined out pits are out of scope. The ”Out of Scope” column also shows several factors that might affect productivity (costs). These are however assumed to be irrelevant because such factors are either unfit for change or pretended to be insignificant to avoid scope creep such as; Truck availability and Blast sequence analysis.

Table 1.1: Research Scope

Within Scope	**Out of Scope**
Subika/Awonsu/Amoma pit data	Underground Mining
Fragmentation/Blast pattern analysis	Apensu pit data
Shovel 6,7,8 performance analysis	Saprolite production data
Loading time	Truck availability
Loading volume	Stockpile handling
Crusher/mill performance analysis	Blast sequence analysis
Power usage by blend	Explosive selection
Throughput by blend	Fortis Advantage
Mill feed analysis by VisioRock	Geotechnical parameter selection
Optimal fragmentation/blast pattern selection	Pit design
By shovel performance	Tire life impact analyses
By crusher/mill performance	Chemical process analyses
Kuznetsov-Rosin-Rammler equation	Cost Impact Analysis
Cost impact analysis	Drilling cost
Explosive cost	Maintenance cost
Crusher/Mill cost	
Secondary breaking cost	

1.4.3. Methodology

The Lean Six Sigma Methodology [14] was applied to improve productivity performance. Lean Six Sigma is a successful worldwide acknowledged combination of Lean Manufacturing; a management philosophy based on the Toyota Production System, and Six Sigma; A combination of techniques and tools to minimize variability in manufacturing and business processes introduced by Motorola. Define, Measure, Analyse, Improve, Control (DMAIC) is a Six Sigma methodology that is used to improve the current capabilities of existing processes. DMAIC stands for [14]:

- **Define**
  - *The project is defined during the "Define" phase. The project's purpose and scope are defined by setting thesis objectives. Background information of the mine to mill processes are collected by interviews and audits, after which the needs and requirements for the research are defined.*
- **Measure**
  - *The current situation is investigated and historical data and information is put together. Baseline data is gathered in order to measure how the current mine to mill processes meet their requirements. The scope will be more focused during the "Measure" phase.*
- **Analyse**
  - *The purpose of the "Analyse" phase is to identify root causes for the problem statement as defined in the first phase of the project. These root causes must be confirmed with data, after which the hypotheses can be tested and confirmed.*
- **Improve**
  - *When the hypotheses are confirmed, performance- and cost models can be designed. Solutions to root cause problems shall be implemented in order to improve the mine to mill processes. The improved designs will be compared to the current situation to provide a "Before" and "After" data analysis.*
- **Control**
  - *After the current situation has been improved, it is important to maintain the processes by standardizing these improvements. This will be done by providing a clear overview of the research results, learnings and recommendations to Newmont.*

Note: In order to fulfil the academic report writing requirements set by the graduating universities, it was decided to divide the report in conventional chapters, as discussed on the next page. The project deliverables relevant to the DMAIC methodology can be found in the appendices.

1.4.4. Thesis Outline

A short summary and description of the content of this thesis report:

Introduction	The first section of this report introduces the background of the project and the necessity for change in production operations at Newmont's Ahafo Mine site. The project objectives and research methodology were described. A brief introduction in rock fragmentation is provided.
Data Acquisition	This section of the report describes how data was gathered, the inconsistencies between data, data that was desired but unavailable and data reliability.
Data Analysis	When all data was acquired, statistical analyses were done to determine root causes to the thesis problem statement. This section provides an overview of the analyses methods and results.
Productivity Improvement & Cost Reduction	After the data was analysed, possibilities for productivity improvement were assessed by looking at possible cost reduction strategies.
Discussion	The results of the research were discussed and the feasibility of the corresponding improvement possibilities is considered.
Conclusion & Recommendation	Finally, several recommendations were presented based on the discussion and conclusion of the research. It should be noted that these recommendation only apply within the scope of the thesis.

2

The Ahafo South Mine Site

2.1. The Ahafo South Mining Operations

The Ahafo South Mining operations move around 45 million tonnes of rock every year. Over the last 4 years, roughly a third of the annually total moved tonnage was ore (15 Mty), leaving around two thirds to be waste (30 Mty) (stripping ratio of 3:1). The stripping ratio for the life of mine is estimated to be 6.84:1, meaning that over the last four years, a relatively high percentage of mined material consisted of ore. As of early 2017, two of the four pits are in production; Subika and Amoma. Apensu is mined out and Awonsu is planned to get back into production in 2019. Amoma will be mined out by the end of 2017. All of the pits are planned to be mined out by the end of 2029, leaving Subika and Awonsu to be of interest for this research.

Figure 2.1: The Subika Pit (March 2017)

The geological properties of Amoma, Apensu and Awonsu are nearly identical, since these three pits lie in the same deposit. The UCS of this deposit varies between 90 and 150 MPa. Subika lies in another deposit with slightly different geological characteristics, with a UCS that varies between 100 and 150 MPa. Metso states [5] that the slight differences in geological properties don't correlate to mill performance and that fragmentation is the driving factor in the efficiency of the processing plant. This means that any data on fragmentation, irrespective of which of the four pits this data originates, can be used to analyse the effect of fragmentation on overall production and future recommendations. The target set [5] for fragmentation, is that 80% of the blasted rock should pass a 350 mm sieve. This so called P80 target should be met regardless of rock-type or classification (ore/waste).

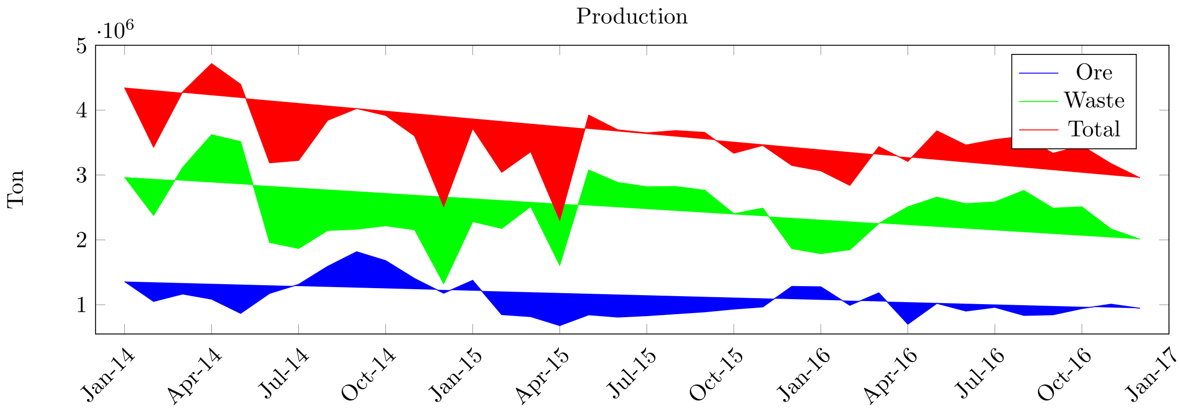


Figure 2.2: Monthly Actual Production

It has been observed that production is occasionally delayed as a result of muck shortage. This occurs when the drill (and blast) team are not able to meet their daily targets, mostly because of the unavailability of drilling rigs. Weekly production performance meetings that where attended between March and May 2017 pointed out that muck shortage is the primary cause for production delays. The primary mine advisor stated (pers.com; 04-2017) that "*No matter which mine, there should never be a shortage of drilling equipment. Drilling is the first production step in any conventional hard rock mine and could therefore delay the whole operation.*" It is thus assumed that drilling rig availability is irrelevant, and that Ahafo South should invest in new rigs if necessary.

Figure 2.2 shows a visualization of the monthly actual production trends. The production of ore has slightly decreased over the last 3 years due to a moderate gold price, where the waste production dropped as a result of mine planning. The gold production has however been kept constant by using several stockpiles, where high grade ores have been stored as a backup. Ore with a high gold grade can be processed economically at a lower gold price.

2.2. The Ahafo South Processing Operations

The Ahafo South processing operations begin with the primary crushers and end with the production of gold and tailings. The ore product of the mining operations is either stored in stockpiles or fed directly to one of the primary crushers. Saprolite ore is fed to the oxide sizer, where the primary ore is fed to the gyratory crusher. The gyratory crusher can handle muck with fragments up to 1000 mm if fed in a favourable position. However, in most cases when the feed contains oversized material, a so called ”hang-up” will occur, where a boulder blocks the flow of material into the crusher. It is therefore essential that the crusher feed meets the P80 target, so that certain delays are avoided. A rock-breaker is usually in stand-by to assist in case of a hang-up. The P80 target after crushing is 140 mm.

Once the material has been crushed, it is transported to the ”processing stockpile”, which serves as a buffer in case of an unplanned crusher breakdown. This stockpile is centred above a feeder system, where three feeders regulate the flow towards the conveyor belt. This belt directs the ore, both oxide and primary ore, towards the ”SAG Mill”. ”SAG” is an acronym for Semi-Autogenous Grinding, meaning that the ore grinds itself. Steel balls are continuously added to act as grinding media in order to improve the grinding capacity of the SAG mill. The outflow of the SAG mill is sieved by a discharge screen, where the passed material continues to the ”Ball Mill”. This screen has a sieve size of 12 mm, the oversized material is fed back into a pebble crusher, which feeds it discharge back into the SAG mill. The Ball mill also uses grinding media to grind the ore and feeds its discharge into cyclones, the overflow of these cyclones passes a 106 μm sieve. The Ball mill is the last step in the resizing process of the ore, after which the gold is recovered through cyanide leaching.

Fig. 2.3 provides two pictures of the Ahafo South processing plant, where Fig. 2.3a shows the SAG- and Ball mill closely together just right of the middle and the acid leaching cyclones on the left of the picture. Fig. 2.3b provides an aerial impression of the entire processing plant, with the mined out Apensu pit in the far back, just in front of the tailings lake.

(a) (b)

Figure 2.3: The SAG- and Ball mill (a) and an Aerial of the Processing Plant & Camp (b) [pers.com; 05-2017]

Fig. 2.4 provides a schematic overview of all processing steps. It is evident that the processing plant executes most of the resizing processes, where the SAG and Ball mill together contribute to roughly 30% of the overall production costs (pers.com; 04-2017). The SAG and Ball mill account for over 50% of the overall resizing costs, when only the resizing/liberation activities are considered (Drilling & Blasting, Crushing, Milling). It is essential that the processing- and mining department work closely together and that they make sure the fragmentation targets are met for the sake of productivity improvement and cost reduction. Such a cooperation should be continuous and automated through a constant and regular system where data is exchanged and discussed.

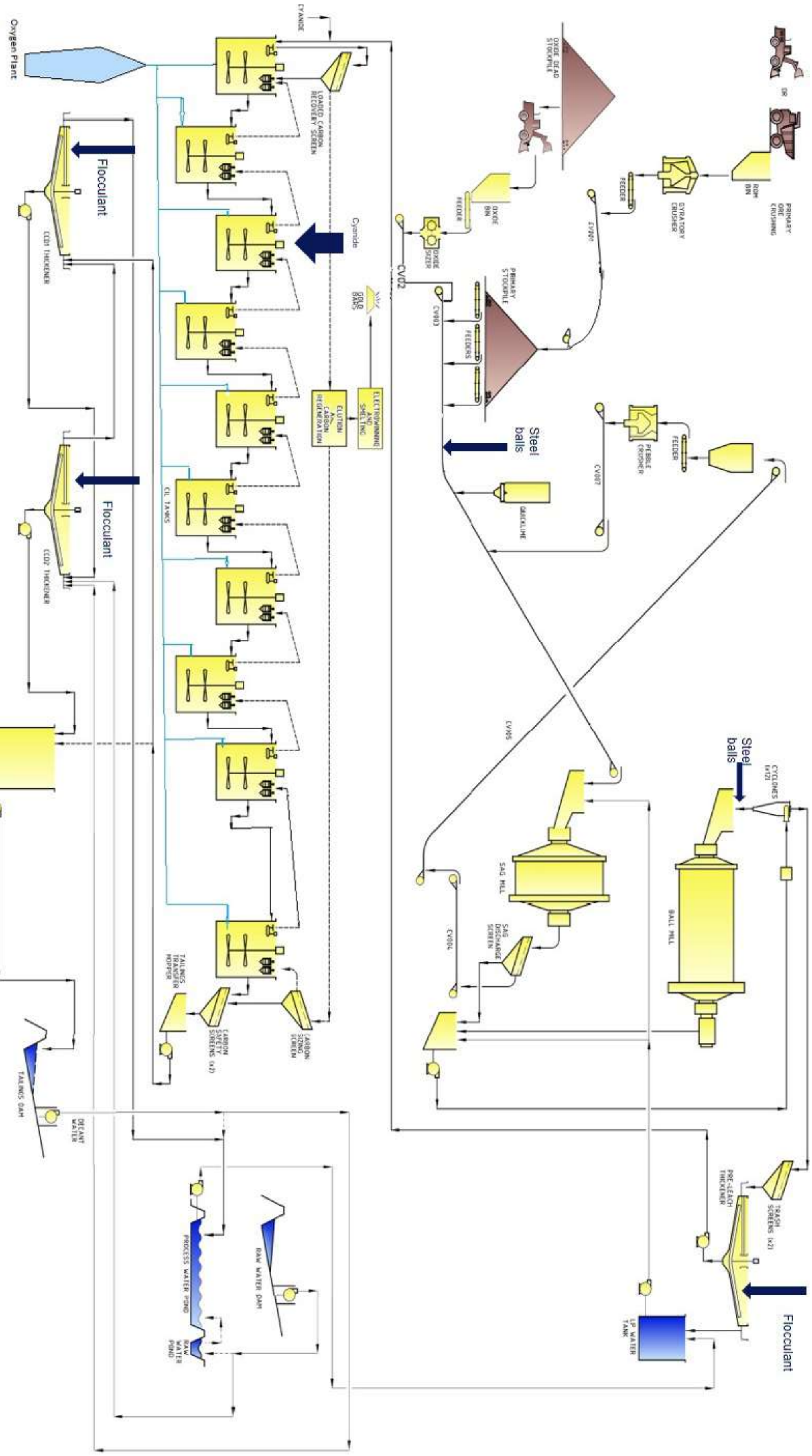


Figure 2.4: A Schematic View of the Process Flow in the Plant

2.3. An Introduction to Rock Fragmentation

Rock (or blast) fragmentation is a technical term used in the mining industry to describe the effect of blasting operations on the initial rock [4]. It therefore characterizes the broken ore or rock by blasting, called 'muck'. Rock fragmentation is determined by several factors, such as; drill design, blasting sequence, explosives used and rock conditions. Relevant rock conditions include the rock structure, tensile strength, Young's modulus and rock impedance (a result of rock density and P-wave velocity). The first steps in the (hard) rock breaking and separation processes are drilling and blasting. Drilling and blasting is the most cost effective method to break large volumes of rock, but only when the production chain and rock conditions are well understood. This makes it possible to efficiently plan the most cost effective way to break rock into the desired fragmentation size, by optimizing the balance between drill-, blast-, crusher- and mill efforts. Rock fragmentation has an enormous economic impact on the entire mining and processing operations of any mine site, such as loading, transportation, crushing and milling. Therefore, the optimization of fragmentation should always consider the effect on all downstream processes. Fragmentation optimization should be site specific and flexible in order to deal with changes in rock and market conditions. Several models based on blast design and rock properties have been proposed to predict rock fragmentation after blasting. One of these models is the "Kuz-Ram fragmentation model", including several variations on the original model.

2.3.1. The Importance of Rock Fragmentation

Rock fragmentation is an important key performance indicator (KPI), since an unfavourable fragmentation negatively affects the production as a result of delays in the loading and hauling cycle. This basically means that it has a big influence on the production cost per unit, which is gold (oz.) in the case of the Ahafo South Mining operations. Therefore, rock fragmentation management and control is essential to any successful mining operation. There are several methods to monitor and control rock fragmentation, divided between passive or interactive methods. Fragmentation models such as the Kuz-Ram fragmentation model [7] are validated and calibrated by comparing the predicted fragmentation with actual "post-blast fragmentation" data from image processing monitoring systems, either passive or interactive [6]. Since rock fragmentation is that important to an efficient production, it is generally advised not to save money on rock fragmentation control systems. Sandvik suggests [10] that the following criteria should be met in order to avoid rock fragmentation related production issues:

- The shovel bucket fills with a single smooth pass
- The shovel remains stable during digging, without violent movements or rocking
- The muckpile flows during digging
- Haul trucks dump at the crusher without delay
- The throughput and power draw of the crusher is consistent
- Secondary breakage is not required on a regalar basis
- The desired product sizes are produced without waste

Throughout this report it will become clear whether or not these criteria are currently met. Another important aspect of rock fragmentation are the economic considerations that go with it. An unfavourable (coarse or badly distributed) rock fragmentation can be the result of two things; a badly planned blast pattern (e.g. due to an incomplete understanding of the geology) or a blast pattern that is too sparse. A sparse (or wide) blast pattern is cheaper to blast since less explosive material is required.

2.3.2. Current Rock Fragmentation Monitoring and Control at Ahafo South

The importance of rock fragmentation (control) has been discussed in section 2.3.1, which is why it is vital to understand the current measures that are taken to control rock fragmentation at Ahafo South. After an extensive research, including audits and daily meetings with miners, mining-, processing-, and maintenance engineers, an understanding of the current rock fragmentation control was developed. The gathered data was visualized and analysed as described in chapter 3 & 4.

The rock fragmentation is monitored through a passive method, using a rock fragmentation size analysis Software called "Split-Desktop". After each blast, three to five pictures are made with a conventional digital camera, using two basketballs as a reference size. These pictures are loaded into the software, after which each image is calibrated to the reference size. When this is done, the software calculates the following parameters:

- Passing Percentage per Sieve Size, according to the Schumann or Rosin-Rammler equation
- 20 Percentage Passing Size
- 50 Percentage Passing Size
- 80 Percentage Passing Size
- Top size [99.95% Passing Size]
- Fines Cutoff Size (mm) according to the Schumann or Rosin-Rammler equation

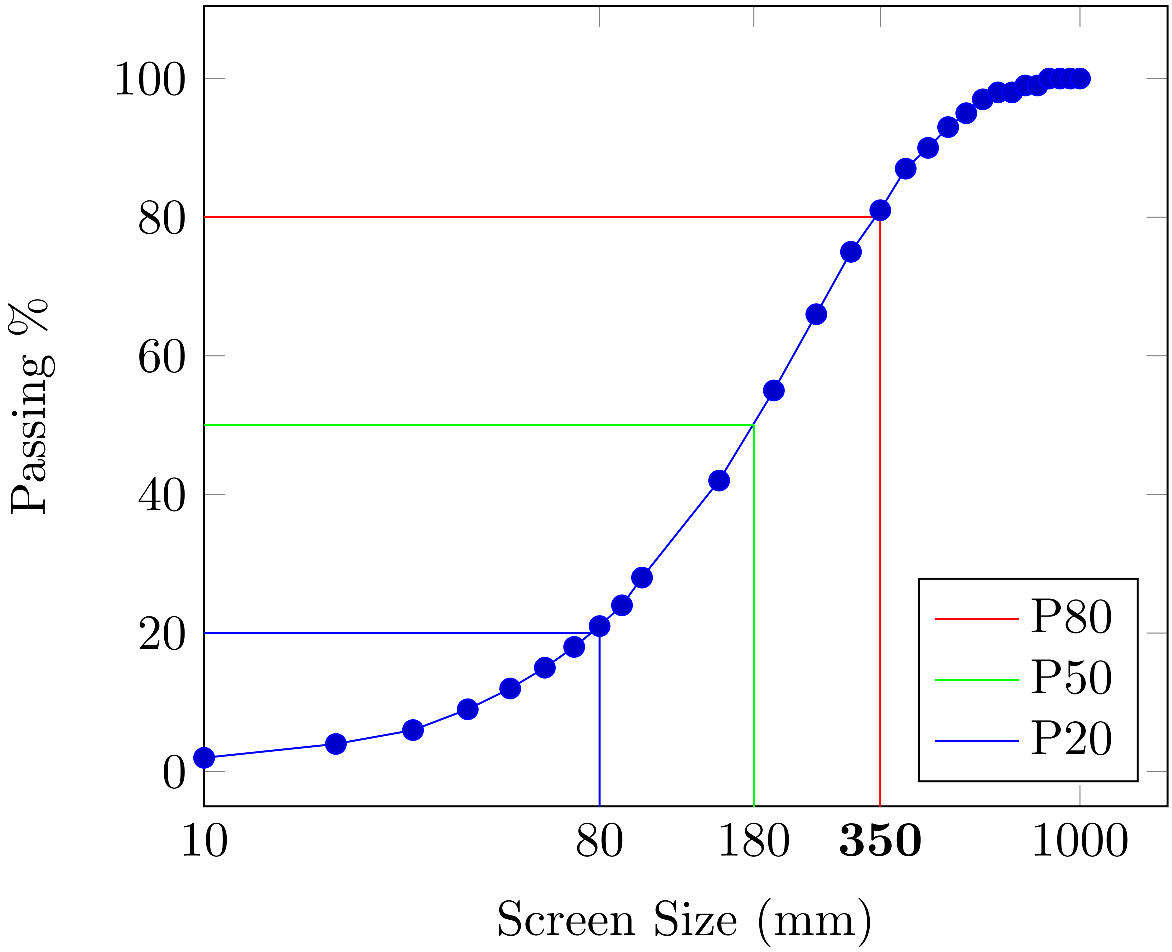


Figure 2.5: An example of a Fragmentation Distribution Curve with Corresponding 80%, 50% and 20% Passing Sizes

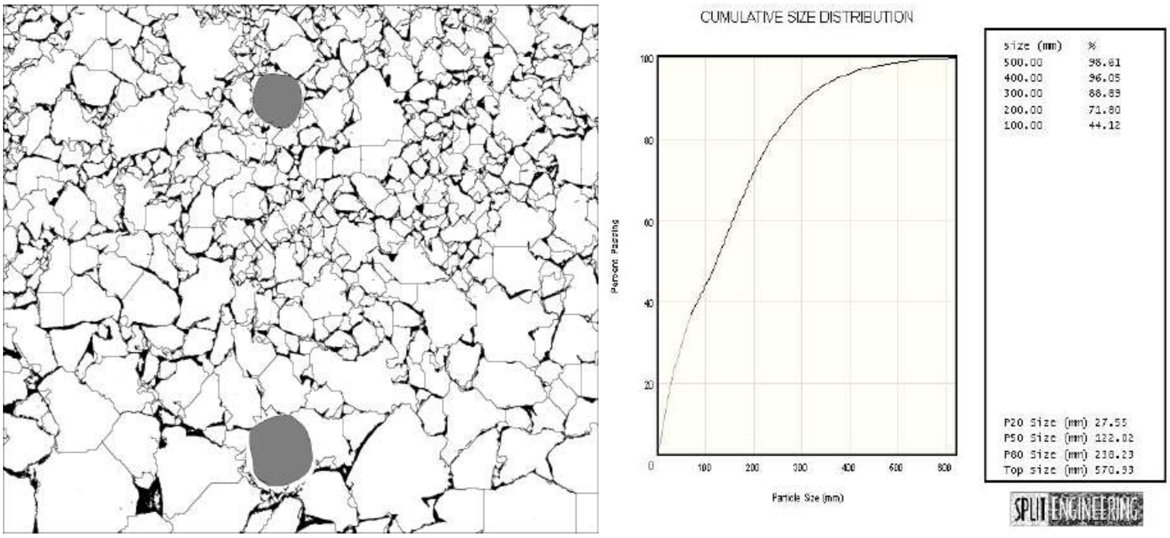
Fig. 2.5 provides an example of the plotted results. The Y-axis shows the passing percentage of the material, with the corresponding maximal fragment size, or sieve size, on the X-axis. Such curves are unique for each blast, since the calculations are based on the pictures taken after the blast. It is therefore essential that the pictures capture a representative part of the muck pile.

One can clearly see the difference in effort taken to make a picture that captures a representative presentation of the fragmentation. The picture made in September 2013 (Fig. 2.6a), clearly shows the full size of the reference balls, including a bright fragmentation sample. The last picture made in September 2016 (Fig. 2.6b), does not display the reference balls properly, is not focussed and has a low brightness that may have impact on the fragmentation analysis.

(a) (b)

Figure 2.6: The First (a) (September 2013) and Last (b) (September 2016) Fragmentation Pictures Made at Ahafo South

Figure 2.7 shows the results of the Split-Desktop software. The reference balls are shown as grey objects and used to estimate the size of each fragment. The picture is analysed by an algorithm that draws lines on the edges of each fragment, after which the software calculates the corresponding distribution curve. This is shown on the right (Fig. 2.7b).



(a) (b)

Figure 2.7: The visual analysis of the fragments (a), The cumulative size distribution after visual analysis (b)

Such a distribution curve was obtained for 583 blasts that were executed between January 2014 and September 2016. The data was manually separated by pit, shovel and date before it could be analysed. All distribution curves were checked and anomalous results were compared with the corresponding original pictures. After this selection, the analysis could commence, as described in section 5.4.

2.3.3. Overview of Ore Resizing Processes

A brief overview of the complete resizing process is delineated in Fig. 2.8, starting with the design of the drill & blast pattern and ending at the outflow of the ball mill, which is the last step in resizing the ore. In order to optimize fragmentation, the ”Kuz-Ram” model [4] is applied (See Chapter 3.1 & 3.2). It is crucial that the rock properties are fully understood so that the model predicts a realistic outcome for the distribution of fragment sizes. Once this model is applied, a drilling pattern is designed based on the predicted fragmentation in combination with the planned explosive. When the drill holes are charged and blasted, shovels can start loading the muck into haul trucks. These trucks transport the material to either the primary crusher, a stockpile or a waste dump, based on the load.

The primary mine advisor stated (pers.com; 03-2017) that it is common for the primary crusher to be operated by the mining department, which is not the case at Ahafo South. Once the haul trucks dump their load at the primary crusher, it is up to the processing department sort the ore. This means that secondary breaking by drilling & blasting and feeding the gyratory crusher is managed by the processing department. It is not unusual for the mining- and processing department to act as two seperate operations, meaning they rarely work together. This results in the fact that the mining department does not see or handle its own product, the so called ”Run-of-Mine” or ROM, at Ahafo South. So when the ROM consists of badly fragmented rock, this is not directly noticed by the mining- but the processing department. This causes unnecessary delays in improving the fragmentation of the ROM.

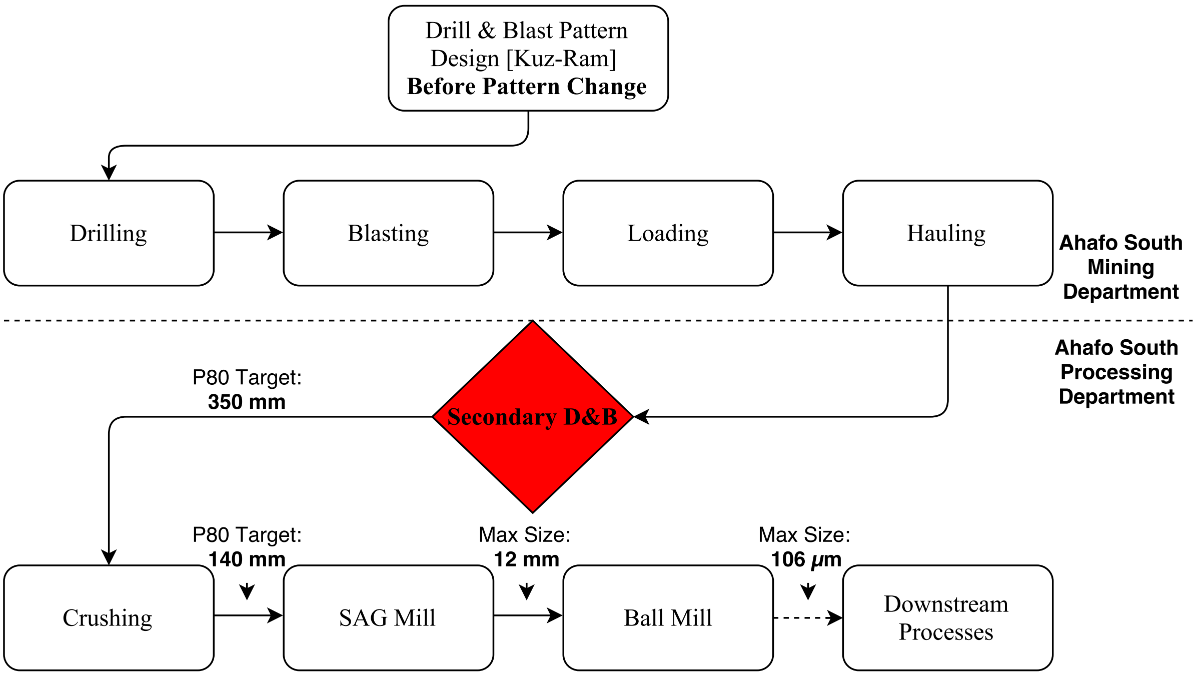


Figure 2.8: Overview of the Mining- and Processing Department Structure and Corresponding Resizing Targets at Ahafo South

Once the material has been crushed, it is should meet a P80 target of 140 mm (pers.com; 04-2017). Since a gyratory crusher works in 2 dimensions, long but thin rocks can fall through without being resized. This may results in undesirably big fragments in the processing stockpile, which feeds the mills after being mixed with water. The mills crush this wet feed with grinding media until the desired maximal size is obtained; 106 μm. When this particle size is achieved, the contact surface is fit for acid leaching and gold recovery.

Fig. 2.8 encompasses all (fragmentation related) downstream processes and points out how crucial (the avoidance of) secondary breaking is. When the mining department fails to deliver a ROM with the required size characteristics, a whole extra resizing step needs to be executed before it can be fed to the crusher, resulting in expenses that could be avoided.

2.4. Drill & Blast Operations at Ahafo South

Dril & Blast operations are the first steps of production in every conventional hard rock mine and it is crucial that all planning efforts and calculations are dealt with responsibly. Inaccuracies within a drill pattern will have a negative effect on the downstream transportation and processing activities, in terms of delays and excessive equipment wear-and-tear due to boulders. The drillers should inform the blasting engineer in case of any irregularity, such as ”redrills” or ”short holes”, since these defects negatively affect the fragmentation capacity of a blast. Drilling & blasting by pattern is called primary drill & blast. When necessary, secondary drill & blast is introduced, this should however be avoided as much as possible to avert unnecessary costs.

2.4.1. Primary Drill & Blast

The most efficient way to break in situ rock is by primary drilling & blasting. Fig. 2.9 [26] explains the drill and blast pattern parameters of a bench that is prepared to be blasted. At Ahafo South, a staggered drill & blast pattern is used in order to further maximize the efficiency of the blast.

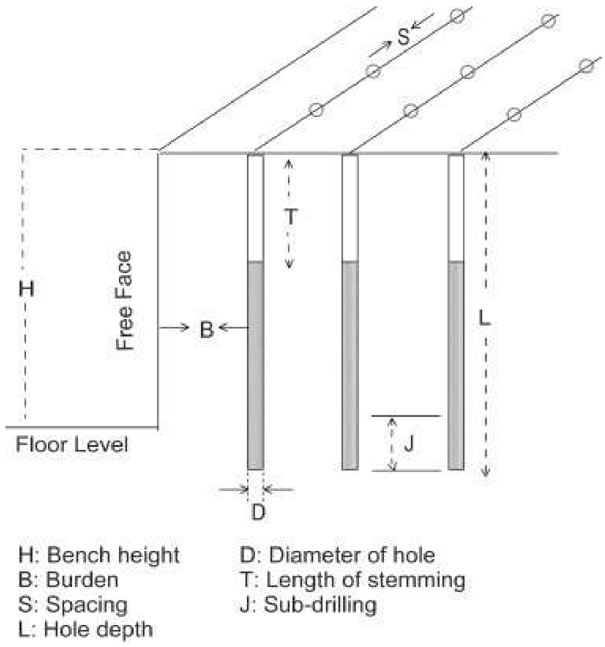


Figure 2.9: Drill and blast pattern parameters of a bench (Modified from [26])

In order to acquire the necessary data for this research, several field inspections were done. Audits were conducted with both drilling- and blasting engineers and operators, from which the following was concluded (pers.com; 04-2017):

- There is no data on borehole- deviation or redrills prior to 2015, since such measurement could only be done after the implementation of the dispatch system.
- From experience, the stemming height is the most important parameter that must be achieved. It regulates the energy of the blast.
- Variation in powder factor data is due to so called ”polygon change”, where parts of blasts are reassigned to other blasts, without reporting this.
- There is no data on drill hole depth variation, since it is assumed to be irrelevant for fragmentation. It however affects the pit floor.
- Boulders originate from the edges of the blasts. Small blasts therefore produce many boulders.
- All drill holes are drilled vertically, except pre-split holes (20° angle from the vertical)

2.4.2. Drill & Blast Patterns

The drill & blast patterns are designed to produce the desired fragmentation and to be as cheap as possible. The cost of explosives has a significant impact on the overall production cost which makes it essential to efficiently plan blasting patterns. The distance between the drill holes along the crest, or free face, is called the spacing, where the distance between the drill holes from the wall to the crest is called the burden (Fig. 2.9). Besides the spacing and burden which determine the amount of drill holes and therefore the explosive cost, no other parameters at Ahafo South changed since the beginning of production in 2006. Fig. 2.10 shows the burden and spacing of every drill & blast pattern during 2014-2016. 513 blasts data for Subika, 359 blasts data for Amoma.

The decision to widen the pattern during late 2015 is clearly visible. During the first half of 2016, patterns in Subika systematically changed between the "old" and "new" pattern.

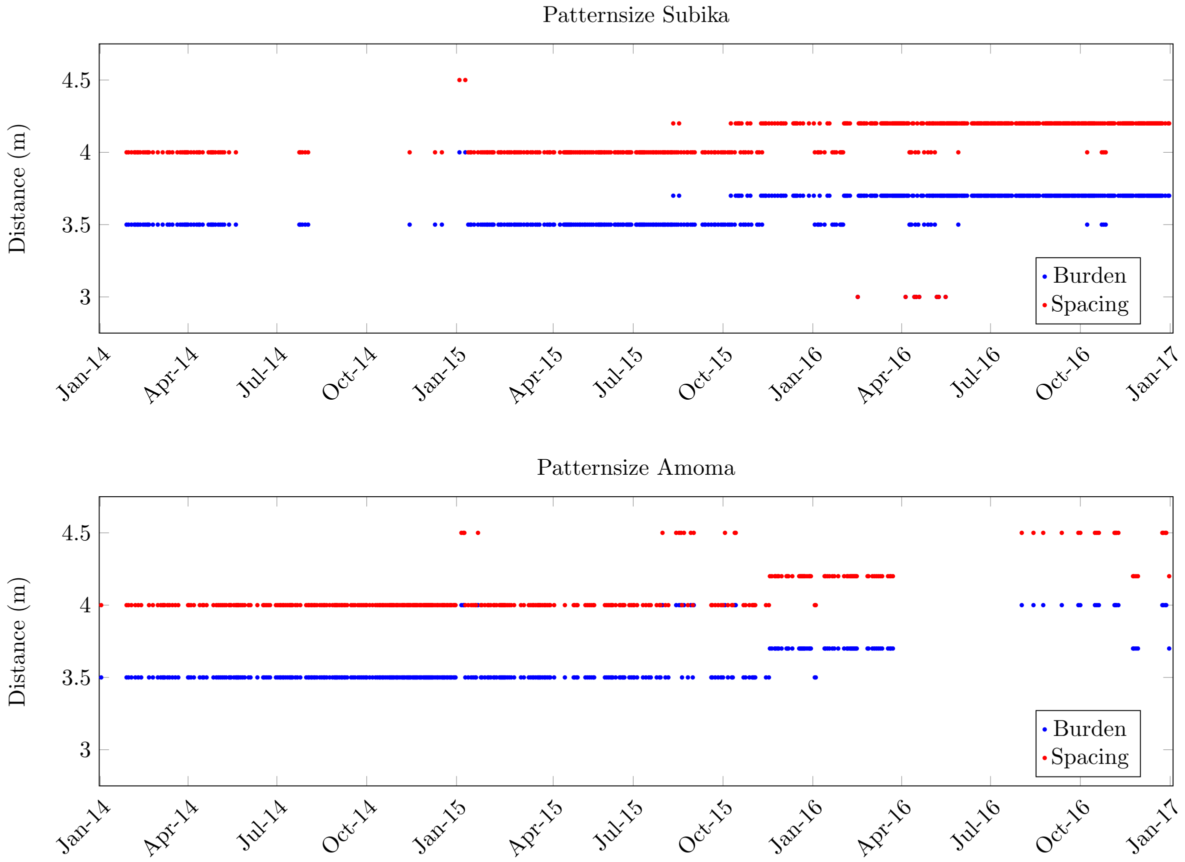


Figure 2.10: Blasting Pattern Sizes at Ahafo South

During the second half of 2016, an even wider pattern was drilled in Amoma, with a burden of 4- and a spacing of 4.5 meters. It is interesting to see that the 3.7- by 4.2 meters pattern is re-introduced by the end of 2016.

2.4.3. Drill & Blast Parameters

The drill and blast parameters of Ahafo South are summarized in Table 2.1. These parameters were chosen in 2012, after a period of severe irregularities with regards to rock fragmentation. This blast design provides, in combination with the explosive used (Fortis™ Advantage, provided by Orica Mining Services), a theoretical fragmentation that precisely meets the P80 target, according to Hamdani [11]. This design considers no human or mechanical errors, and it is therefore unrealistic to assume that the current drill & blast system produces the desired fragmentation.

Table 2.1: Drill & Blast Parameters Ahafo South

Parameter	Unit	Ahafo South Value
Burden	m	3.7 (*3.5**)
Spacing	m	4.2 (*4**)
Collar Deviation	m	>0.3 (*0**)
Diameter	mm	165
Charge Length	m	5.9
Stemming Height	m	3.3
Height of Bench	m	8
Sub-Drill	m	1.2
Rock Density	t/m^3	2.8
Weight of Explosive per hole	kg	145 * *values that are currently used for estimation purposes*

Fig. 2.11 shows a distribution curve of what is currently assumed to represent the fragmentation distribution at Ahafo South. This curve has not been updated since 2012 or adapted to changes in drill & blast patterns and explosives used. It also does not consider inaccuracies due to human or mechanical errors. The Kuz-Ram Model used by Ahafo South predicts that the P80 target of 350 mm is not met (78%). This model, however, considered an explosive with a RWS of 89. The model has been adjusted for the correct explosive type (Fortis™Advantage) with a RWS of 100 [24]. The adjusted model predicts that the P80 target is met (81%) when no errors are assumed.

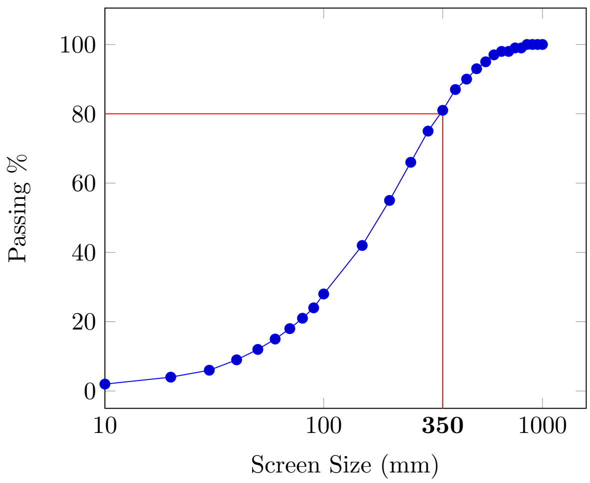


Figure 2.11: Distribution Curve that is assumed to reflect the Current Fragmentation Representation

2.4.4. Secondary Drill & Blast

Most primary drill & blast operations will however leave oversize boulders. As discussed, Ahafo South produces an excessive amount of boulders, which puts a lot of accountability with secondary drilling & blasting. The primary crusher is designed to meet the following criteria [22] regarding feed, or ROM, size:

Table 2.2: ROM Design Criteria for the Primary Crusher at Ahafo South

ROM Size (mm)	1,000	400	300	250	200	150	105	50	25	14	5	1
Cumulative Passing (%)	100	92.8	66.6	54.0	41.7	29.9	19.8	8.4	3.8	1.9	0.6	0.1

The P80 ROM size target of 350 mm deviates from the criteria shown in Table 2.2. Fig. 2.7a shows the primary crushing station, which contains a gyratory crusher that can theoretically handle fragments up to 1,000 mm. An experienced maintenance engineering company states [18] that crushers often break down or generate an undesired product as a result of some of the following actions;

- Neglecting maintenance
- Poor Housekeeping
- Fail to check for wear
- Shock loading with feed material
- Using the crusher for wrong applications (undesired feed size)

Boulders significantly contribute to wear and tear of the crusher, it is therefore of great importance that boulders are resized by secondary drilling. A rock breaker (Fig. 2.12a) is used to resize boulders.

(a) (b)

Figure 2.12: The Primary Crusher (a) and a Rock Breaker used for Secondary Breaking (b)

It was observed that at least some of actions mentioned above, are relevant for the primary crushing plant at Ahafo South. Haul trucks dump their whole load at once on the gyratory equipment from roughly 8 meters of height, which is called shock loading. When the P80 ROM size target is not met, it can be concluded that the crusher is used for a wrong application. These actions can be easily avoided by adapting the management of the crushing station. It is assumed that fragments bigger than 500 mm are critical contributors to excessive wear-and-tear due to ”shock loading”. Therefore all fragments exceeding 500 mm are referred to as boulders for this particular research. This is in line with the shovel loading time delays due to big fragments, which mostly occur once they exceed 500 mm.

2.5. Shovel Loading Operations at Ahafo South

At Ahafo South, four Liebherr 9400 shovels operate as loading equipment. Three of the shovels use a "Face shovel Attachment" (Fig. 2.13) and one of the shovels uses a "Backhoe Attachment". NGGL requested that this research focussed on the face shovels, leaving out the backhoe shovel. The bucket capacity of these face shovels is 22 m^3 at 1.8 t/m^3 [9]. Several efforts have been made to optimize the buckets by removing excessive steel plates and adding a nickel-chrome layer to reduce wear and tear, resulting in a capacity of roughly 20 m^3 at 2.8 t/m^3. It is of great importance that the shovels load the material in a quick and smooth way, which means that a good fragmentation is required. It has been observed that not all loading criteria (section 2.3.2) for an efficient production are met at Ahafo South.

Figure 2.13: A Liebherr 9400 Face Shovel loading a Caterpillar 785C Truck in the Subika pit

Data on shovel loading time was available, providing the daily average loading time of each of the three face shovels and all (documented) benches of the pits. The data could easily be separated between data related to waste- and ore loading. The separation between specific benches, pits and shovels had to be done manually. It was assumed that there would be enough variation in daily average shovel loading times to find trends related to fragmentation variation.

An important note is that the mining department does not consider specific truck load weights. The initial plan of this research was to investigate the variation in both time and tonnage per truck load, so that the effect of fragmentation on the amount of shovel buckets needed to fill a truck could be analysed. The optimal load capacity of a haul truck is called "payload", which is usually given in a range between minimum- and maximum payload. In stead of using the built-in "Payload Speed Manager", which monitors all loads, it is assumed by the mining department that each load is equal to the maximum payload which is 143 tonnes for a 785c Caterpillar truck. It was therefore not possible to conduct a payload variation analysis. The spreadsheet contained a significant amount of errors and outliers, which had to be manually reviewed. In consultation with the primary operator trainer and coach (pers.com; 04-2017), it was decided to filter out average loading times under 1.7 minutes (≈ 100 sec.) and above 4 minutes. The lower limit was set because it is mechanically impossible to fill a 785c Caterpillar truck in under 100 seconds with a Liebherr 9400 shovel. The upper limit was set to act as a filter to remove situations where shovels stand idle (i.e. waiting for a truck). It was stated (pers.com; 04-2017) that the average loading time should be around 2.4 minutes (144 sec.) and that the majority of the values should be inside the interval of 2.4 m. $\pm$ 20 s. Once the data was cleaned, filtered and sorted, it became possible to visualize the variation of daily average shovel loading time per pit and per shovel. It became clear that the Awonsu pit had been out of production for the predominant time of the period to be investigated. Therefore, only the Amoma and Subika pit data was visualized.

2.5.1. Shovel Key Performance Indicators

The performance of each industry is measured by different ”Key Performance Indicators”, or KPI’s. Mining companies usually compare the daily performances of the biggest, which are in general the most expensive, equipment. The Liebherr 9400 shovel KPI’s (Table 2.3) are requested on a daily basis by the Mining department of NGGL, in order to maintain or where appropriate improve production performance efficiency.

Table 2.3: Key Performance Indicators (KPI’s) as defined by NGGL

KPI Metric	Department KPI	Definition	Formula
Availability	Maintenance	Measurement of Down Time	$\frac{Ready + Delay + Standby}{TotalTime}$
Use of Availability	Operations	Measurement of Idle/Spare Time	$\frac{Ready + Delay}{Ready + Delay + Standby}$
Use	**Operations**	**Measurement of Delay Impact**	$\frac{\textbf{Ready}}{\textbf{Ready + Delay}}$
Usage	Operations	Measurement of Delay and Spare Impact	$\frac{Ready}{Ready + Delay + Standby}$
Productivity	Operations	Measurement of tonnage produced	$\frac{Tonnage}{Ready}$

It was decided to focus on the ”Use” KPI of the shovels, since this reflects the impact of boulders on shovel loading time averages significantly. I.e. when a boulder blocks the material from flowing out of the face shovel attachment, which is called a ”hang-up”, this is recognized by the dispatch system and marked as a ”delay”. Once the shovel continues loading, a time period is assigned to this delay. The ”Use” KPI therefore, to a certain extend, reflects the amount of boulders in the muck. Other delays [12], as stated by Hays and categorized between planned and unplanned events, are:

Table 2.4: The Most Common Shovel-Truck-System Delays as stated by Hays

Fixed (Planned) Delays	Variable (Unplanned) Delays
Shift change	Haul road maintenance
Equipment refuelling	Equipment breakdown
Equipment inspection	Queuing and waiting
Blasting	Loading oversized rocks
Lunch/coffee breaks	Loading area clean-up
	Confined space at loading point
	Extreme weather conditions

It can be assumed that fixed delays occur systematically and therefore contribute to a constant KPI value. The unplanned delays are of interest when analysing the ”Use” KPI. Most mentioned unplanned events have to do with fragmentation issues, pitfloor achievement or equipment breakdown (as a result of excessive boulders), which all apply to drill & blast pattern change.

3

The Theory Behind Rock Fragmentation

3.1. The Kuz-Ram Model

Rock fragmentation is obviously controlled by the blast. There is a system in place to anticipate on the product of each blast, by applying the "Kuz-Ram model". The Kuz-Ram model was proposed by Cunningham [7] in 1983, by combining Kuznetsov's equation [15] (3.1) with Rosin-Rammler's formula [21] (3.5).

Kuznetsov developed an empirical relation between applied blast energy per unit volume of rock and the mean fragment size (X_m) as a function of rock type, known as the "powder factor". The equation predicts the product of a blast in terms of mass percentage passings through different sieves [15]:

$$x_m = A\left(\frac{V_0}{Q_e}\right)^{0.8} Q^{\frac{1}{6}} \tag{3.1}$$

Where A is the "rock factor", V_0 is the broken rock volume (m^3) per each blast hole and Q_e is the mass of the explosive charge converted to the similar energy equivalent of Trinitrotoluene (TNT) (kg). TNT is considered to be the standard measure of explosive yield. K is the powder factor (kg/m^3) and can be written as:

$$K = \left(\frac{V_0}{Q_e}\right)^{-1} \tag{3.2}$$

Eq.(3.1) therefore becomes:

$$x_m = AK^{-0.8}Q^{\frac{1}{6}} \tag{3.3}$$

A correction should be applied if the Relative Weight Strength (RWS) of the used explosive differentiates from TNT. TNT has a RWS of 115. The Ahafo South Mining Operations use an emulsion with a RWS of 89, provided by Orica Mining Services. Hence, Eq.(3.3) can be rewritten [4] as:

$$x_m = AK^{-0.8}Q_e^{1/6}\left(\frac{115}{RWS}\right)^{\frac{19}{30}} \tag{3.4}$$

The next step is to implement the Rosin-Rammler formula, which is used to predict the size distribution of the fragments. This formula is generally recognized as giving a reasonable description of fragmentation in blasted rock [8]:

$$R_m = 1 - e^{-(X/X_c)^n} \tag{3.5}$$

R_m Is the percentage of material passing the sieve, where X is the screen size (cm), X_c is the characteristic size (cm) and n is the uniformity index, as proposed by Cunningham [4]. The characteristic size X_c is the sieve size through which 63.2% of the particles passes [27], which is used to determine the passing R_m per sieve size X. The typical fragmentation curve can be plotted once X_c and Cunningham's uniformity index n are known. It is convenient to arrange eq.(3.5) to:

$$X_c = \frac{X}{\sqrt[n]{-ln(1-R_m)}} \tag{3.6}$$

Kuznetsov's equation calculates X_m where 50% of the material passes, which can be substituted into the rewritten Rosin-Rammler equation (3.6):

$$X_c = \frac{X_m}{\sqrt[n]{0.693}} \tag{3.7}$$

3.1.1. Rock Factor

From Kuznetsov's equation (3.1) it can be seen clearly that the rock factor has a big influence on the outcome of the Kuz-Ram model. Based on his experiments, Cunningham [3] indicated that the lower limit for A should be 8, even for incompetent rock masses, where the upper limit should be 12. Rock factor A is obtained by:

$$A = 0.06 * (RMD + JPS + JPA + RDI + HF) \tag{3.8}$$

Where RMD stands for "Rock Mass Description", JPS for "Joint Plane Spacing" (vertical), JPA for "Joint Plane Angle", RDI for "Rock Density Influence" and HF for "Hardness Factor". Lilly [17] was the first to introduce the Blastability Index, which has been adapted to better fit the Kuz-Ram model. The rock factor parameters and ratings that are used to calculate A are found in Table 3.1.

Table 3.1: Rock Factor (A) Parameters and Ratings

Parameter:		***Rating:***
RMD		**Rock Mass Description**
Powderly/Friable		10
Vertically Jointed		JF
Massive		50
JPS		**Vertical Joint Spacing**
<0.1 m		10
0.1 m to MS		20
MS to DP		50
JPA		**Joint Plane Angle**
Dip out of Face		20
Strike perpendicular to Face		30
Dip into Face		40
RDI		**Rock Density Influence**
RDI = 25 * RD - 50		RD: Rock Density (t/m^3)
HF		**Hardness Factor**
Y/3		if Y<50
UCS/5		if Y>50
	Meaning:	**Unit:**
MS	Oversize	m
DP	Drill Pattern Size	m
Y	Young's Modulus	GPa
UCS	Uniaxial Compressive Strength	MPa
JF = JPS + JPA		

Holmberg [7] states that one should always attempt to improve the derived rock factor by applying a site specific constant "C_A", which is found by comparing preliminary results against known results. C_A should range between 0.5 and 2. This should be an iterative ongoing process.

3.1.2. Powder Factor

Once the RWS correction factor is added to Kuznetsov's equation (3.4), it is possible to calculate the mean fragmentation X_m for a given powder factor K. This also means that (minimal) K can be calculated in order to yield the desired X_m, giving:

$$K = \left[\frac{A}{X_m} Q_e^{1/6} \left(\frac{115}{RWS}\right)^{19/30}\right]^{1.25} \tag{3.9}$$

3.1.3. Cunningham's Index of Uniformity

Cunningham [4] tested and used the relationship between fragmentation and drill patterns to estimate the blasting parameter n. This parameter is used in Rosin-Rammler's formula (3.5) to calculate X_c. When a staggered drill pattern is used, which is the case at the Ahafo South Mining operations, the following applies; $n_{staggered} = n * 1.1$. The estimation of the blasting parameter is calculated by:

$$n = \left(2.2 - \frac{14B}{d}\right)\left(\frac{1}{2} + \frac{S}{2B}\right)^{0.5}\left(1 - \frac{W}{B}\right)\left(\frac{L}{H}\right) \tag{3.10}$$

Where B is the burden (m), D is the borehole diameter (mm), S is the spacing (m), W is the standard horizontal deviation of the planned borehole location (m), L is the total charge length (m) and H is the height of the bench (m). This equation assumes a single column charge, which is in alignment with the Ahafo South Mining operations.

Since n is an exponent, the value of n has a significant impact on the Rosin-Rammler curve, where high values indicate a uniform fragmentation. Low values indicate a wide range of sizes, both fines and boulders.

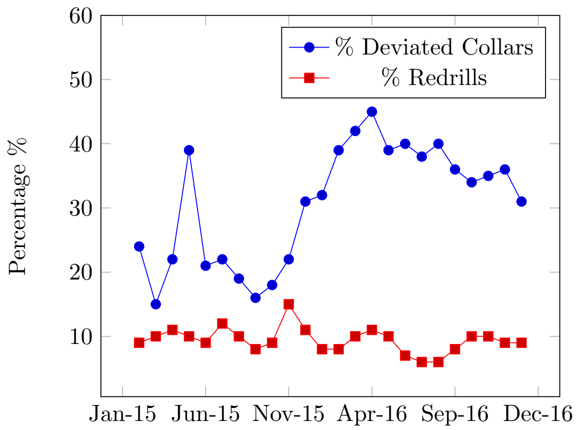


Figure 3.1: Redrills and Collar Deviations during 2015 and 2016

Irregular factors such as collar deviation- and redrill percentages (Fig. 3.1) should be considered when implementing n into the Rosin-Rammler equation. Cunningham's Index of Uniformity does not consider the percentage of redrills, which introduces inaccuracies. A redrill means that there is a charged hole outside the pattern, resulting in an increase in W and reduces the blasting effect due to a chimney effect. These negative effects, however, can be reduced when filling the uncharged hole with stemming material.

3.2. Applying the Kuz-Ram Model at Ahafo South

The Kuz-Ram model has been applied once at Ahafo South, by Hamdani [11] during early 2012, to verify whether or not the current blasting efforts reach the P80 target of 350 mm, a comparison will be made below. The first step is to find rock factor A (Eq.3.8), using the geotechnical parameters provided by Newmont:

Table 3.2: Rock Factor (A) Parameters and Ratings for Ahafo South

Parameter:	**Rating:**
RMD	**Rock Mass Description**
Powderly/Friable	10
Vertically Jointed	JF
Massive	**50**
JPS	**Vertical Joint Spacing**
<0.1 m	10
0.1 m to MS	**20**
MS to DP	50
JPA	**Joint Plane Angle**
Dip out of Face	**20**
Strike perpendicular to Face	30
Dip into Face	40
RDI	**Rock Density Influence**
RDI = 25 * **2.8** - 50 = **20**	RD: Rock Density (t/m^3)
HF	**Hardness Factor**
21/3 = **7**	if Y<50
UCS/5	if Y>50

These values give A = 7.02. Hamdani [11] suggested a site specific constant C_a of 1.25, resulting in a A of 8.78. The second step is to apply Kuznetsov's equation (3.4), where V_0 = 112 m^3, Q_e = 145 kg and RWS = 100, resulting in x_m = 21.22. x_c Can be calculated using Eq. 3.7, which gives x_c = 27.31. Figure 3.2 shows the current versus the updated fragmentation distribution curve, which introduces the actual drill pattern parameter values B = 3.7 m., S = 4.2 m. and W = 0.38 m. (Collar deviation average of 2016, which is assumed to reflect the current drill practices). The target (P80) sieve size of 350 mm is passed by 76% of the muck.

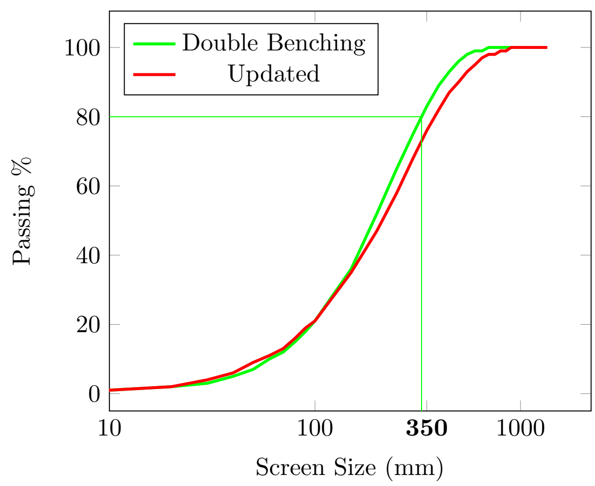


Figure 3.2: Updated Theoretical Fragmentation Distribution Curve

4

Data Used

This chapter describes the acquisition, quality and quantity of the obtained data. A plan was set up to efficiently utilize the available time on site in order to finalize the acquisition. The data on fragmentation was provided by the Senior Mine Engineer and a Rock Engineer. The data on shovel performance was provided by a Dispatch Mine Engineer. The financial data was provided by a Business Planning Analyst. The data from the processing plant was provided by a Metallurgical Engineer. All data were discussed with- and checked by the corresponding department manager (Manager Processing Plant & Acting Mine Manager). All data were provided in the form of spreadsheets.

4.1. Rock Fragmentation

In order to conduct research on the effect of rock fragmentation on shovel-, crusher- and mill performance, is it is essential to have both high quality and high density data on specific blasts. This research therefore fully depends on the fragmentation monitoring and control procedures. Fragmentation data were available from in field monitoring reports until September 2016. During this month it was decided to stop monitoring the rock fragmentation in the pits, after a boulder toppled from the top of a muck-pile. This resulted in a ”near miss”, which was reported (Chapter 3). Fig. 4.1 displays an example of the fragmentation data that was acquired. This example concerns data related to the month June of 2014 in the Subika pit. The pattern name is given, and the corresponding passing percentages based on the fragment sizes. The percentages exceeding 500 mm have been coloured using a conditional format where higher values have been marked red and lower values have been marked green. Red values thereofore indicate a high presence of boulders. The P20, P50, P80 and estimated top size are also included in this example. Fig. 4.1 represents the data that were used to conduct the analysis on fragmentation distribution variation.

MONTH	Pattern	PIT	Tonnage	<=100	200	300	400	500	>500	P20	P50	P80	TOP SIZE
JUNE	SK-1096-306P	SK	104,298	29.90%	28.30%	23.20%	11.40%	4.90%	2.20%	65.4	171.7	291.5	622.5
	SK-1096-307P	SK	65,114	32.00%	26.80%	20.10%	10.60%	5.20%	5.30%	58.3	167.5	307.8	825.3
	SK-1096-308P	SK	52,727	31.80%	24.10%	20.70%	12.40%	7.40%	3.60%	55.9	176.2	321.6	637
	SK-1096-309P	SK	102,308	28.60%	28.90%	21.10%	10.20%	5.60%	5.70%	70.4	173.7	310.2	757.5
	SK-1096-310P	SK	124,490	38.30%	30.20%	15.90%	6.50%	2.50%	6.60%	45.9	136.1	262	1136.4
	SK-1096-311P	SK	100,950	39.50%	31.60%	16.30%	6.50%	3.40%	2.70%	45.9	131.3	242.7	638.8
	SK-1096-312P	SK	95,073	21.60%	7.50%	12.70%	14.80%	13.50%	30.00%	85.9	355.5	580.7	954
	SK-1096-313P	SK	102,425	39.50%	26.80%	13.70%	10.40%	6.50%	3.20%	45.2	131.4	300.7	637.7
	SK-1096-315P	SK	89,123	19.80%	10.10%	12.50%	13.70%	13.30%	30.60%	101.8	355.6	595.4	1028.1
	SK-1096-316P	SK	86,982	26.20%	15.70%	16.10%	13.50%	9.20%	19.40%	67.5	249.8	491.6	1333
	SK-1096-318P	SK	128,013	31.50%	21.70%	18.20%	11.70%	8.50%	8.40%	54.6	185.4	369.6	725.6
	SK-1096-319P	SK	127,777	32.20%	27.50%	22.00%	11.10%	4.60%	2.60%	57.1	165.3	289.5	710.3
	SK-1096-325T	SK	61,839	34.30%	22.50%	17.90%	11.10%	6.80%	7.30%	47.1	169	341.1	811.7
	SK-1096-326T	SK	79,101	26.80%	18.0%	17.00%	14.20%	11.10%	12.90%	68.6	228.6	434	809.5
	SK-1104-339T	SK	51,034	34.90%	26.50%	17.80%	10.80%	5.80%	4.10%	49.8	155.1	305.5	718.5
	SK-1112-347P	SK	113,480	29.20%	24.40%	21.10%	12.20%	7.20%	6.00%	64.5	185.6	337	752.8

Figure 4.1: Example of the Provided Fragmentation Data (June 2016 - Subika Pit)

4.2. Powder Factor

The powder factor indicates the quantity of explosive required to fragment a metric tonne of rock (kg/m^3) [2]. A lower powder factor therefore implies lower explosive costs. Fig. 4.2 visualizes the distribution of the original powder factor data of 2014, 2015 and 2016. The data on the powder factor between January 2014 and September 2016 originates from the short-term planning department and was provided by the Senior Mine Engineer. The data of October, November and December 2016 was provided by the Senior Environmental Representative because of the transition to another database (pers.com; 05-2017). All data was provided in spreadsheet files. The following amount of powder factors were gathered; 2014: 516, 2015: 343 and for 2016: 236. It is unclear why the amount of documented blasts is decreasing, it was stated that the amount of blasts per year did not decrease (pers.com; 05-2017).

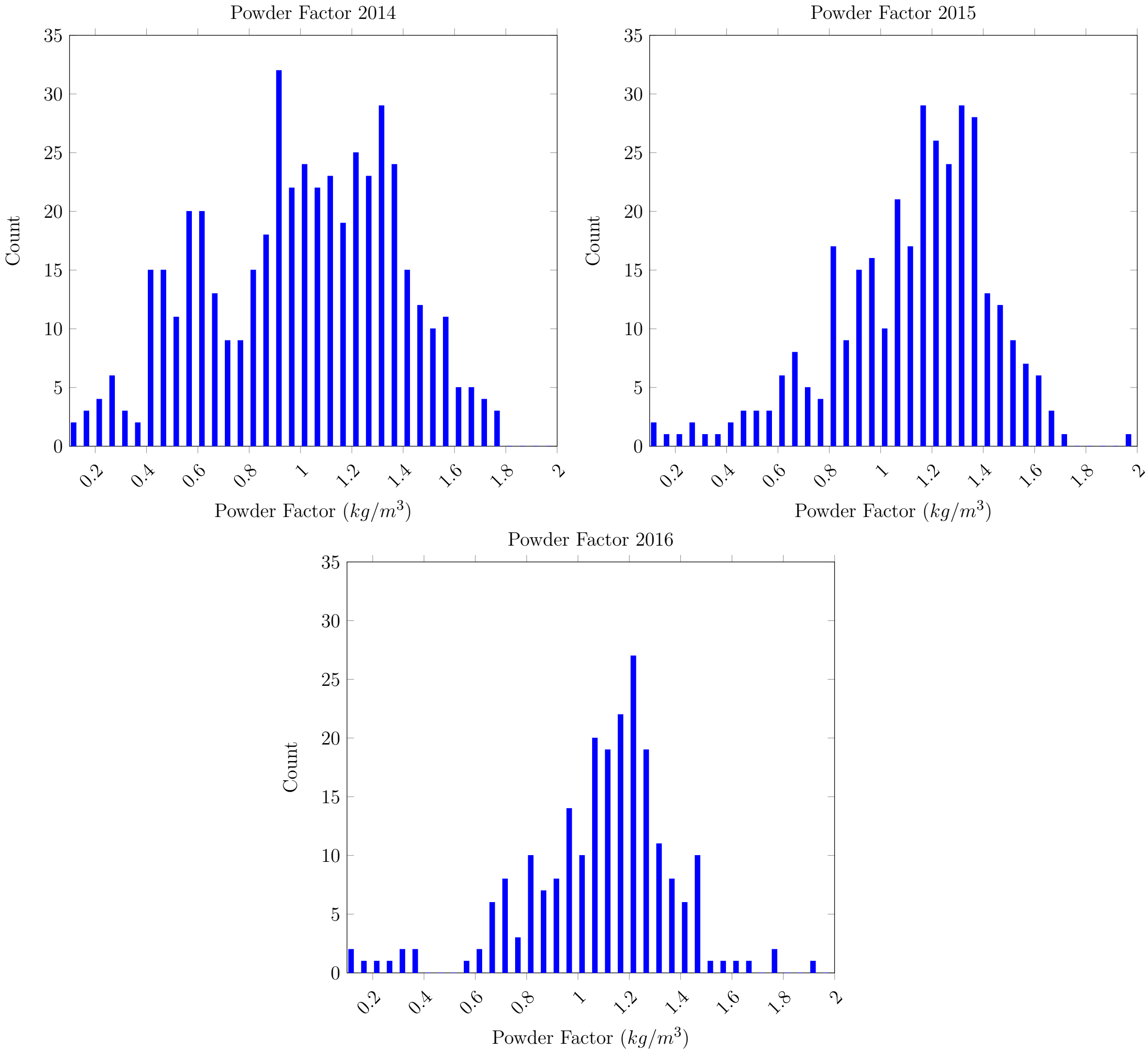


Figure 4.2: Powder Factor Distribution 2014-2016

It can be seen that the variety of powder factor values did decrease as a result of the implementation of the dispatch system in 2015. This systems helps the drill rigs to reduce collar deviation through a GPS guided system, which helps the blast team to fill the right amount of holes with explosives.

4.3. Shovel Loading Time Data

The data on shovel loading time were provided in daily averages per blast, data and pit. The data were separated by shovel and pit in order to analyse the variance between the different operational circumstances.

4.3.1. Subika Shovel Loading Times

Fig. 4.3 provides a scatter plot for each of the three shovels under investigation. The red line indicates the target average shovel loading time (2.4 min). The gaps within the data indicate that the shovels were either not producing (yet), active in another pit or down for maintenance, which usually takes at least a month. Since it is from a production point of view very inefficient to have a shovel change between pits (due to its low travel speed and big distances between pits) it is safe to assume that a shovel is active in just one pit when data points are shown over a certain period. Shovel 6 has 207 documented daily average shovel loading times, Shovel 7 has 131 documented days and Shovel 8, 88.

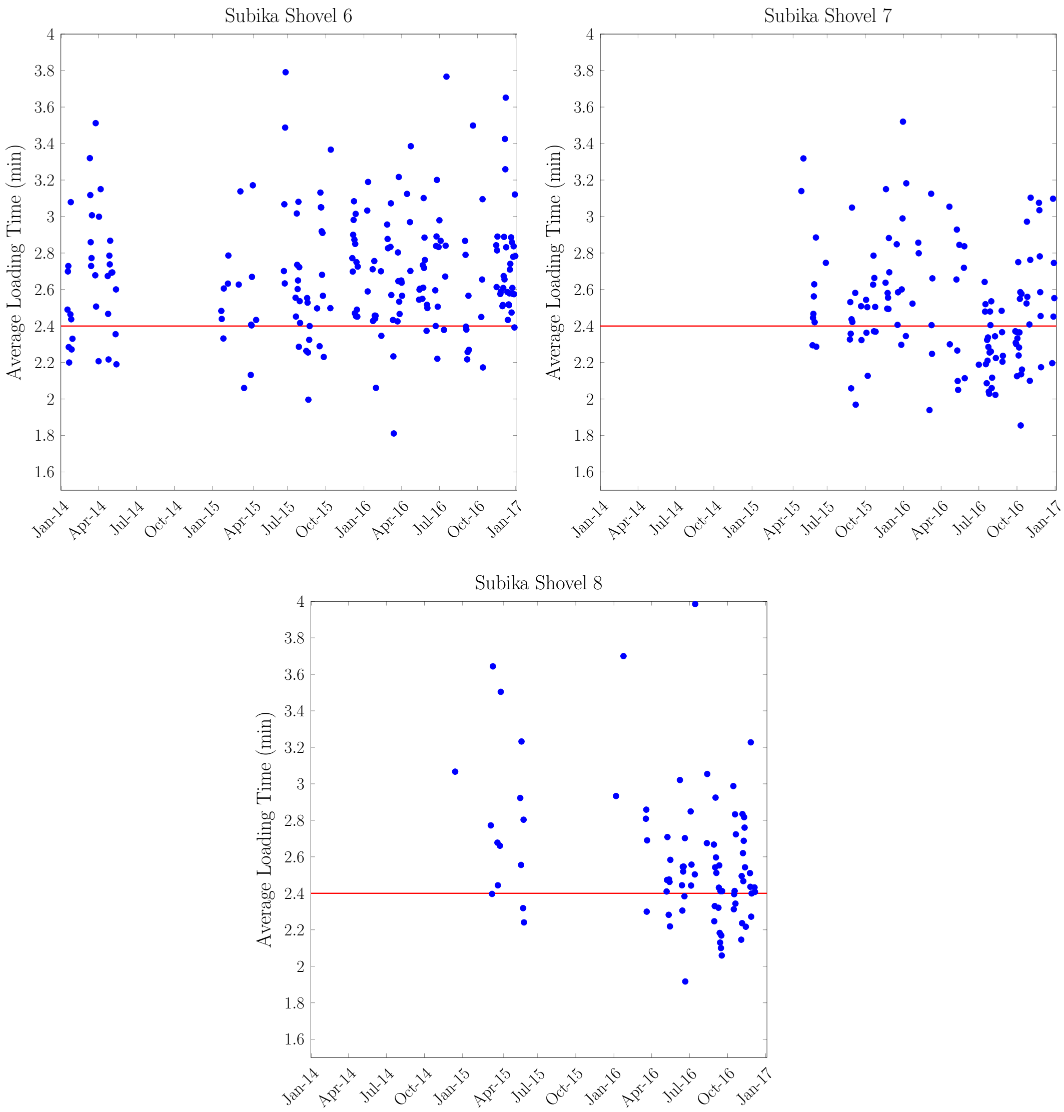


Figure 4.3: Scattered Daily shovel Loading time Average Subika

It can be concluded that the data for the Subika pit is quite sparse. There are nearly 1,100 days in the three years being investigated, meaning there should be same amount of data points.

4.3.2. Amoma Shovel Loading Times

The data density available from the Amoma pit is much more dense than the Subika data, as can be seen in Fig. 4.4. It is clearly visible that Shovel 7 has a loading time average well below target. Shovel 6 has 172 documented daily average shovel loading times, Shovel 7 has 218 documented days and Shovel 8 320.

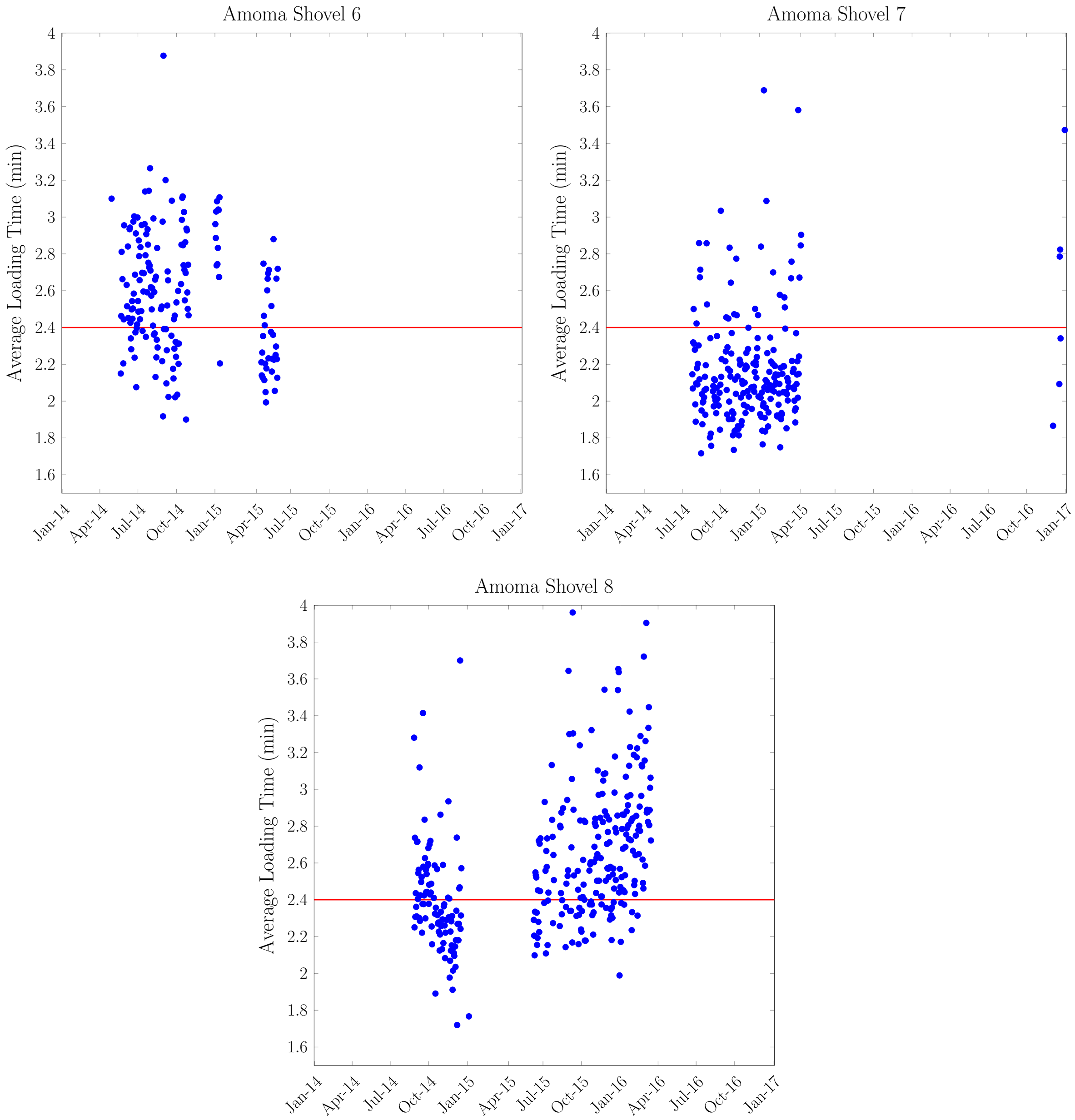


Figure 4.4: Scattered Daily shovel Loading time Average Amoma

The dispatch engineers indicated (pers.com; 04-2017) that the Amoma pit data is more dense as a result of both hardware and software issues occurring at the Subika pit, where data was not saved due to connection loss or operator incompetence. It was mentioned (pers.com; 05-2017) that a significant percentage of the operators doesn't know how to operate the dispatch software and therefore decide no to use the system, resulting in the loss of data.

4.3.3. Dispatch System

The Ahafo South Mine site introduced a new dispatch system during 2015, called: Hexagon Mining; The Jigsaw Operations Suite. This dispatch system is used to monitor several Key Performance Indicators, or KPI's. The monthly KPI trends of the shovels are show in Fig. 4.5. As can be seen, the Use is relatively smooth, making it more accessible to find trends. Shovel 6 shows the most constant value for the Use, where Shovel 7 hits a low point at October 2015 and December 2016. Shovel 8 shows a significant time period where the Use was lower than average, between June 2015 and April 2015.

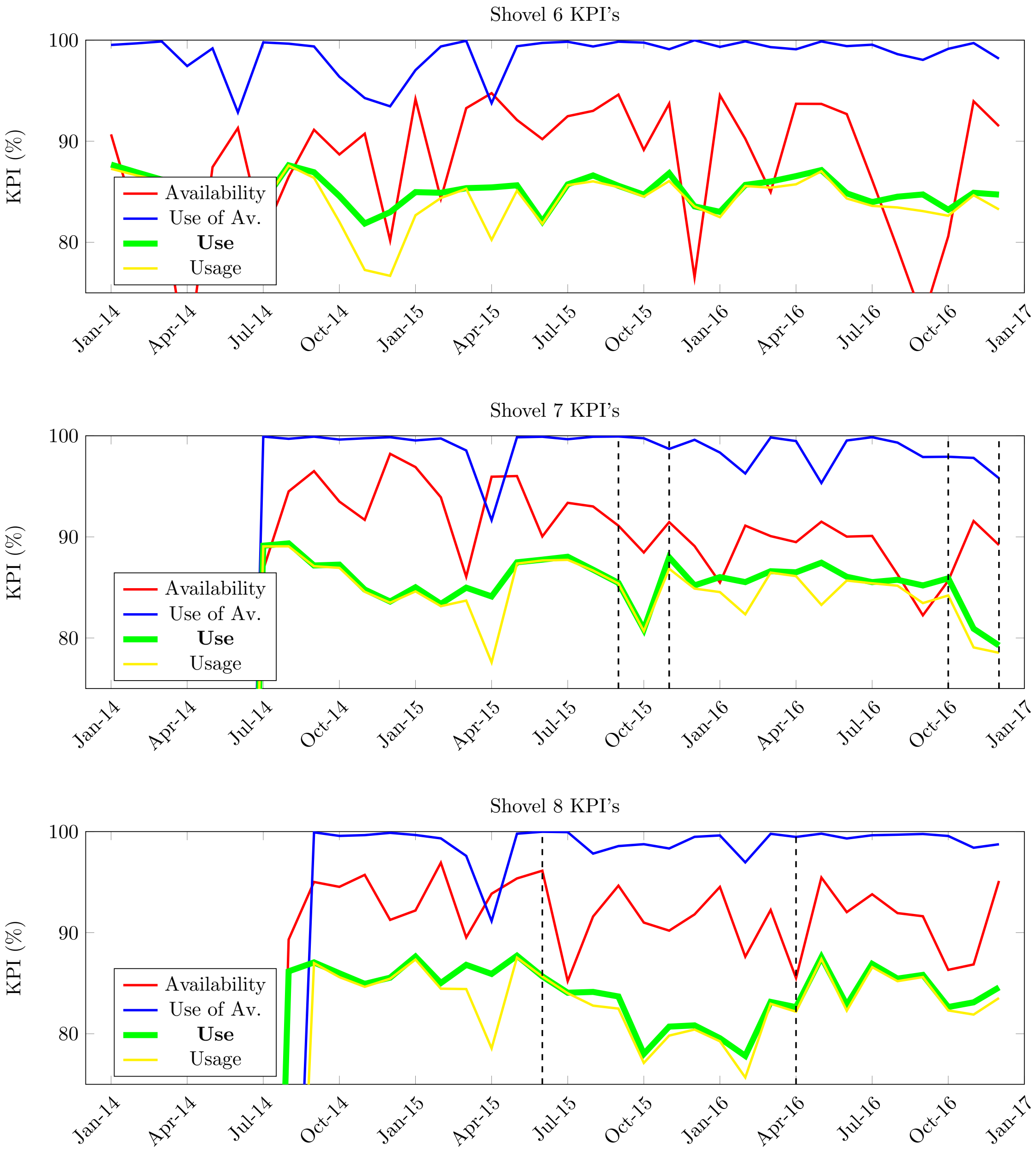


Figure 4.5: Histogram of Daily Average Amoma Shovel Loading Time

As mentioned in Table 2.4, extreme weather condition might cause delays. During the rainy season, which lasts from April to October, many thunderstorms pass over the mine site. These storms may induce a so called "red-alert". During such an alert, everybody must stay inside to avoid getting hit by thunder. These delays can sometimes take up to hours, thus having a big effect on the daily KPI. Fig. 4.5 proves that the rainy season has no significant impact on the monthly KPI averages. The possible effects of the rainy season on production will not be considered.

In order to understand why certain KPI's deviate from their target or average, the circumstances of the shovels need to be mapped. Table 4.1 summarizes the location of shovels. When a shovel changed pit in the middle of a month, the location is assigned to the pit where the shovel stayed the longest during that month. It is clearly visible that the shovels require heavy maintenance every 8-12 months, since there is no documented shovel located once every while.

Table 4.1: Monthly Location of the Liebherr 9400 shovels 6,7 & 8.

Month	**Shovel 6 Location**	**Shovel 7 Location**	**Shovel 8 Location**
Jan-14	SK		
Feb-14			
Mar-14	SK		
Apr-14	AM/SK		
May-14	AM/AW/SK		
Jun-14	AW		
Jul-14	AW	AM	
Aug-14	AM/AW	AM	AW
Sep-14	AM	AM	AW
Oct-14	AM/AW	AM	AM/AW
Nov-14		AM	AM
Dec-14		AM	AM
Jan-15	AW/SK	AM	AM
Feb-15	SK	AM	
Mar-15	SK	AM	SK
Apr-15	AM/SK	AM/SK	SK
May-15	AM	SK	SK
Jun-15	SK	SK	AM
Jul-15	SK		AM
Aug-15	SK	SK	AM
Sep-15	SK	SK	AM
Oct-15	SK	SK	AM
Nov-15		SK	AM
Dec-15	SK	SK	AM
Jan-16	SK	SK	AM
Feb-16	SK	SK	AM
Mar-16	AM/SK	SK	AM/SK
Apr-16	SK	SK	
May-16	SK	SK	SK
Jun-16	SK		SK
Jul-16	SK	SK	SK
Aug-16		SK	SK
Sep-16	SK	SK	SK
Oct-16	SK	SK	SK
Nov-16	SK	Sk	SK
Dec-16	SK	AM/SK	SK

4.4. Crushing and Milling Operations at Ahafo South

The processing department provided data regarding power usage, throughput, feed source & size and grinding media usage. The data were made available per 12 hours, giving 2 data points per day. Fig. 4.6 displays the daily power usage of the SAG- and Ball mill with the daily throughput below. The daily production limit is 26,000 tonnes and is constrained by the SAG mill. The throughput of the SAG- and Ball mill is assumed to be equal, since a ”Pulp Turbo Discharge” system was installed in early 2014. This system prevents back-flow into the mills. After this assumption it is easily concluded that the Ball mill requires more power than the SAG mill.

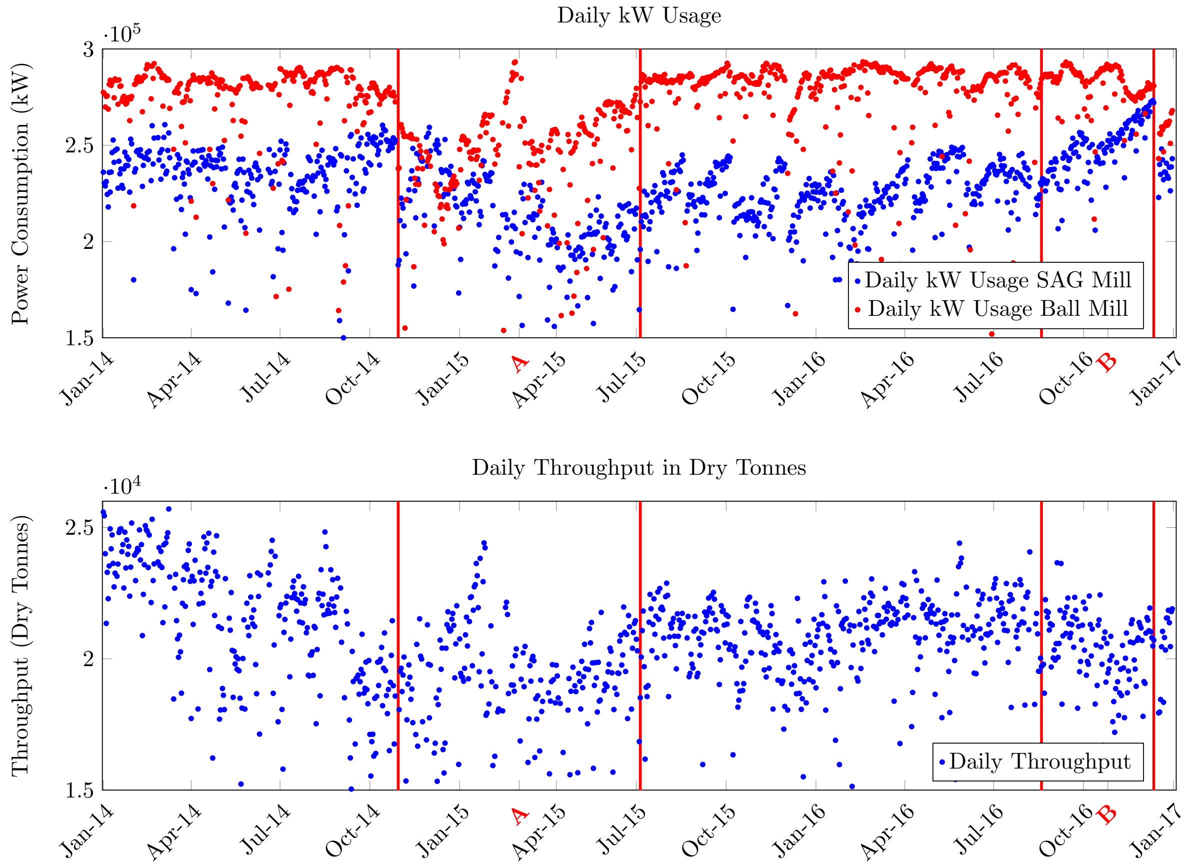


Figure 4.6: Throughput and Power Consumption of the SAG- and Ball Mill

Fig. 4.6 shows interesting time periods, marked A (November 2014 - July 2015) and B (August 2016 - November 2016), which deviated significantly from the ”normal” trend and average. The daily power consumption was kept constant during most of 2014. However the daily throughput dropped from roughly 25,000- to 20,000 tonnes. Period A shows remarkable power consumption related behaviour of the Ball mill, where period B shows the same for the SAG mill. A sinus-like pattern can be recognized in the daily power consumption of the SAG mill between period A and B. The Ball mill also shows such a pattern, where the effect increases towards the end of 2016, which can be clearly seen in period B. The daily throughput recovered between period A and B, but never reached the same numbers as in early 2014. In order to understand the power needed to grind a specific amount of ore, the power per tonne was calculated (Fig. 4.7). The effect of the reduced throughput by a constant power consumption during the first part of 2014 is clearly visible for both the SAG and Ball mill, where the power consumption per tonne shows an increasing trend. Period A shows an interesting feature, as the grinding power required per tonne has a decreasing trend for the SAG mill and an increasing trend for the Ball mill. Period B displays a peak in both plots. The processing performances are documented twice a day, therefore each day has an available average data entry (1097 data points). The processing data has a much higher density than the mining data.

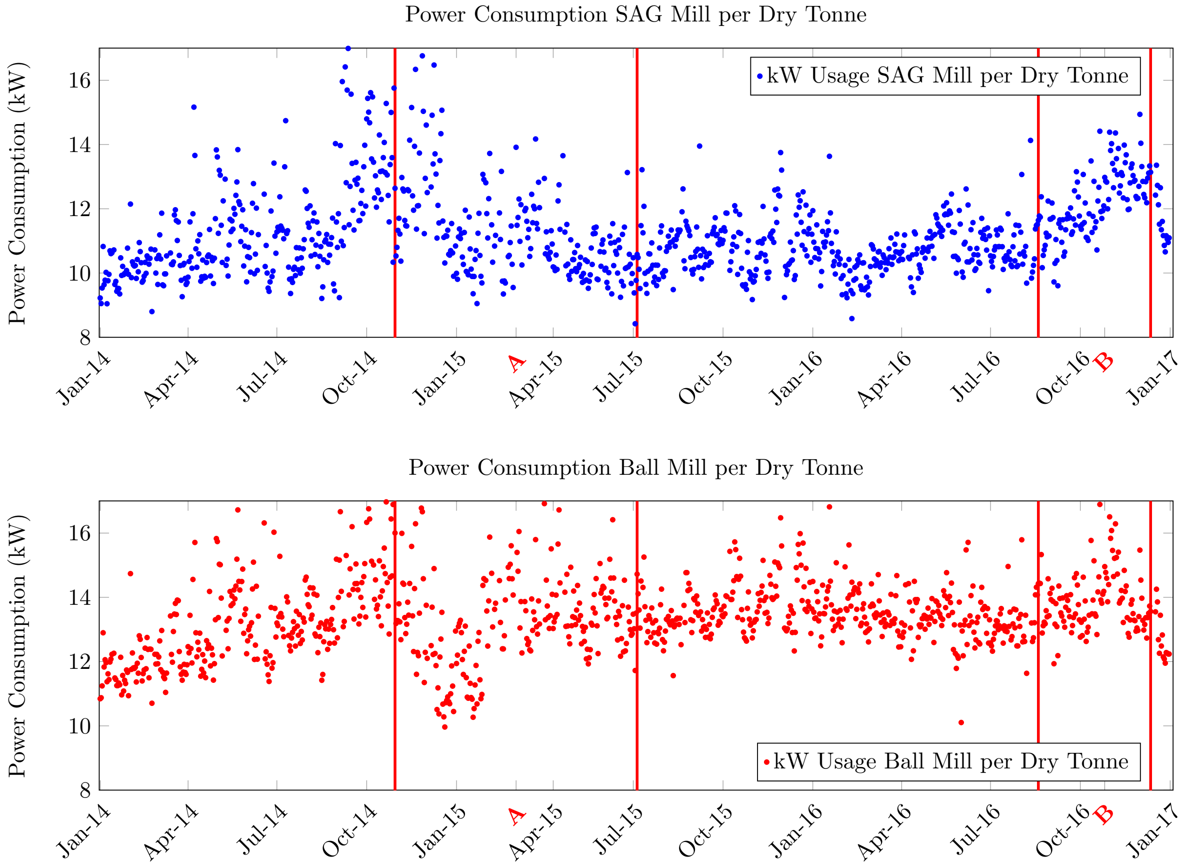


Figure 4.7: Power Consumption of the SAG- and Ball Mill per Dry Tonne

The addition of grinding media is essential for successful milling in both the SAG- and Ball mill (Fig. 4.8). The SAG mill grinds its feed with a combination of steel balls and the impact of the rotating rock itself, while the Ball mill is fully dependant on steel balls. The usage of these balls is continuously monitored because both over- and under supply results in excessive wear and tear of the inside walls of the mills. Also the feed and product size is constantly scanned, so that an optimal setting is achieved between the only 2 parameters that can be adjusted; grinding media addition and mill rotation speed.

The media usage of both mill varied during 2014 between 0.2 and 0.8 kg. per tonne, where the usage in 2015 was significantly higher. The media usage of the SAG mill in 2016 is relatively constant at 0.4 kg. per tonne, where an increasing trend is observed for usage of the Ball mill.

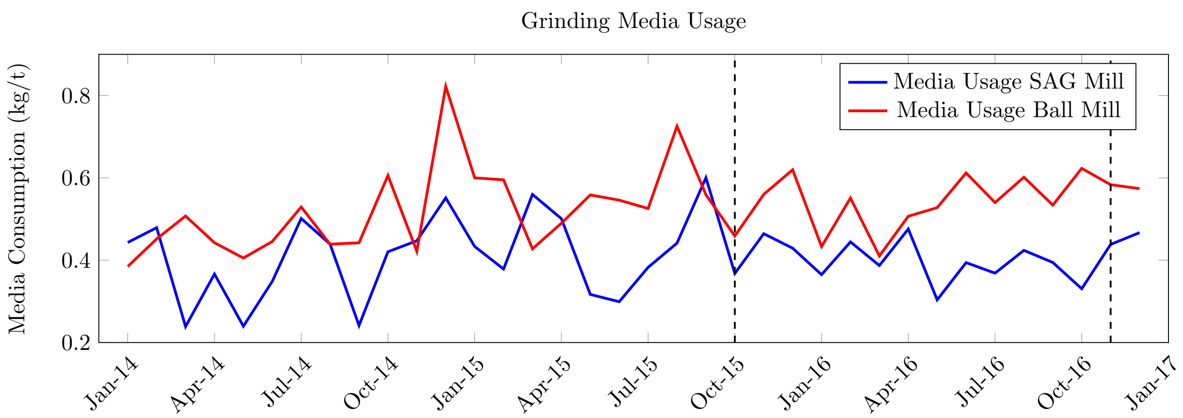


Figure 4.8: Overall Feed Ratio

4.5. Maintenance

Mining companies usually deal with heavy equipment, such as shovels, haul trucks, dozers and graders. At Ahafo South, Mantrac takes care of the Caterpillar equipment. Mantrac is an authorized Caterpillar Dealer and works as a contractor on the Ahafo South Mining Operations. The Liebherr 9400 shovels are maintained by NGGL.

Mantrac uses several subcontractors, which makes it complicated to get an understanding of variation in damages or incidents since most of the work is outsourced. Every month, Mantrac receives an invoice from each of its contractors. These invoices do not specify information that would be relevant for this research. Incidents that caused damage are not of interest to repair workers such as welding contractors and are therefore not documented in a way that makes it feasible to connect these damages with incidents. The variation in monthly invoices should reflect some of the changes in the working conditions in the pits, but there are too many factors that play a role to draw any conclusions from this data.

After several consults with the maintenance manager and several workshop managers, it was decided to exclude the maintenance topic from this research, since it is impossible to give an accurate figure of the specific incidents (and costs) required for this research. The maintenance manager is currently working implementing a system that requires separate cost reporting and stated (pers.com; 04-2017) that ”*Visual inspection currently shows that there are too many incidents that bring excessive damage to the equipment. These incidents are often boulder related (Fig. 1.5 a).*”

Some statements and conservative assumptions were made by the maintenance manager:

- Haul truck annual maintenance costs due to excessive wear on dump bodies, canopies and sideboards are estimated between 500,000-600,000 US$.
- Roughly 50% of this estimation consists of the raw steel price, the other 50% includes workshop and personnel expenses.
- There is currently no ”maintenance cost” model.
- A nickelchrome plating is used to protect the dumpbodies against wear-and-tear.

5

Data Analysis

5.1. Define, Measure, Analyse, Improve, Control (DMAIC)

DMAIC is the main Six Sigma principle and originates from the need to constantly improve the quality of process outputs by identifying and removing the root causes as soon as they occur [14]. Six Sigma is a business management strategy allowing companies to improve their every day activities drastically by applying the DMAIC method and is a world wide acknowledged business improvement method. DMAIC stands for; Define, Measure, Analyse, Improve, Control. These so called ”phases” are briefly described in section 1.4.3. This report will not discuss the full DMAIC procedure, but only the parts required for a good readability of this report, consisting of mainly the ”analyse” and ”improve” phase.

Six Sigma is a methodology that establishes a measurable status on process yield. This yield is defined as defects per million opportunities (DPMO). One speaks of a defect when a ”product” is outside the accepted quality range. A quality range is defined as the maximal variation, a ”product” may have from its target, which could be a time, size, etc. When a process has a higher sigma level, it has fewer defects. The DPMO of a process can be calculated by:

$$DPMO = \frac{1,000,000 * number\ of\ defects}{number\ of\ units * number\ of\ defect\ opportunities\ per\ unit} \tag{5.1}$$

The sigma levels and corresponding DPMO's are based on the standard normal distribution, where the process yield of a certain sigma level is equal to the area under the bell curve limited by the sigma level (Fig. 5.1).

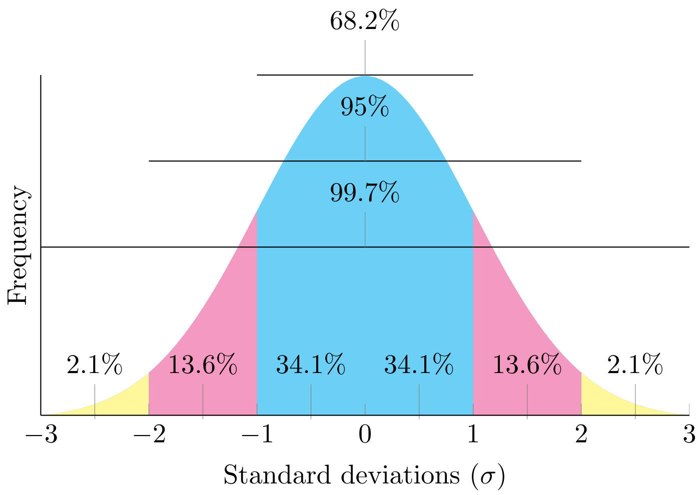


Figure 5.1: A Standard Normal Distribution with the sigma level interval before 1.5 σ shift and the ”68-95-99.7 Rule”

A process with sigma level 1 implies that 68.2% of the products should be within the accepted quality range meaning it has a DPMO of 317,311, where 3 sigma requires 99.7% or a DPMO of 2,700. In order to account for long term variation, a 1.5 sigma shift should be applied [25]. A process with sigma level 2 therefore turns into a -0.5 sigma level, with a DPMO of 691,462 and sigma level 3 turns into a 1.5 sigma level with a DPMO of 66,807. This is commonly known as the ”Long-Term Dynamic Mean Variation”.

The word ”Sigma”, or σ, is used to refer to a unit of measurement in product quality variation and is also referred to as the statistical standard deviation. Six Sigma intends to narrow the DPMO down to 3.4, which is the sixth sigma level (with an actual σ of 4.5).

A normal- or bell shaped distribution can be defined using the ”68-95-99.7 Rule”, where 68-, 95- and 99.7% of the data lie within respectively 1 σ, 2 σ and 3 σ of the mean.

Table 5.1: The Corresponding DPMO per Sigma Level

Sigma Level Short Term	**Sigma Level Long Term**	DPMO Short Term	**DPMO Long Term**	Process Yield (%)	**Process Yield (%)**
1	**-0.5**	317,311	**691,462**	68.27	**30.9**
2	**0.5**	45,500	**308,537**	95.45	**69.1**
3	**1.5**	2,700	**66,807**	99.73	93.3
4	**2.5**	63	**6,210**	99.9937	**99.4**
5	**3.5**	0.6	**233**	99.99994	**99.98**
6	**4.5**	0,002	**3.4**	99.9999998	**99.99966**

Since mining activities vary in many ways from other industrial processes, it was decided to analyse the data at a 1 σ level, meaning the accepted interval is between - 1 σ and + 1 σ of the target. This becomes -0.5 σ when the 1.5 σ shift is applied. Because the available data originates from 3 consecutive years, a long term standard deviation could be calculated. Therefore, such a 1.5 σ shift will not be necessary, thus the accepted target interval should include 68% of the data (Fig. 5.1). This is in agreement with the business improvement manager of NGGL (pers.com; 05-2017). Later on it became clear that the obtained data is too sparse to conduct a full 6 σ improvement research. When a specific short term period (E.g. a month with a high density of data points) within these three years would be used to predict and improve the productivity on the long term, it is advised to apply the 1.5 σ shift.

Eq. 5.1 shows that the ”number of defect opportunities” is relevant for the DMPO value. A defect opportunity can be described as a characteristic of the corresponding process, which may affect the quality of the end product. The number of defect opportunities is therefore process specific. For example: The (end) product of the shovel loading process is a moved volume per time unit. Characteristics that may influence the quality of this product, given the desired quality is the target average time of 2.4 minutes, are: variation in time and variation in moved volume. As described in section 2.5, specific truck loads are not documented. It is therefore not possible to analyse the moved tonnage variation, thus this can not be considered as a defect for this analysis. The amount of possible defects is therefore considered 1 for this specific analysis.

It was decided to implement the Six Sigma principle only for the analyses of the average shovel loading times. The trends that were observed with the other acquired data such as the throughput data of the mills can be explained by external factors. This statement, in combination with the limited time available for the research, was decisive for the choice to conduct one Six Sigma analysis.

5.2. Analysis of the Powder Factor

The powder factor target was set to 1.2 kg/m^3 (Fig. 5.2 - red bar) before the pattern change. After the pattern change, the target was set to 1 kg/m^3 (Fig. 5.2 - green bar). In order to remove unreliable input as discussed, a cut off range was applied. All reported blasts with a powder factor under 0.5 kg/m^3 or above 2.0 kg/m^3 are assumed to be erroneous due to inaccurate administration by the blasting crew. This assumption was approved by the Mine General Foreman (pers.com; 05-2017).

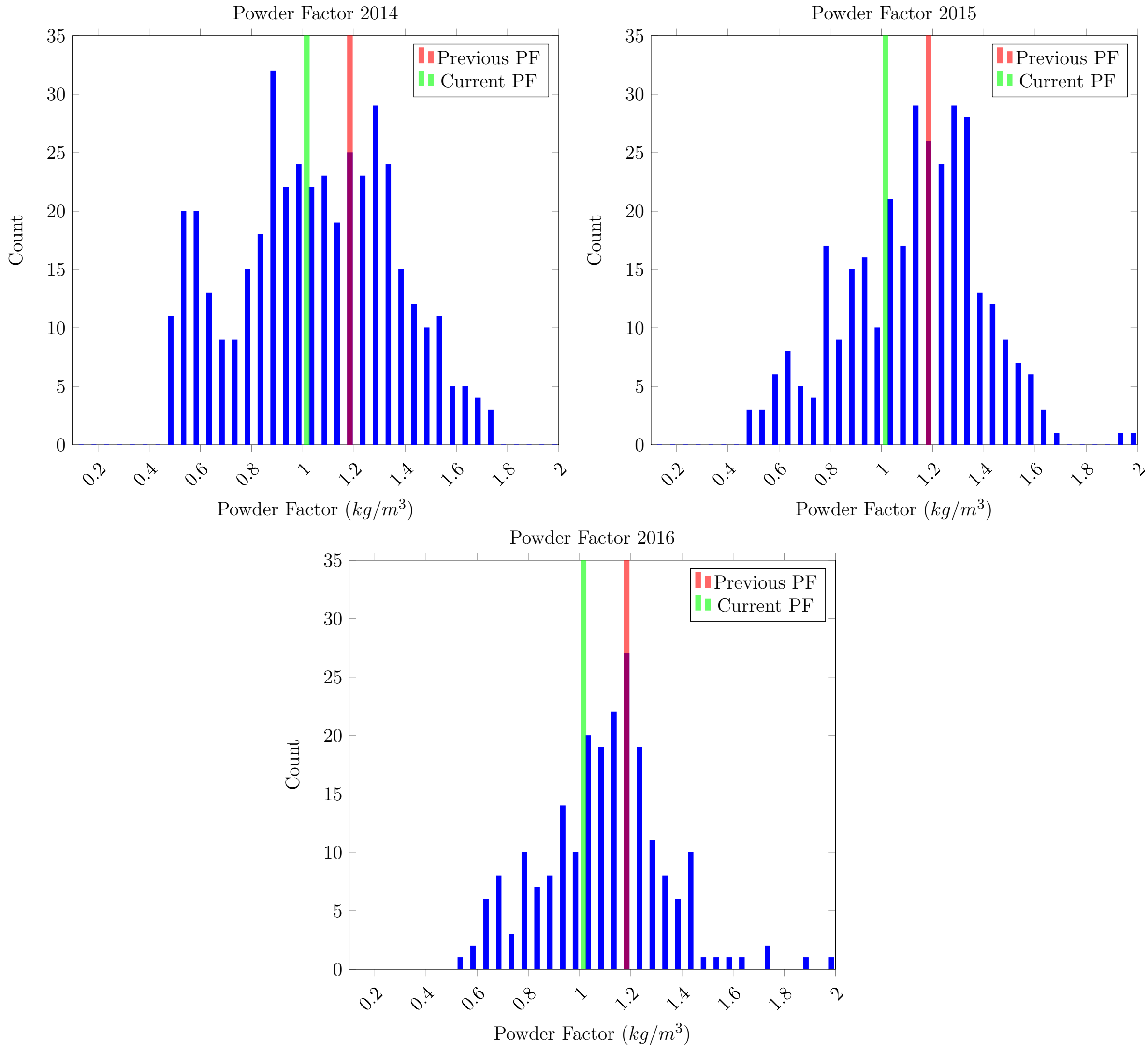


Figure 5.2: Powder Factor Distribution 2014-2016

Table 5.2 summarizes the statistical results of the analysis on powder factor variation, after the data was cleaned. It is remarkable that the mean powder factor of 2014 is lower than 2015 and 2016. 2015 does not show any improvement with regards to the previous year, where 2016 improved considerably compared to the former.

Table 5.2: Statistical Results of Powder Factor Analysis

Powder Factor	**2014 Raw**	**2014 Clean**	**2015 Raw**	**2015 Clean**	**2016 Raw**	**2016 Clean**
Mean	0.98	1.05	1.41	1.13	1.12	1.09
Median	0.99	1.06	1.16	1.14	1.10	1.10
Standard Deviation	0.40	0.25	0.62	0.24	0.28	0.18

5.3. Analysis of the Shovel Loading Time

The data were visualized using scatter plots, which makes it easy to find and verify both trends and anomalies. A cut-off range was applied, as described in Section 2.5, to account for erroneous data. These scatter plots and the realized trends are presented in Fig. 5.4 and 5.6, where the transparent lines indicate the trend of the shovel operating in another pit. Annual histograms were created to obtain an overview of the variation and spread of the daily average shovel loading time (Fig. 5.5 & 5.7).

Fig. 5.3 shows an example of the visualisation by scatter plots, as described above. A random data set was created using a normal distribution with a mean of 2.4 and a σ of 0.2 to obtain an "ideal" set of data points. The green lines indicate the target interval, which is defined as the target time of 2.4 minutes $\pm$ a variation of 20 seconds. The 20 additional or subtractive seconds reflect the suggested accepted variation from the target (section 2.5), based on the statement of the primary operator trainer (pers.com; 03-2017). An average σ of 0.35 (level 1 sigma) is found (Table 5.3 & 5.6), this translates to approximately 20 seconds. The suggested accepted variation is based on this "natural" standard deviation of the whole dataset.

The data points between the red trend lines comprise 68% of the monthly data (1 σ).

Ideally, the red and green lines would have the same inclination with the green lines amply compiling the red lines. The majority of the data points should fit abundantly between the red lines. Some anomalies are observed just outside the target interval, these are however uncommon and therefore not considered as significant. It should be noted that Fig. 5.3 strongly exaggerates the "ideal" situation of the green lines encompassing the red lines.

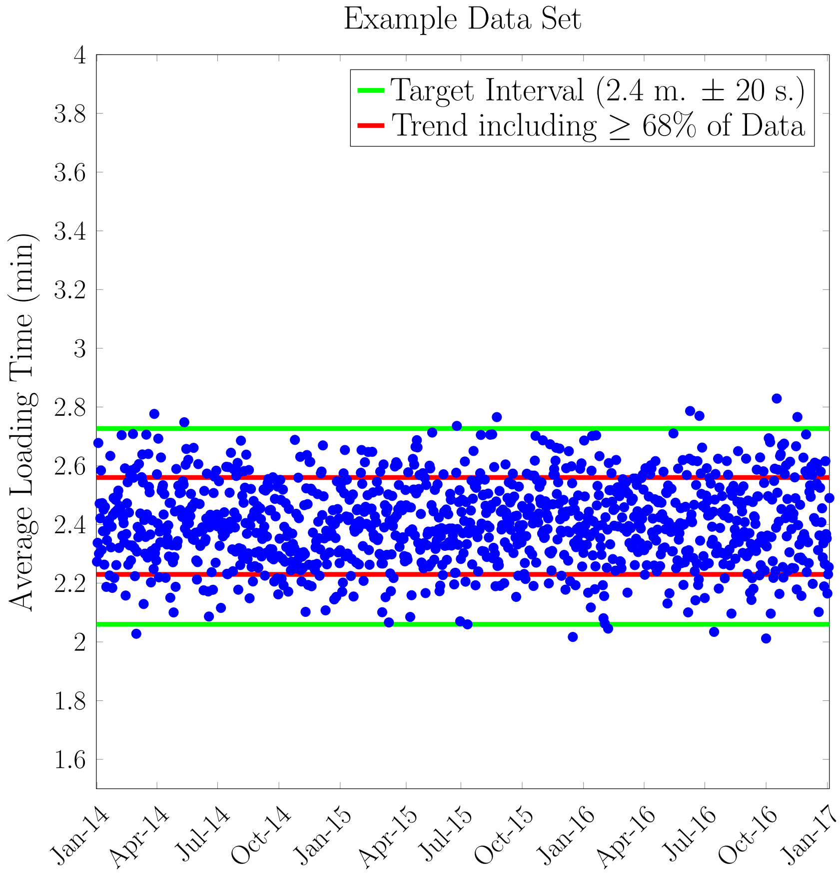


Figure 5.3: Example of Ideal Average Shovel Loading Time Data Set

5.3.1. Analysis of Subika Shovel Loading Time

When observing the variation of all three average shovel loading times in the Subika pit, it is clearly visible that the target time of 2.4 minutes is mostly not met. The red lines (Fig. 5.4) indicate the trend with the 1 σ variation from the monthly mean (Subika [Sk]). Naturally it would be logical to assume that each shovel (of the same type, age, etc.) has the same performance for identical working conditions. Shovel 6 however performs significantly below average when compared to Shovel 7 and 8 (Table 5.3) and also has the widest trend, which indicates a high (but sparse) variety of data points. Shovel 7 has the best performance based on Fig. 5.4, since the trend is more or less within the target interval.

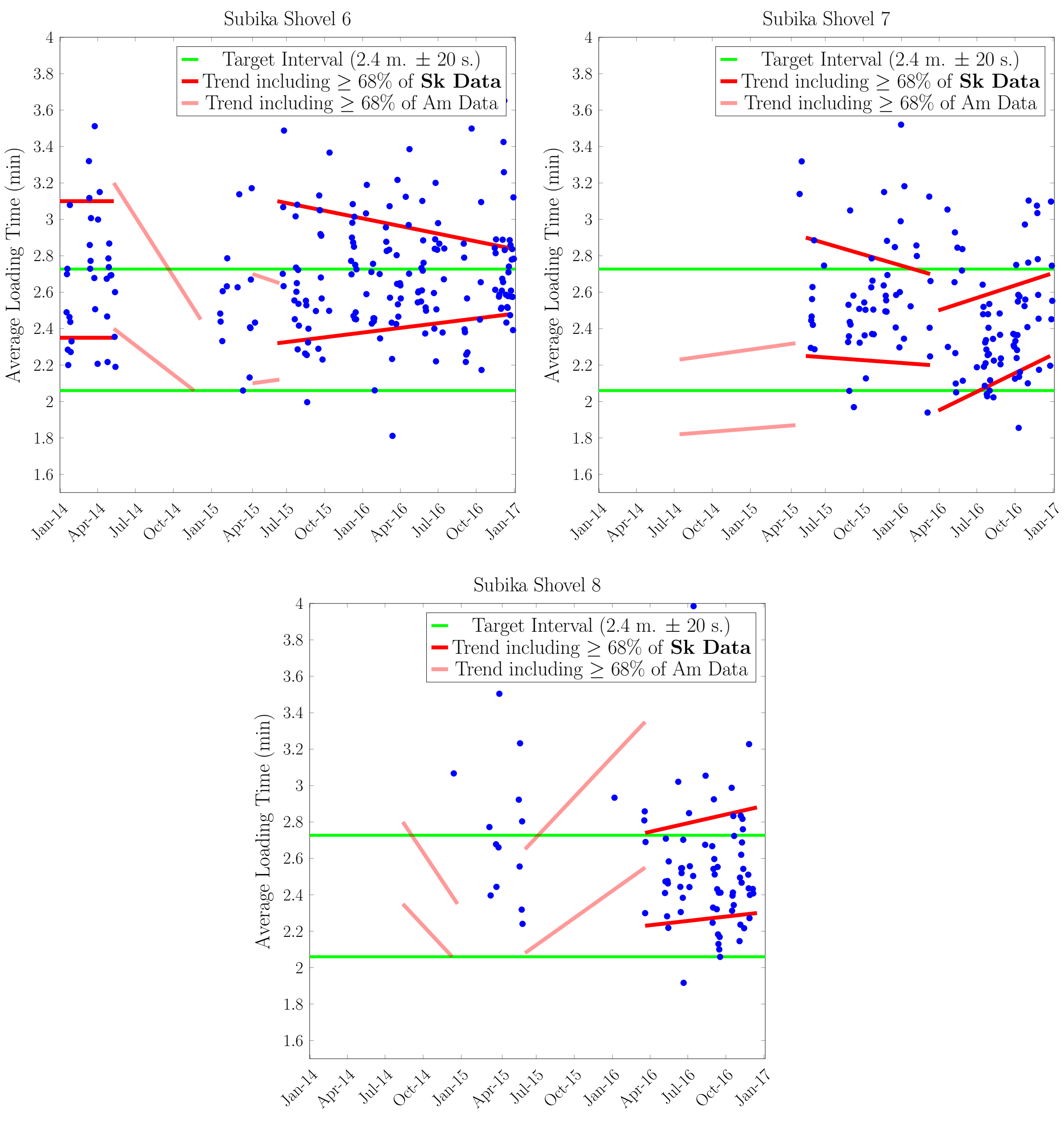


Figure 5.4: Scattered Daily Shovel Loading time Trend Subika Analysis

The transparent red lines in Fig. 5.4 and Fig. 5.6 indicate the trend of the shovel when operating in the other pit (Amoma [Am]). These transparent lines therefore provide an insight in the overall performance of the shovel (regardless of the pit). This information is used to determine whether or not the variation average shovel loading times is induced by the equipment itself. Each shovel shows an increase in average loading time towards the end of 2016. This is an interesting feature, since it was mentioned in section 4.1 that the monitoring of fragmentation was put to a halt during the second half of that year.

Fig. 5.5 visualizes the distribution of average shovel loading times in Subika with the accepted range of 1 σ as defined in section 5.1. The data was cleaned as described in section 2.5.

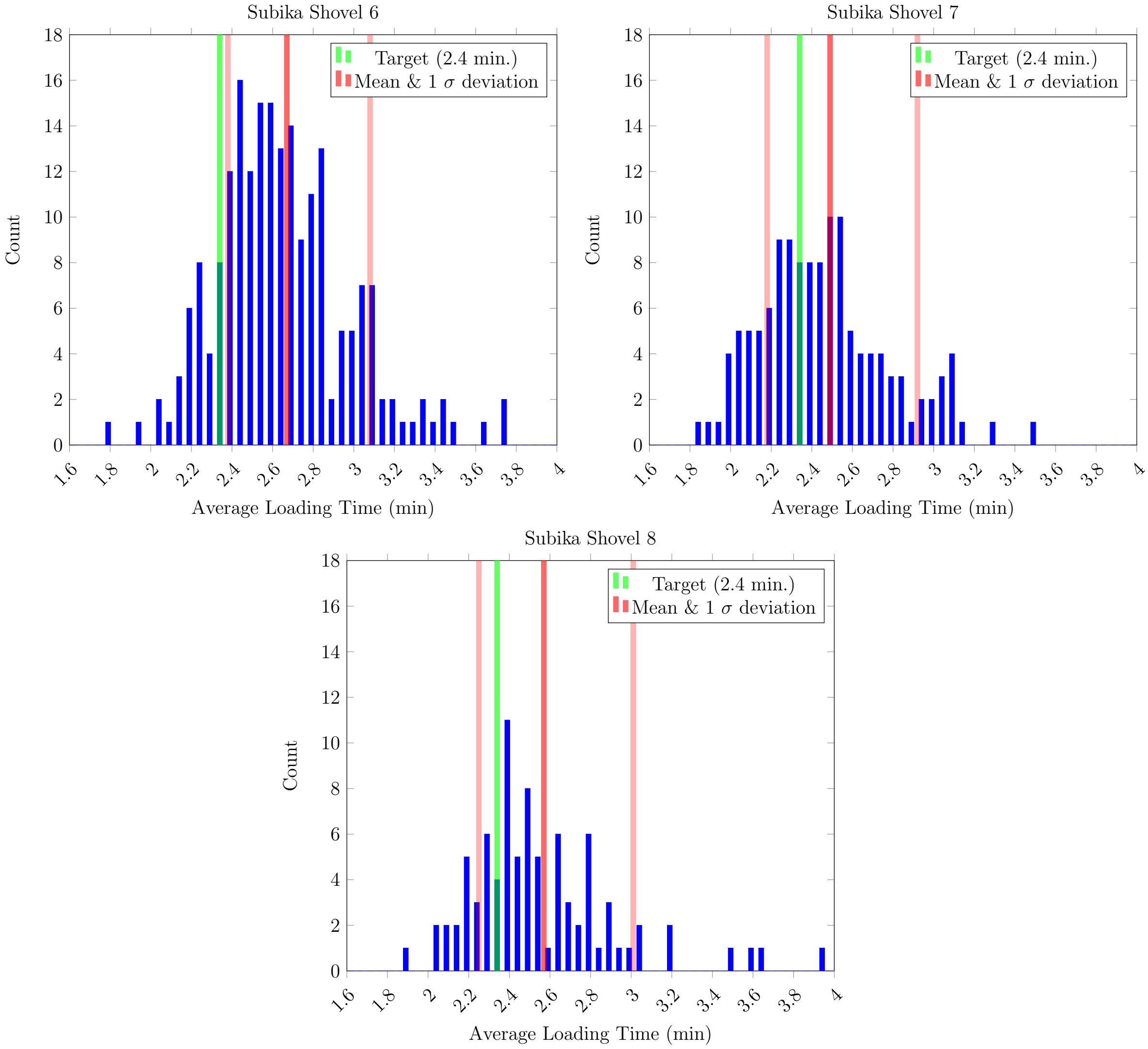


Figure 5.5: Histogram of Daily Average Subika Shovel Loading Time

Table 5.3 summarizes the statistical parameters of the distributions as shown in Fig. 5.5. It can be concluded that Shovel 7 has the best performance and that the standard deviation (σ) is constant for each of the three shovels. The table also summarizes the raw Subika average shovel loading time parameters, which show that the initial standard deviation was higher due to erroneous inputs.

Table 5.3: Statistical Indicators of Subika Shovel Loading Time Variance

Subika (minutes)	**SH006**	**SH007**	**SH008**	Subika Raw
Mean	2.69	2.51	2.59	2.60
Median	2.65	2.47	2.51	2.56
Standard Deviation	0.33	0.35	0.36	0.42

Shovel 6 and 7 both show two easily separable trends in the Subika pit. It was therefore decided to separate these areas in order to get an understanding of the statistical behaviour of each trend. For Shovel 6, period 1 (January 2014 - June 2014; data count: 33) and period 2 (May 2015 - December 2016; data count: 156) were defined. The statistical parameters (mean, median, standard deviation) of the two periods for Shovel 6 are summarized in Table 5.4. The variance is the same for both periods, where period 2 shows a slightly better median, meaning the daily average shovel loading times are skewed towards the target time.

Table 5.4: Statistical Indicators of two Periods of Shovel 6 in the Subika pit

Shovel 6 Subika (minutes)	**Period 1**	**Period 2**
Mean	2.7	2.7
Median	2.7	2.6
Standard Deviation	0.33	0.33

For Shovel 7, period 1 (May 2015 - March 2016; data count: 56) and period 2 (April 2016 - December 2016; data count: 71) were observed.

Table 5.5: Statistical Indicators of two Periods of Shovel 6 in the Subika pit

Shovel 7 Subika (minutes)	**Period 1**	**Period 2**
Mean	2.6	2.4
Median	2.5	2.4
Standard Deviation	0.32	0.37

Period 2 has a lower mean and median than period 1, however period 1 shows a decreasing trend where period 2 shows a decreasing trend. The increasing trend of period 2 can possibly be explained by a worsening fragmentation. Shovel 8 shows a similar trend in the Subika pit during the same period.

5.3.2. Analysis of Amoma Shovel Loading Time

The data that originates from the Amoma pit has a much higher density than the Subika pit data, which makes it much more suitable for a statistical analysis. Fig. 5.4 shows the accepted data range with a variation of 1 σ from the mean. Shovel 7 shows an excellent performance record with a trend well below the target interval, where Shovel 6 and 8 were making improvement during 2014 and early 2015. The steep incline of the trend of Shovel 8 lasting from mid 2015 until mid 2016 is remarkable.

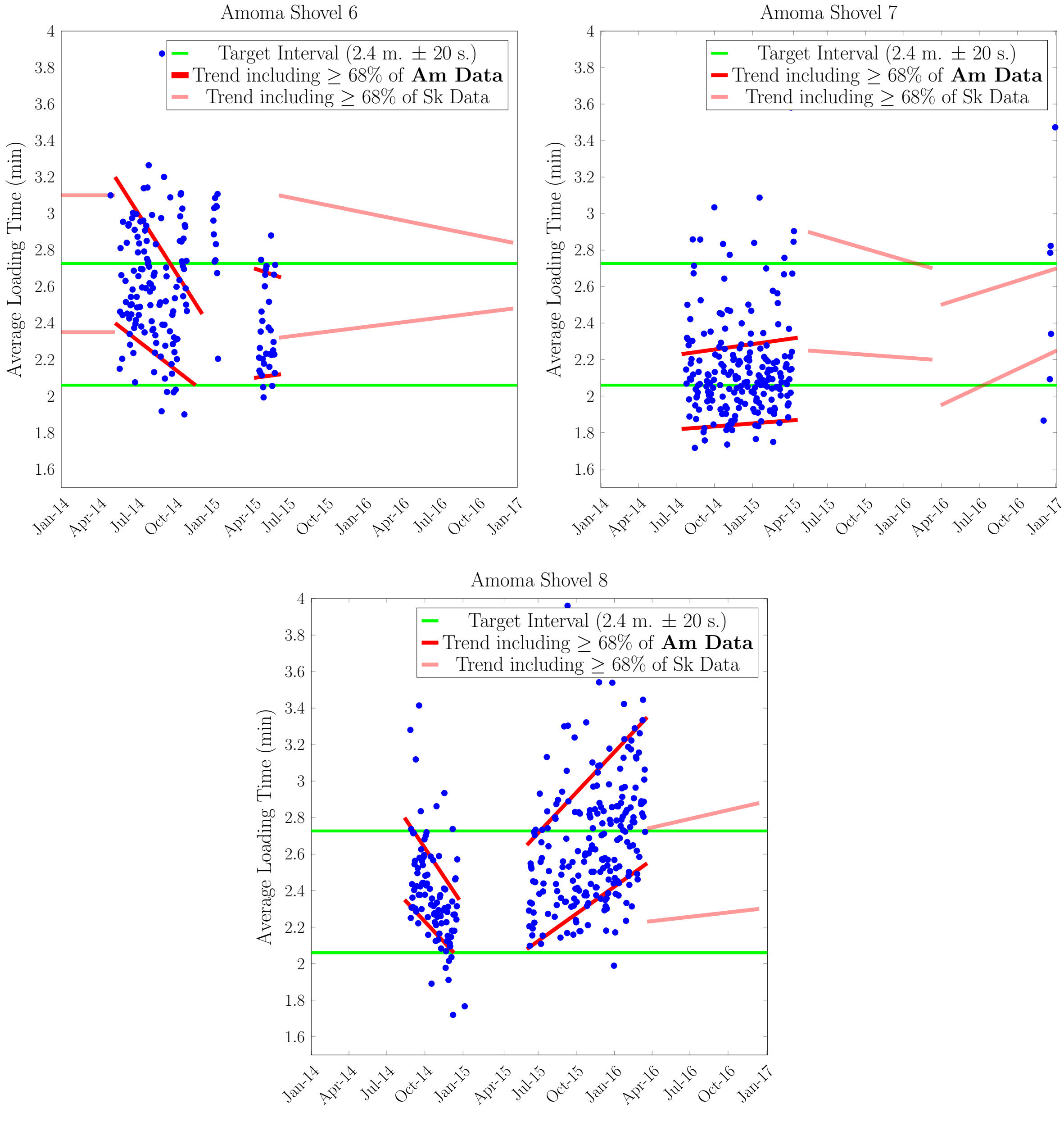


Figure 5.6: Scattered Daily Shovel Loading time Trend Amoma Analysis

The performance of Shovel 7 evoked some suspicion. A discussion with the maintenance superintendent provided clarification, since it was already assumed that Shovel 7 was a better piece of equipment than Shovel 6 and 8. The data was therefore assumed to represent the actual average loading times. It was stated by the maintenance superintendent (pers.com; 05-2017) that a possibility for a deviating performance between identical equipment could be explained by slight differences in adjustments of the hydraulics system, since these are extremely sophisticated and impossible to equate.

Fig. 5.7 displays the distribution of average shovel loading times in the Amoma pit. It became clear that Shovel 6 has a low number of data points, where Shovel 7 and 8 show a clear bell curve.

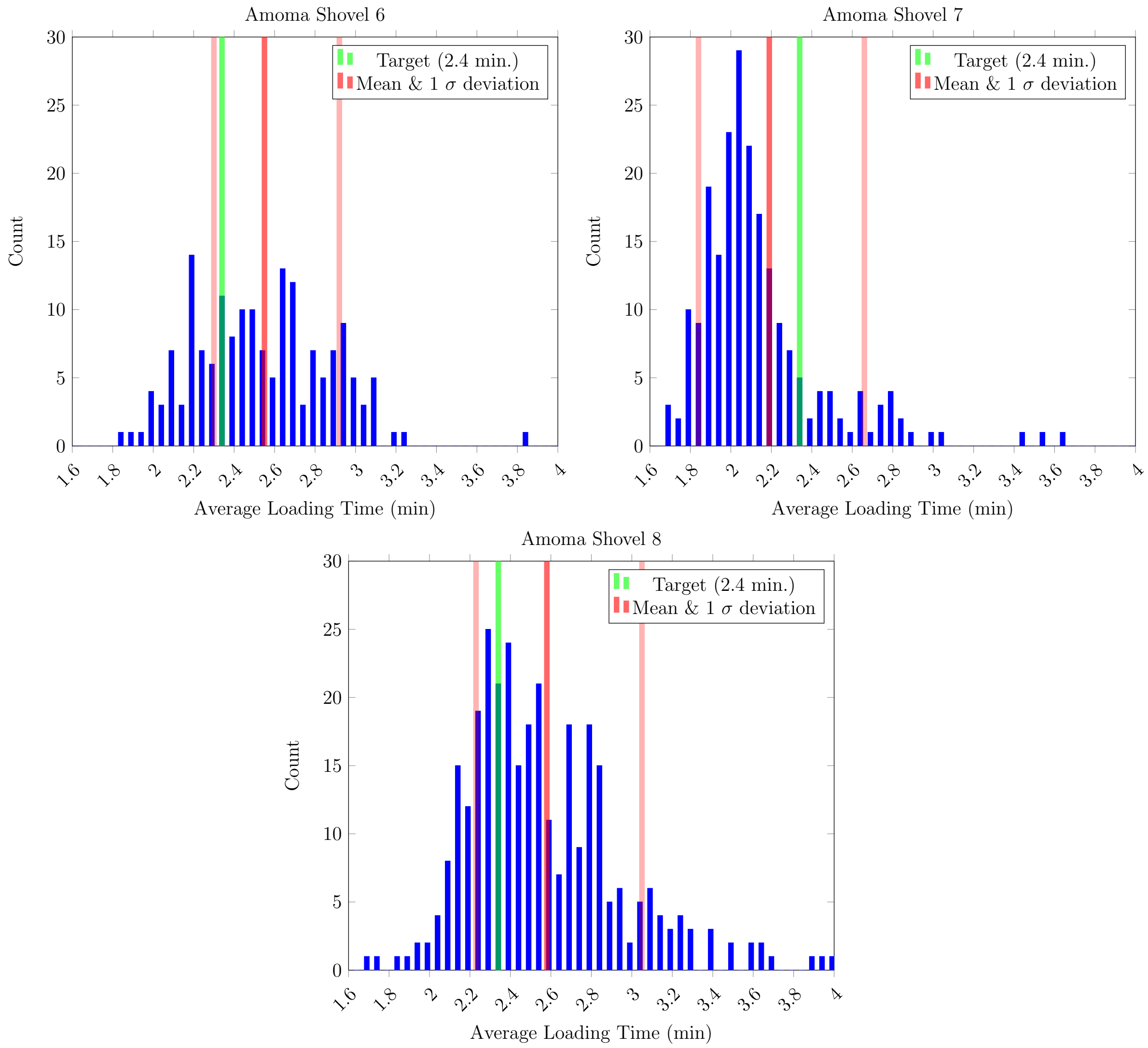


Figure 5.7: Histogram of Daily Average Amoma Shovel Loading Time

The results of the statistical analysis are summarized in Table 5.6, it shows that Shovel 7 has the biggest standard deviation

Table 5.6: Statistical Indicators of Amoma Shovel Loading Time Variance

Amoma (minutes)	**SH006**	**SH007**	**SH008**	Amoma Raw
Mean	2.57	2.21	2.60	2.62
Median	2.55	2.10	2.52	2.53
Standard Deviation	0.33	0.43	0.39	0.56

For Shovel 6, three different trends were observed while operating in the Amoma pit. Period 1 (May 2014 - November 2014; data count: 124), period 2 (January 2015; data count: 11) and period 3 (June 2015 - July 2015; data count: 32).

Table 5.7: Statistical Indicators of three Periods of Shovel 6 in the Amoma pit

Shovel 6 Amoma (minutes)	Period 1	Period 2	Period 3
Mean	2.6	2.9	2.3
Median	2.6	2.9	2.3
Standard Deviation	0.32	0.24	0.24

Shovel 8 is the only shovel that shows two separate high density data periods, namely in the Amoma pit. The first period (August 2014 - January 2015; data count: 101) shows a decreasing trend, where the second period (June 2015 - March 2016; data count: 217) shows an increasing trend, which can again possibly be explained by a worsening fragmentation.

Table 5.8: Statistical Indicators of two Periods of Shovel 8 in the Amoma pit

Shovel 8 Amoma (minutes)	Period 1	Period 2
Mean	2.4	2.7
Median	2.3	2.6
Standard Deviation	0.30	0.39

5.4. Analysis of the Fragmentation

The fragmentation data had to be separated, sorted and cleaned before it could be analysed. The data were provided in the form of parameters as discussed in Section 2.3.2 per each documented blast, including the estimated tonnage of the blast. The data had to be manually ordered and sorted by date, pit and blast pattern. All erroneous and duplicate data was checked, marked and removed if required. Some fragmentation data were available from the Awonsu pit. It was decided to include Awonsu pit data in the fragmentation analysis, since this pit will be brought back into operation as discussed in Section 2.1. The assumption is made that the fragmentation in the Awonsu pit is nearly identical to the fragmentation in the Amoma pit (Section 2.1) and that an investigation in the Amoma pit will therefore be relevant for future recommendations regarding the Awonsu pit. The following amount of documented fragmentation results were used: Subika: 302, Amoma: 198 and Awonsu: 64 with a total of 558. As discussed in section 2.3.2, the results of 584 documented blasts were gathered. The remaining 26 blasts were left out since these were specific or irregular blasts.

The P20, P50 and P80 were visualized in a scatter plot in order to attain an overview of the variation over time (Fig. 5.8). All data was considered during the visualization, it was however decided to leave unusual blasts like ”trimshots”; used to create a smooth crest, or ”rampshots”; used to create a steady ramp, out of this analysis. These form the 26 results that were left out. Such special blasts are not designed for regular production and would therefore only act as noise. Subika was not in operation during the marked red period (June 2014 - December 2014), while Amoma was intensely monitored. It is clearly visible that this period has the best overall performance regarding the P80 target, which is the red line marked at 350 mm. As discussed in section 2.1, at least 80% of the ROM should pass a 350 mm sieve in order to avoid boulder related delays or damages.

There is only little data on fragmentation available from before 2014, however there is enough to demonstrate that fragmentation was bad, with an average P80 of over 400 mm. This is due to inaccurate drilling, the pattern was laid out by ropes with knots. It was stated by the primary mine advisor (pers.com; 04-2017) that these knots were situated between irregular distances on these ropes. No data is available for blasts after September 2016, an increase in P80 can be observed, but through a few points. This is highly unfortunate since it would be valuable to see whether or not the blast pattern change (October 2015) influenced the P20, P50 and P80 values. For now it can be concluded that a peak in high P80 values is visible during 2016.

Fig. 5.9 visualizes the presence of boulders, as defined in Section 2.4.4. The obtained percentage of fragments exceeding 500 mm from visual analysis, as described in Section 2.3.2, was plotted per pit. As could be expected from Fig. 5.8, Amoma and Awonsu fragmentation analysis results show a low percentage of boulder presence, where Subika shows a significant amount of boulders. This is an indication that drill and blast is less effective in the Subika pit. The last fragmentation records originate from September 2016, Subika, showing a boulder presence of over 30% of all fragments.

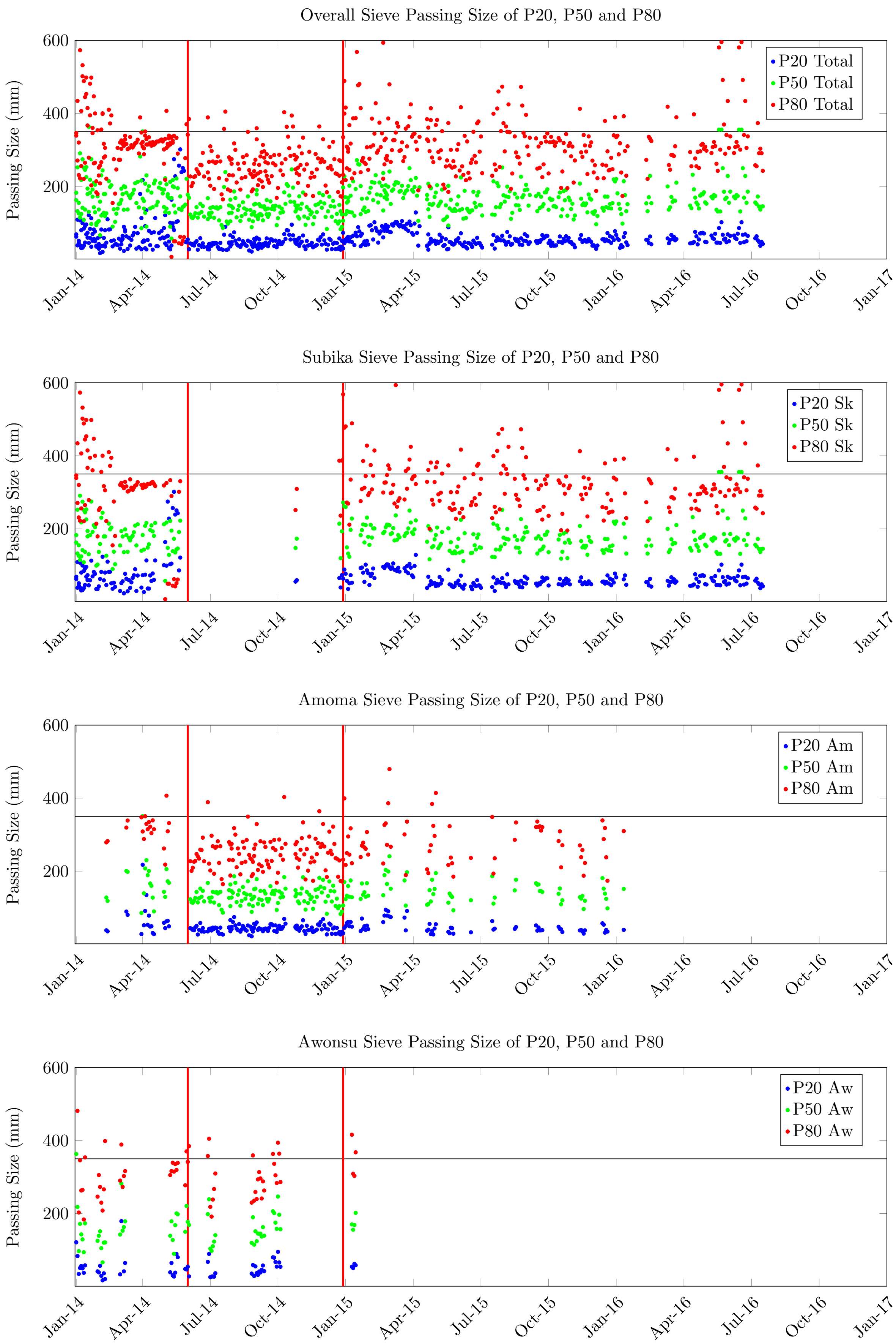


Figure 5.8: All documented P20, P50 and P80 Passing Sizes between 01-01-2014 and 31-12-2016

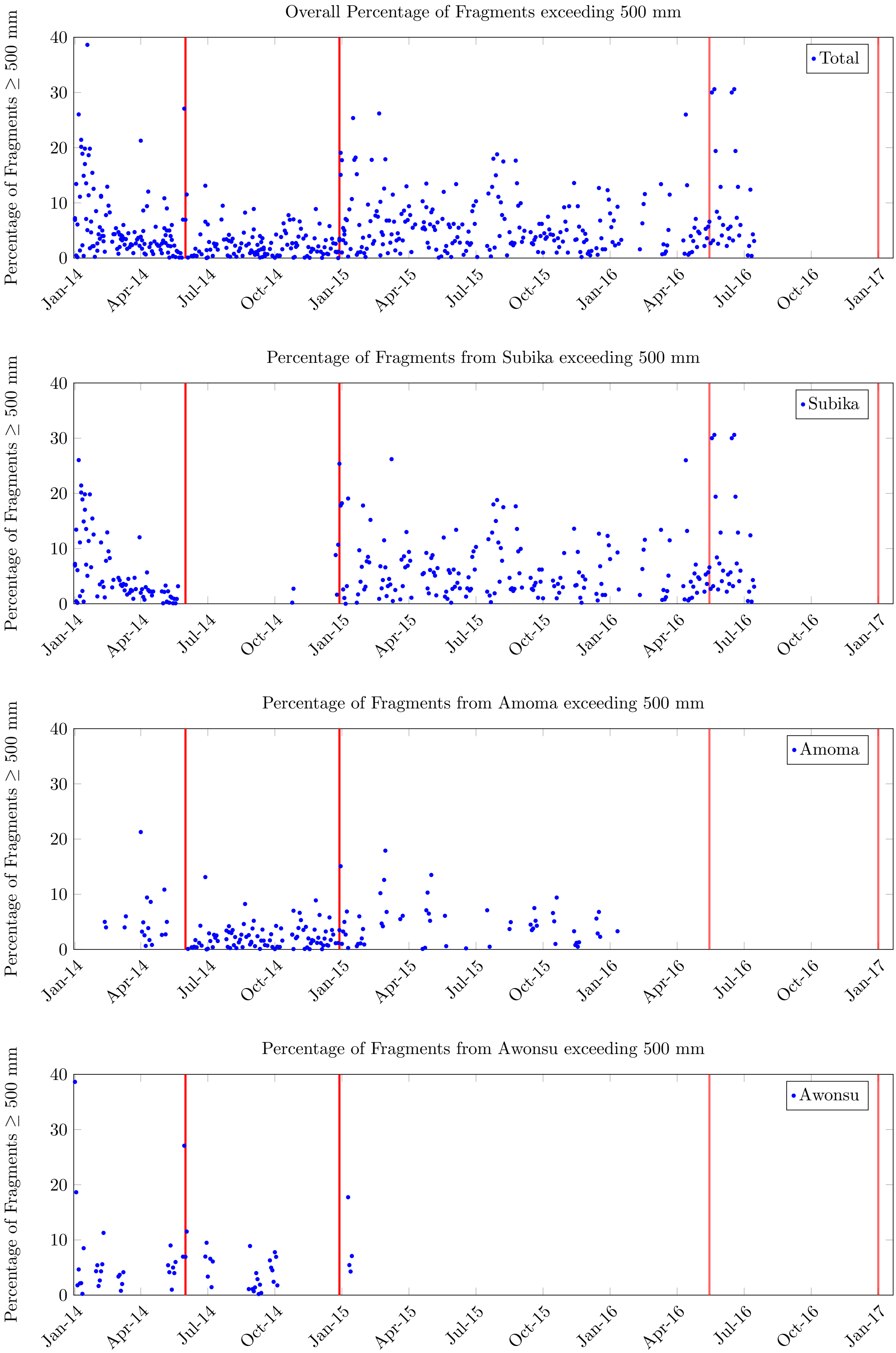


Figure 5.9: Oversized Material

5.5. Feed Blend Processing Plant

A good understanding of the feed characteristics is essential when aiming to improve processing performance. Not all the ROM arrives at the primary crusher, as discussed in Section 2.2. In order to comprehend a variation of processing performance, it is vital to understand what material is fed to the primary crusher and where it comes from. This could either be a stockpile or directly from any of the pits. Once the source is a stockpile, it is impossible to match the feed to its corresponding fragmentation. When ore is dumped on a stockpile, it gets mixed with ore that may have been there for months or even years. Some data were available on feed source, which was entered in a data sheet. This sheet was manually separated, so that the planned, actual-overall and actual-directly from pit could be visualized. The actual feed that came directly from the pit can be matched to the corresponding fragmentation analysis (if both were documented) and could therefore provide insight in the effect of fragmentation on processing plant performance.

5.5.1. Subika Feed

Fig. 5.10 provides an overview of the daily planned, actual and actual-directly from pit feed percentage of the Subika pit. The planned and actual feed percentages show a comparative trend, only between April 2015 and October 2015 some discrepancy is observed. The feed that originated directly from the Subika pit was not relevant during most of 2014 and 2015. Only in 2016 a trend can be seen where between 10- and 20% of the daily feed originated directly from the Subika pit. It seems that a Subika feed strategy was implemented from October 2015 onwards, this is also when the drill and blast pattern changes were enforced.

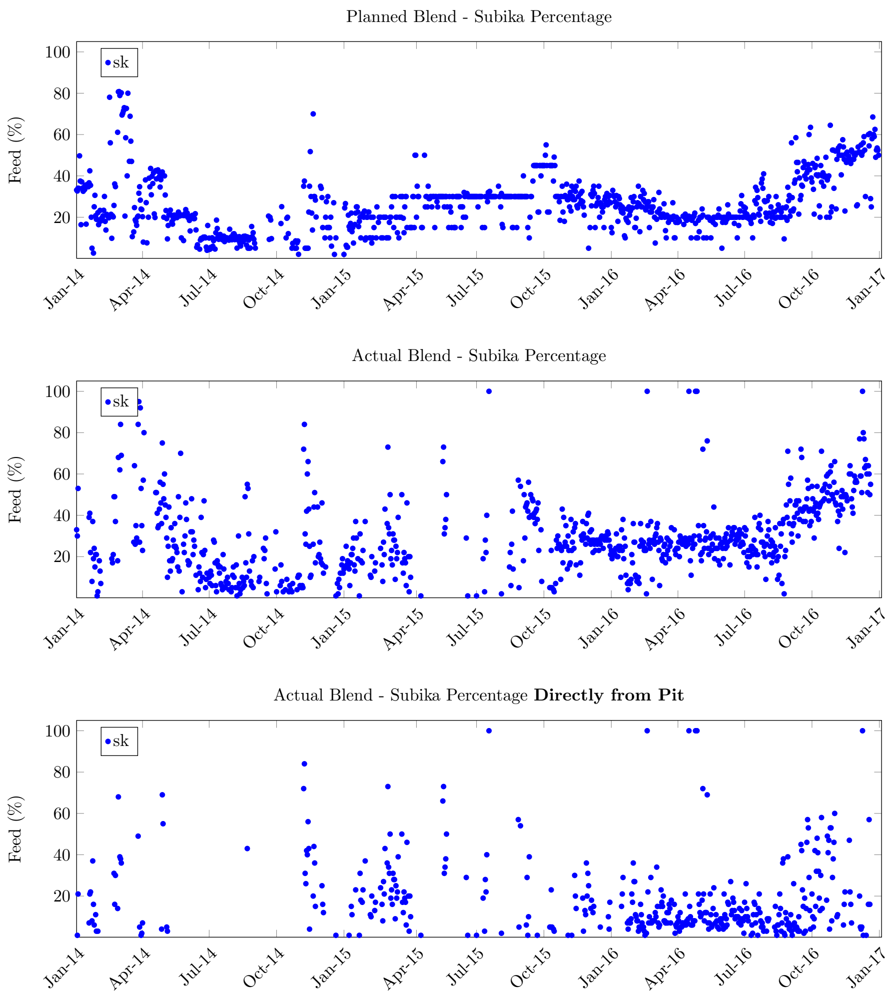


Figure 5.10: Subika Material Percentage in Blend (Planned/Actual/Actual Directly from Pit)

5.5.2. Amoma Feed

The source of the Amoma share feed is visualized in Fig. 5.11. As can be seen from the planned Amoma blend percentage, no clear strategy exists, where seemingly random Amoma percentages were blended with the feed. Values mostly vary between 30- and 80% where no Amoma feed was planned during the better part of 2014. It can be concluded that most of the actual blend percentage originated directly from the pit, however no feed directly from the pit was used for blending after April 2016.

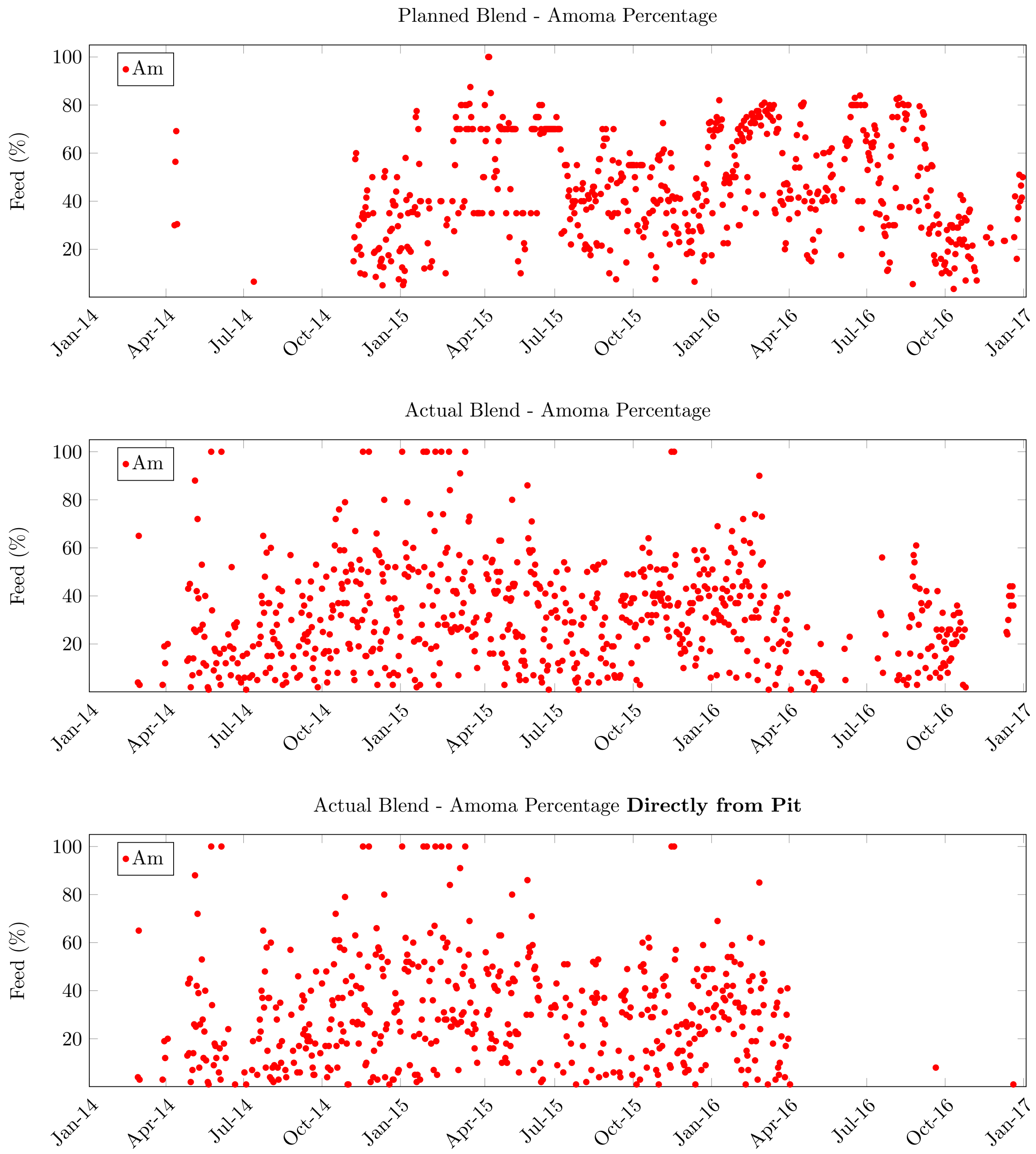


Figure 5.11: Amoma Material Percentage in Blend (Planned/Actual/Actual Directly from Pit)

5.5.3. Remaining Feed

For a full understanding of the blend percentages within the processing plant feed, it is vital to know what other material is included besides Subika and Amoma material. Fig. 5.12 shows the percentages of Apensu and Awonsu material in the blend. It is easily seen that Apensu (ap) material is rarely used for blending. The planned blend (aw) shows no clear strategy, where a strong discrepancy is observed between the planned and actual percentages during 2014.

The most remarkable observation that was made is in the ”Feed directly from pit” graph; As summarized in Table 4.1, Awonsu was only producing sporadically during 2014. During 2015 and 2016, Awonsu was out of production, where Apensu has been out of production for the whole three years. The ”actual directly from pit” blend percentages in Fig. 5.12 are therefore in contradiction with the information in Table 4.1. It is not possible that Apensu or Awonsu material from the pit was used, yet does the database explicitly provide daily moved tonnages from specific blasts. Initially it was assumed that the ”actual blend percentage” and ”actual blend percentage directly from pit” had been mixed up in the database. The two plots are however not identical, this can clearly been seen between October 2015 and January 2016. The data is thus unreliable and was not included for further analyses.

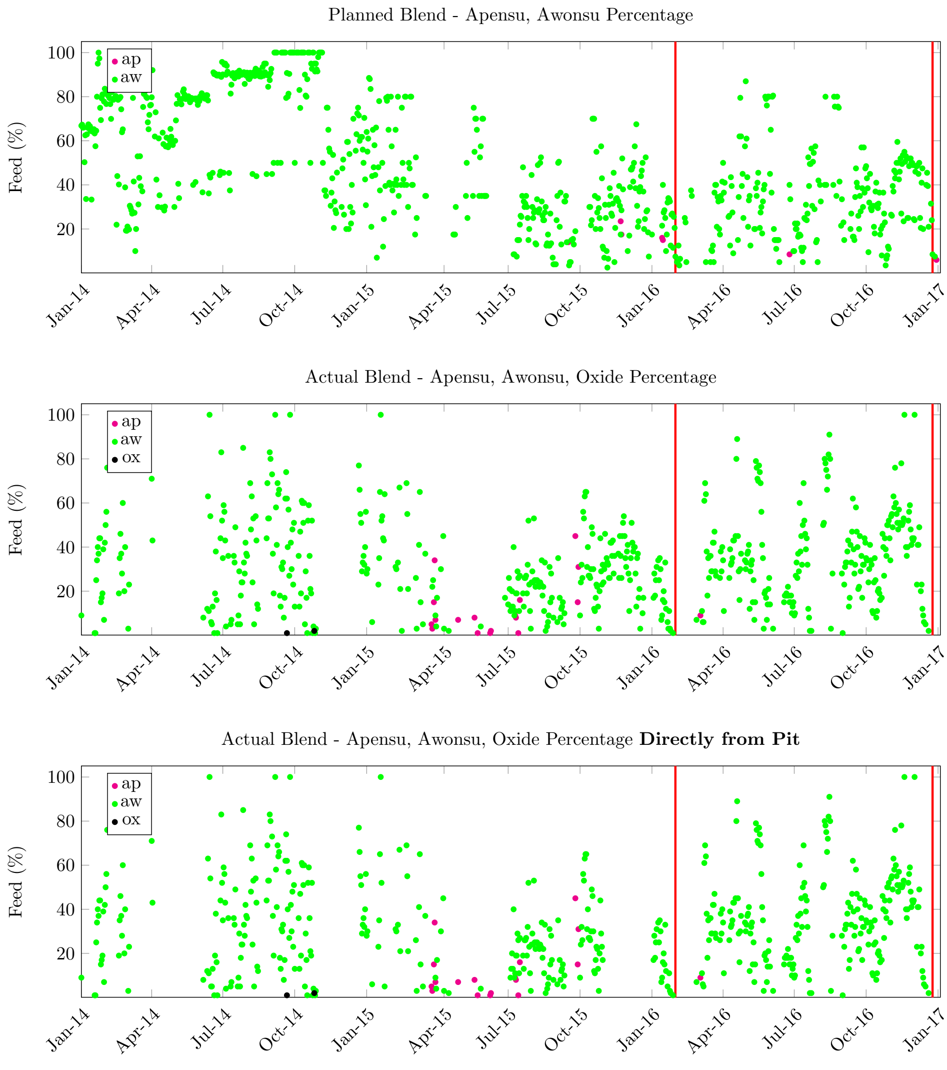


Figure 5.12: Apensu and Awonsu Material Percentage in Blend (Planned/Actual/Actual Directly from Pit)

5.5.4. Processing Plant Pit Feed

Fig. 5.13 summarizes the planned blend percentages of all sources. The sum of each day adds up to a 100%, this has been verified. As discussed before, no clear blending strategy seems to have been implemented. The most remarkable feature is that the Subika blend percentage shows an increasing trend during 2016. Another interesting aspect is with the Awonsu blend percentage, which were very high during 2014.

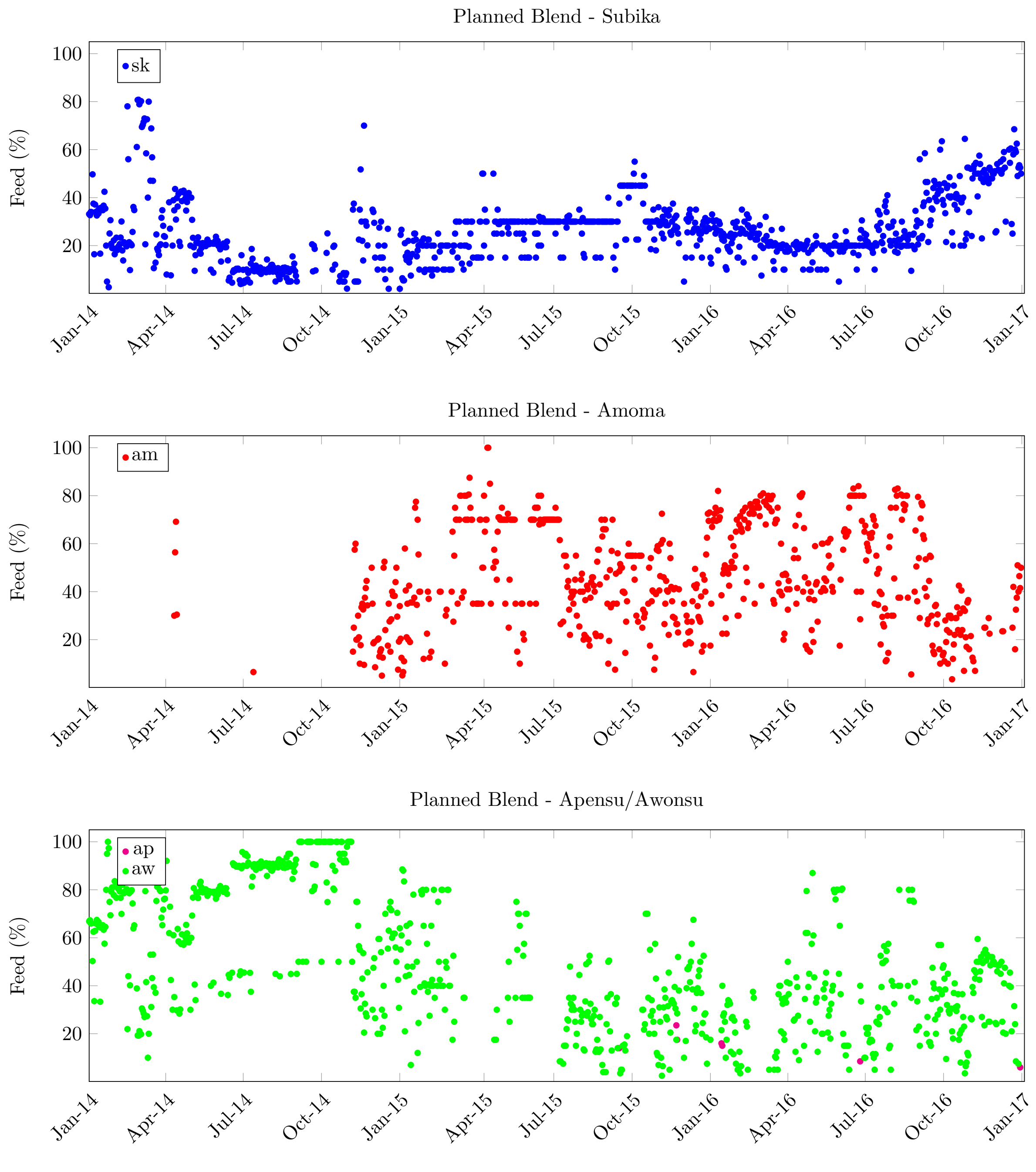


Figure 5.13: Planned Blend Percentage Overview

The actual blend percentages (Fig. 5.14) show that the planned blend was not achieved. Only the increasing trend of the Subika percentage during 2016 is noticeable. These planned targets are more or less accomplished. These three graphs always add up to 100% every day, this has been verified.

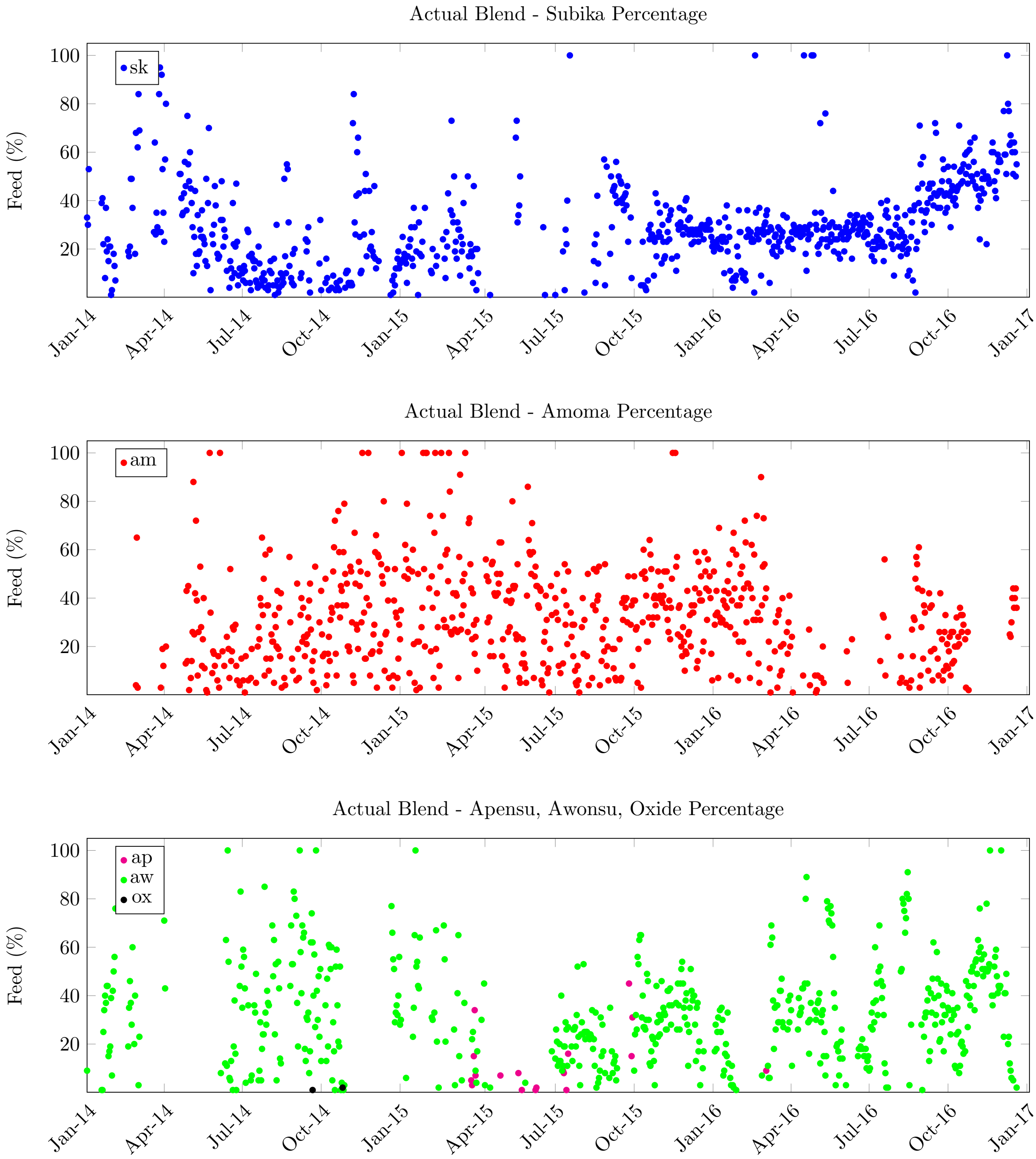


Figure 5.14: Actual Blend Percentage Overview

Fig. 5.15 summarizes the information that is needed to conduct the research. Based on these blending percentages, certain fragmentations that have been analysed on known dates and locations could be linked to processing plant performances. Since not all mined material is fed directly to the processing plant, it was decided to focus on days where ≥ 80% of the blend consisted of material directly from the pits. As discussed earlier, the "actual blend directly from pit" concerning the Apensu and Awonsu pit is unreliable. Therefore only Subika and Amoma were considered within this ≥ 80%. This is visualized in Fig. 5.16.

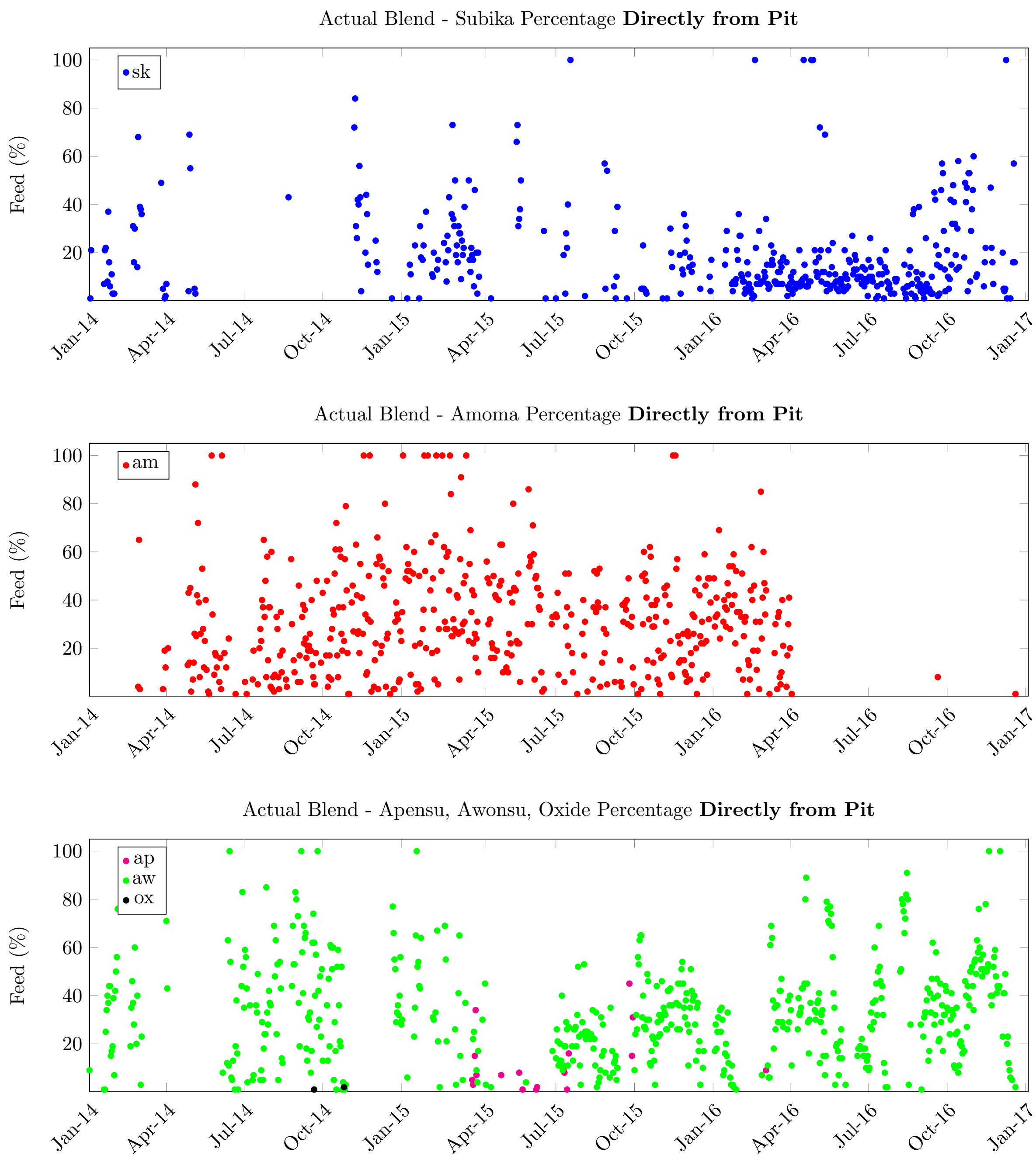


Figure 5.15: Actual Directly from Pit Blend Percentage Overview

There have been only a few cases where the processing plant was fed directly from the pits. This is mainly the result of a moderate gold price, leaving the company no choice but to consume all high grade stockpiles in order to continue to keep the operation economic. Fig. 5.16 visualizes the daily percentage (≥ 80%) of feed that originated directly from the pits. There are 1097 data points in total,

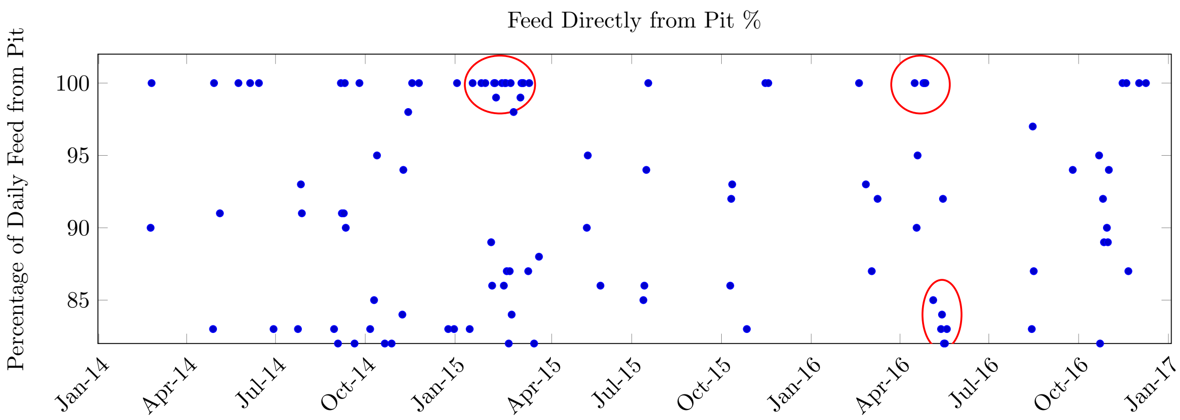


Figure 5.16: Days where at least 80% of the processed material originates directly from the pit

one for each day, but not all are visible since only the higher range is visualized. This means that the data is very dense and that it is hard to recognize whether or not certain points succeed each other. Table 5.9 therefore summarized periods of interest. These periods meet the following requirements; A duration of at least three days where a minimum of 80% of the feed originated directly from the pits. Period B, C, D and E are circled as a whole since these periods lie within one month, period I is circled since it included three days with 100% pit feed and period J contains 8 straight days with over 80% of pit feed. These three marked areas were used to analyse mill throughput and performance.

Table 5.9: Periods of Interest with High Feed from Pit Ratio

Period	Start Date	End Date	Low (%)	High (%)	Average (%)	Duration (Days)
A	06-09-2014	11-09-2014	80	100	92	6
B	10-02-2015	12-02-2015	99	100	100	3
C	20-02-2015	23-02-2015	86	100	93	4
D	25-02-2015	28-02-2015	82	100	88	4
E	09-03-2015	12-03-2015	99	100	100	4
F	16-05-2015	18-05-2015	81	95	89	3
G	10-10-2015	12-10-2015	86	93	90	3
H	16-04-2016	19-04-2016	60	100	86	4
I	25-04-2016	27-04-2016	100	100	100	3
J	13-05-2016	20-05-2016	80	92	83	8
K	14-08-2016	16-08-2016	83	97	89	3
L	30-10-2016	01-11-2016	89	94	91	3

It is not possible to match precise fragmentation figures to these periods, since it is not known when exactly a muckpile was mined by the shovels. Depending on the situation, it might take up to several days or even weeks before the actual blasted and analysed rock is transported to the crusher (or stockpile). Weekly fragmentation distribution averages were therefore used to analyse the downstream effect. Fig. 5.8 shows that Period B, C, D and E are of interest for such a comparison, since the P20, P50 and P80 show exceptional high values during the dates covered by these periods. The remaining marked periods could unfortunately not be linked to a fragmentation distribution since the data is too sparse (Fig. 5.8).

5.5.5. Crusher Delays

The data on delays of the primary crusher were obtained in order find a potential correlation between the presence of boulder with the performance of the crusher. All delays that are not caused by boulders have been filtered out. The official causes of delays that were included are: ”Bogged”, ”Bridged”, ”Clogged”, ”Hang-up” and ”Large Rock”. The daily delay in minutes was visualized in Fig. 5.17. Two periods were marked, A and B, by red lines and show an interval with exceptionally long delays. Period A, January 2014 - January 2015, displays a wide spread of delay duration. Period B, May 2016 - Dec 2016, shows a significant increase in long daily delays. From each day, data were available, which means that a minimal daily delay of up to 20 minutes was documented in July and August of 2016. The red circle possibly matches the increase of boulder presence to an escalation in (long) crusher delays during late 2016.

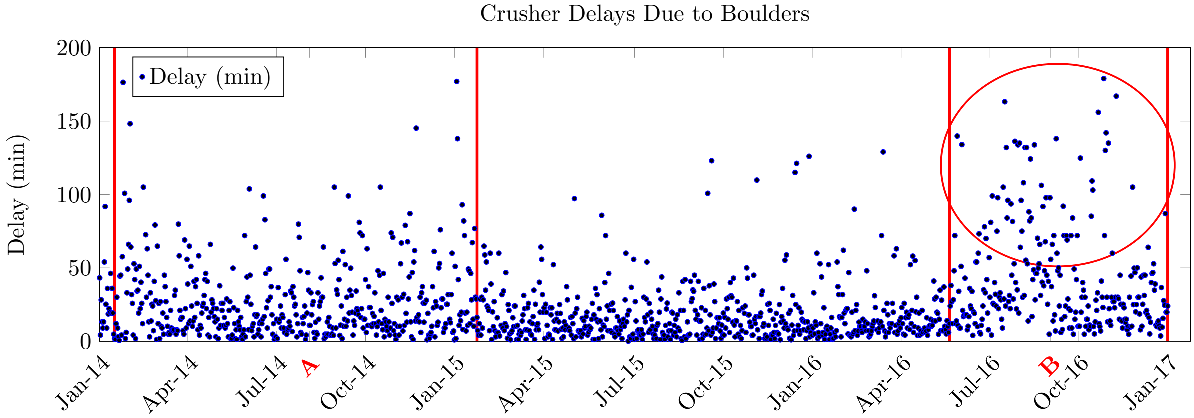


Figure 5.17: Delays at the Primary Crusher due to Blockings caused by Boulders

5.5.6. VisioRock™ Data

Once the material has passed the primary crusher, it is conveyed to the processing stockpile. The material is scanned before it is dumped on the stockpile using a VisioRock™ camera. This is a real time camera that constantly scans and calculates the size distribution after crushing (Fig. 5.18).

Figure 5.18: The VisioRock™ system as visualized by Metso [20]

Fig. 5.18 illustrates the VisioRock™ camera as located on a conveyor belt. The camera is placed in a sheltered box above the belt, where it continuously scans the passing material using a laser that emits a signal and a receiver that captures the reflected signal from the material on the whole width of the conveyor belt. A computer then calculates the size distribution per time unit, which is sent to the operators.

The desired amount of fines is 20% (pers.com; 05-2017) as NGGL considers all material $\leq$ 14 mm as fines, since a higher percentage of fines would relieve the SAG mill too much of its task. This would result in excessive wear-and-tear of the inside of the SAG mill. The P20 target is therefore set at 14 mm, the P80 target is set at 140 mm as discussed in section 2.2.

Fig. 5.19 visualizes the daily average size distribution of the passing material on the conveyor belt.

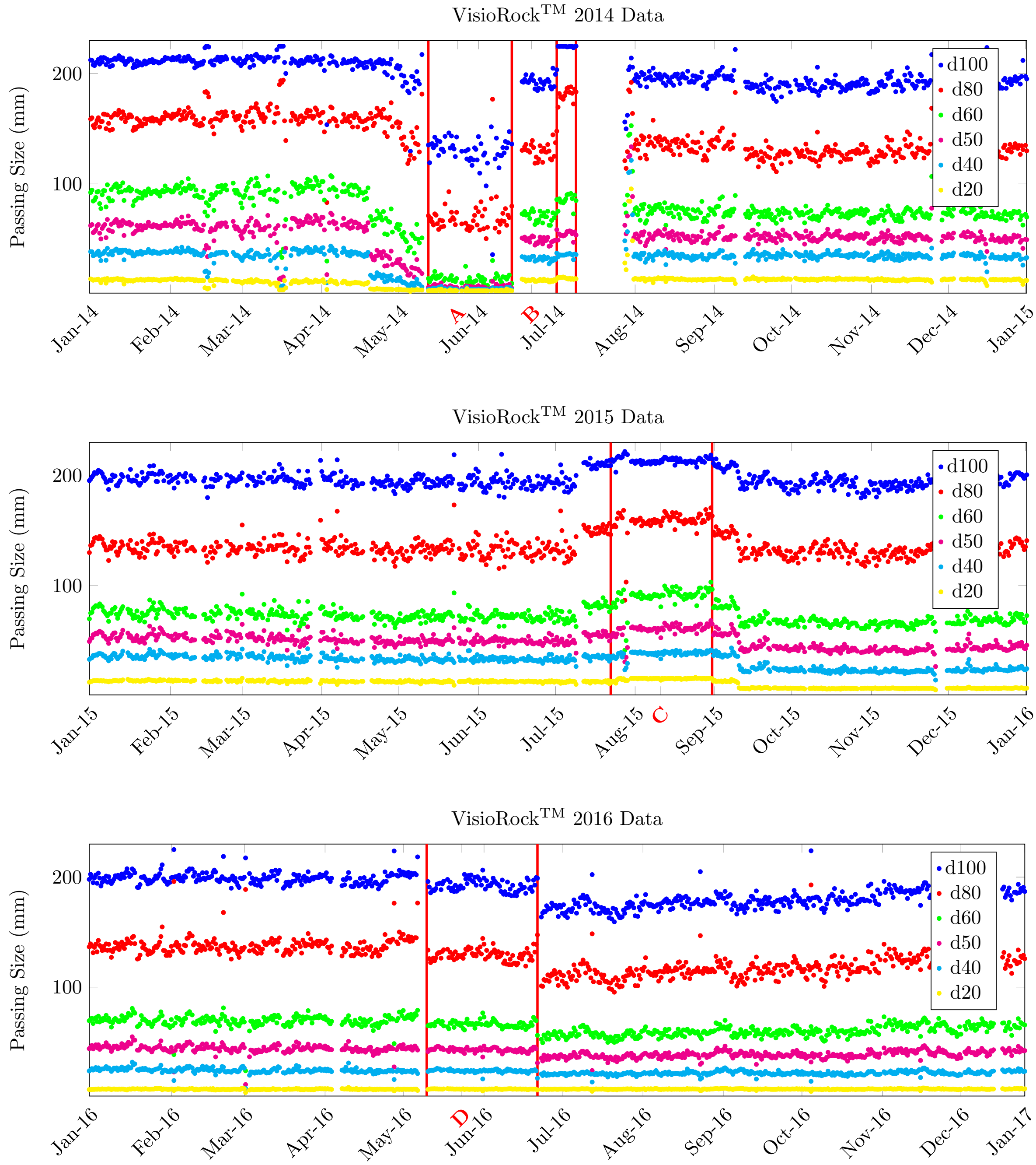


Figure 5.19: VisioRock Fragmentation Data 2014-2016

Several remarkable periods have been marked as A (12 May 2014 - 13 June 2014), B (1 July 2014 - 9 July 2014), C (22 July 2015 - 30 August 2015) and D (9 May 2016 - 19 June 2016), where significant shifts were observed. These periods could indicate a change in blend of the feed, or they could be calibration errors. As discussed in Section 2.3.3, fragmentation variance can still occur downstream of the primary crusher. This made the VisioRock™ Data of high interest for the research.

Fig. 5.20 up to Fig. 5.25 show a detailed course of respectively the D20, D40, D50, D60, D80 and D100 daily actuals. D stands for diameter and gives the passing diameter at fixed (20, 40, 50, 60, 80, 100) percentages of the distribution. The D100 gives the maximum detected fragment diameter per day. The marked areas A, B, C and D have been included in these figures so that a schematic comparison can be done. The first noticeable observation that was done is that the "effects" of certain activities increase with the fragment size. A clear example is provided by area D; the D20 measurements show no change after period D, where the D50 shows a moderate "jump" and the D100 shows a big "jump". This observation is valid for all of the four marked periods. Period A was disregarded as erroneous due to calibration inaccuracies, since no other explanation was found within the blend- (Fig. 5.15) or throughput (section 4.4) data for a sudden drop. A very low throughput was documented during period B, this does however not explain why the crusher would produce material that doesn't meet the D80 target.

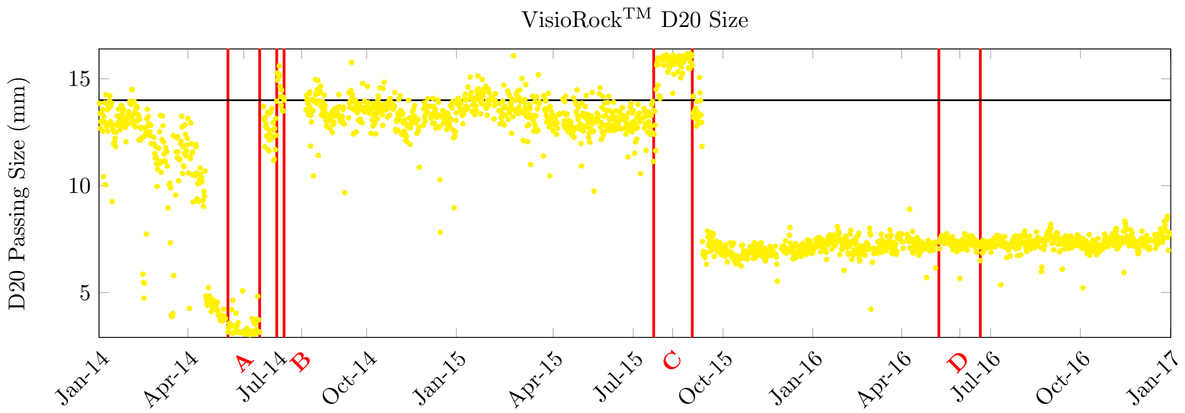


Figure 5.20: VisioRock™ D20 Size

Both the D20 and D40 sizes show a strong decrease after period C. This means that the material became finer, since the 20% and 40% passing target was already met at a lower diameter. The D20 size reduced from ± 15 mm to ± 7 mm after period C. The D40 reduces from ± 40 mm to 25 mm. During period C, a sudden jump in values was observed in the D20 graph, this jump has become much smoother in the D40 graph.

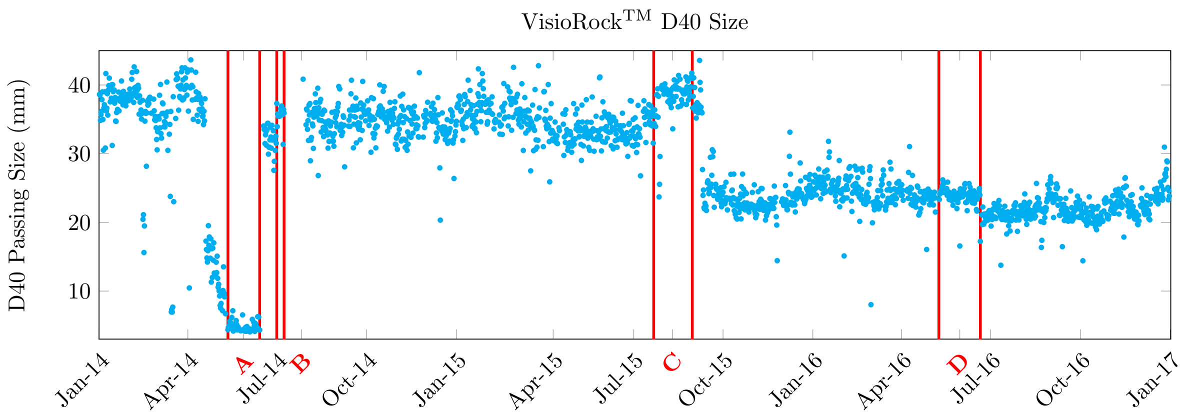


Figure 5.21: VisioRock™ D40 Size

The change in the VisioRock™ values, triggered by an activity during period D, is not visible in the D20 graph. A small drop was observed after period D in the D40 graph.

Period C became more of an anomaly than a jump, since the D50, D60, D80 and D100 graph shows similar value before and after period C. This was not the case in the D20 and D40 graph. The jump after period D however increases with the screen size. Where period D does not seem to affect the D20 values, it does considerably influence the D80 and D100 values.

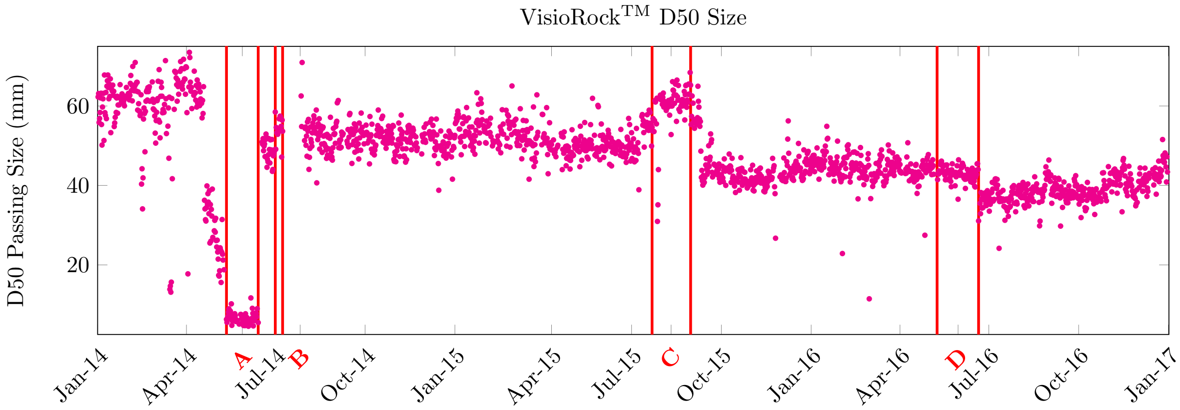


Figure 5.22: VisioRock^{TM} D50 Size

The D50 values were interpreted as the median of the distribution, since the median is defined as ”The value that separates the higher half of a distribution from the lower half”. The median shows a decreasing trend over the three year time span, where period D introduces the lowest median (excluding period A). An increasing trend was observed towards the end of 2016.

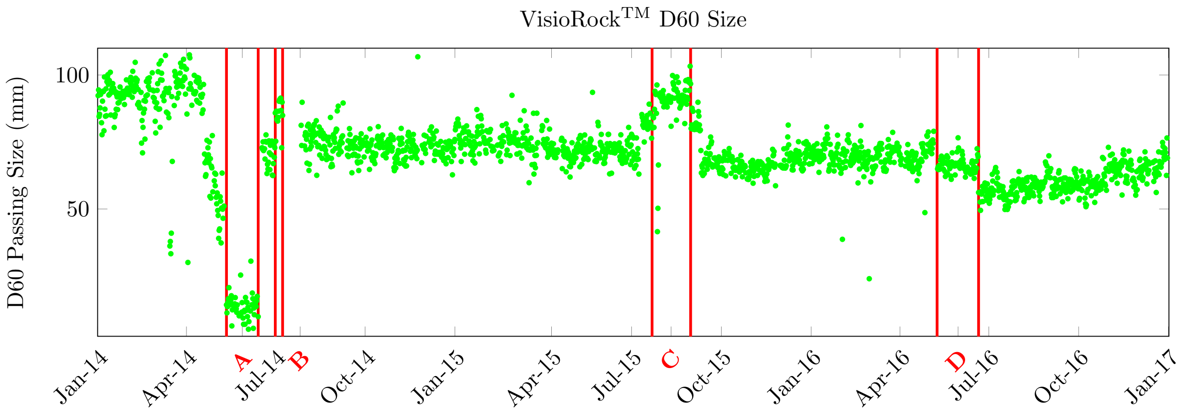


Figure 5.23: VisioRock^{TM} D60 Size

The regressing trend that occurs just before period A is visible in all graphs. While it seems to have a smooth transfer towards the lower values within the period, it becomes clear in the D60 graph that there is a sudden jump in the values. This backs the assumption that period A consists of erroneous data, since a sudden jump is not desired.

Fig. 5.24 illustrates the performance of the crusher. 80% Of the material should pass through a 140 mm sieve. This means that the D80 values should be under 140 mm, the D80 target is therefore an upper limit. Prior to period A, the D80 target was not met. After both period A and B it was observed that efforts are made to stay under the 140 mm. Just short before period C and D, an increase is observed in D80 values. After period D, the values are well below target, however it seems that the values are getting close to 140 mm by the end of 2016.

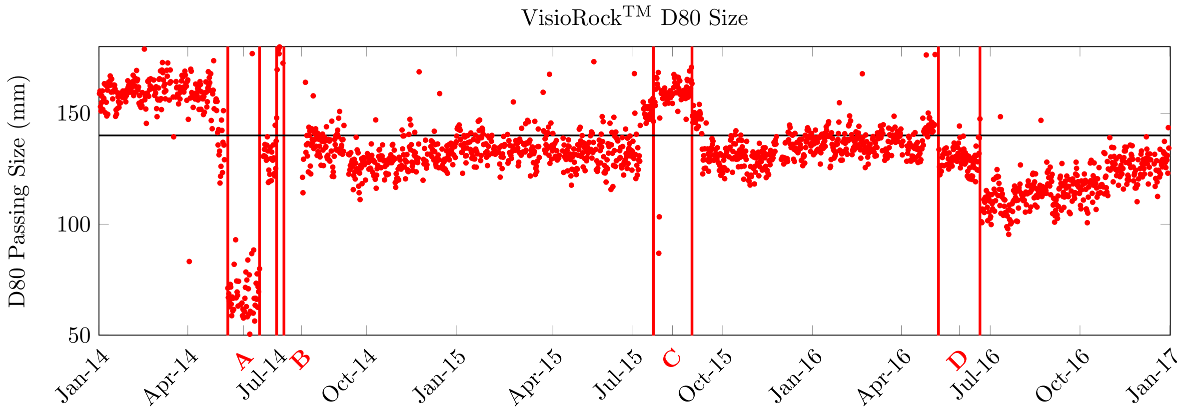


Figure 5.24: VisioRock™ D80 Size

The maximum sizes that were observed have been visualized in Fig. 5.25. These values vary the most, when period A and B are not included. This is an interesting observation since the varying fragmentation distribution of the ROM may be the cause of this. As discussed before, the assumption made by the mining department, is that the crusher eliminates all issues that come with a varying fragmentation. Fig. 5.25, and the other VisioRock™ Data, proved that this is not the case.

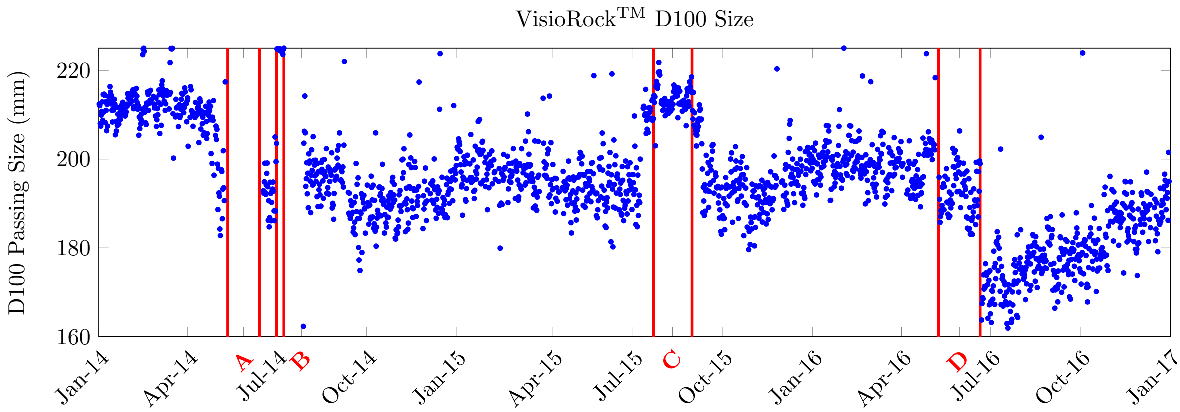


Figure 5.25: VisioRock™ D100 Size

5.5.7. Throughput Model

A throughput model was constructed by the mining department in order to predict SAG mill throughput, since this mill is the limiting factor in the processing plant. Each pit and its corresponding deposit have been given a linear equation, of which the constants A and B have been summarized in Table 5.10. The initial point on the y-axis indicate the process-ability of the ore, the lower this value, the harder it is to break. The gradient is defined by the mill-ability of the oxide material of that particular pit, however no oxide has been included the blends since 2013. The red line indicates the maximum capacity of the processing plant, which is 8 Mt per year.

These values are based on yearly feedback data and are updated each year, it was however recommended in the ”Ahafo Processing Models Presentation 2017” to keep using the 2014/2015 model. During this presentation (pers.com; 05-2017) the following note was addressed: *”The modeled throughput on a monthly basis is based on the blend data provided which not always aligns with tonnes processed for a particular month (survey accuracy, accuracy of truck factors, coarse ore stockpile in between, etc.).”*

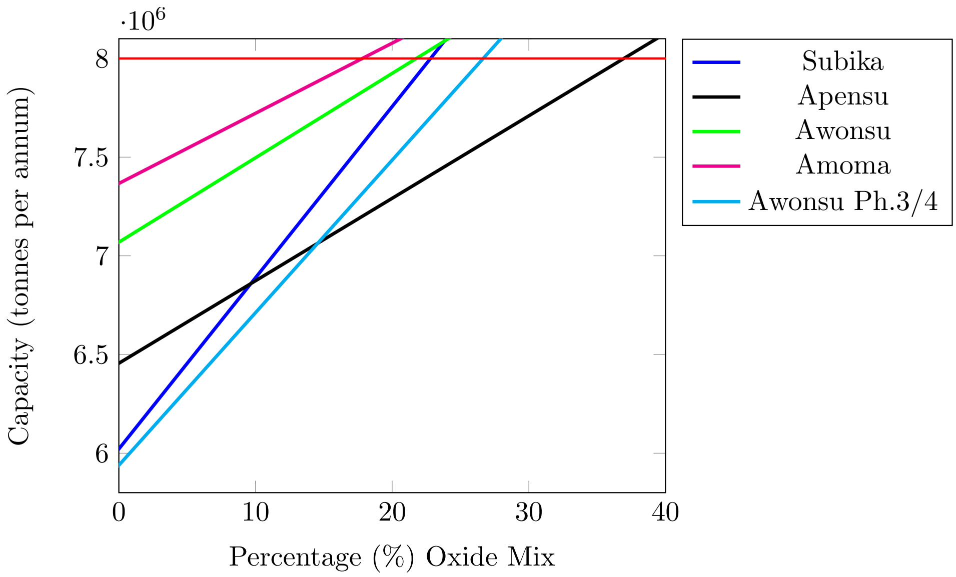


Figure 5.26: Throughput Model Proposed for 2014-2017 by Ahafo South

Fig. 5.26 shows the linear equations of each of the four pits. Section 2.1 mentions that the properties of Apensu, Amoma and Awonsu ore are nearly identical. It is therefore surprising that Awonsu Phase 3&4 (commencing 2019) are expected to be hard to mill, where a 100% blend has an annual capacity of under 6 Mt. This is way below the capacity of the processing plant, there will however be some oxide to mix due to the necessary push-backs.

Table 5.10: Throughput Model 2016 Ahafo South

Throughput Model	**A** (Primary)	**B** (Oxide)	**Maximum Capacity**
Subika	8,674,294	6,021,369	8,000,000
Apensu	4,178,981	6,455,533	8,000,000
Amoma	3,555,209	7,366,545	8,000,000
Awonsu	4,277,101	7,068,970	8,000,000
Awonsu Phase 3/4	7,730,940	5,938,686	8,000,000

6

Improvement in Productivity & Cost Reduction

Based on the comparative historical analysis described in Chapter 3, it was possible to suggest several possibilities for productivity improvement and cost reduction.

6.1. Improvement in Productivity

In order to improve productivity, several ”Quick Wins” were summarized. These may however not be financially interesting and should therefore be analysed;

- Improve Fragmentation: A finer fragmentation results in an elimination of secondary drill & blast and an increase in diggability, road competence, tire life, equipment life expectancy and processing plant throughput.
- Improve shovel loading times: resulting in a lower load & haul cost per moved tonne.
- Improve documentation of production figures to obtain a better understanding of the operation.
- Optimizing the Blend: results in an increase of processing plant throughput.

6.1.1. Improving Fragmentation

There were two possibilities considered to improve fragmentation:

- Double benching: Benches of 16 meters heigh (2 * 8 m. bench) are drilled & blasted.
- Optimize the drill & blast pattern: Narrow down the pattern to where the Kuz-Ram model predicts that the P80 target is met.

Double benching; As described in section 3.1.3, one of the parameters affecting the (predicted) fragmentation distribution is the height of the bench (H). When a double bench height (16 m.) is applied in eq. 3.10, a higher blast parameter n is obtained (n = 1.59). The drill & blast team would benefit from a double benching method, since they only need to drill half of the holes they currently drill. These holes are however twice the depth, but the primary mine advisor stated (pers.com; 04-2017) that this can be done without any modification on the equipment. In order to use no more explosive than the current amount per tonne, an alternative equation is suggested [8] where two separate charges are used in a single hole:

$$n = \left(2.2 - \frac{14B}{d}\right)\left(\frac{1}{2} + \frac{S}{2B}\right)^{0.5}\left(1 - \frac{W}{B}\right)\left(\frac{L}{H}\right)x\left(0.1 + abs\left[\frac{BCL - CCL}{L}\right]\right)^{0.1} \tag{6.1}$$

Where BCL stands for ”Bottom Charge Length (m)” and CCL stands for ”Colum Charge Length (m)”. This formula indicates that a borehole with two separate charges always results in a slightly lower n

value. On the other hand, using only one charge in the hole would result in a higher n value, which also implies that more explosive is needed. With a H of 16 meters, the Kuz-Ram model predicts that 79% passes a 350 mm sieve. One single charge (using Eq. 3.10) would result in an n value of 1.67 with a predicted 350 mm passing of 84% of the ROM. A financial analysis will have to evaluate the economic potential of this new strategy, possibly in combination with the selection of another explosive with the right chemical properties.

Optimize the drill & blast pattern; Section 3.2 demonstrates how the Kuz-Ram model should be applied at the Ahafo South mine site. In order to apply the Kuz-Ram model it was assumed that the Rock Factor (A) parameters are correct, these may however be fit for a revision. Using the current drill & blast pattern, the predicted fragmentation does not meet the P80 ROM target of 350 mm (Fig. 3.2). A drill pattern with a burden (B) of 3.5 m., a spacing (S) of 4 m. and an expected collar deviation of 0.38 m. would produce a fragmentation distribution that meets the P80 target.

Combining the double benching method with an optimization of the drill & blast pattern as discussed above, 84% of the ROM would pass a 350 mm sieve.

6.1.2. Improving Shovel Loading Time

The shovel loading time averages have been analysed in Section 5.3. It was already concluded that Shovel 7 performs relatively better and that Shovel 6 and 8 should have a priority. Shovel 6 and 8 show (Fig. 5.6) a decreasing trend in the Amoma pit during 2014; Fig. 5.8 shows that the fragmentation during 2014 was way better in Amoma than in Subika. The decreasing trend in loading times (Amoma - 2014) can be explained by the operators getting used to this favourable fragmentation while improving their loading strategy. Shovel 8 shows an increase during late 2015, it is unfortunate that only little is known about the fragmentation during that time. Shovel 6 has reduced its loading time average spread towards the end of 2016 (Fig. 5.4), the average is however well above the target of 2.4 minutes. No fragmentation data were available from the second half of 2016, therefore no fragmentation related improvement strategies could be drawn. The delays at the crusher (Fig. 5.17) did however give an indication of the fragmentation, especially the presence of boulders in the ROM in combination with Fig. 5.15 it can be seen that Subika feed partly contributes to the increase of crusher delays. This could indicate the excessive presence of boulders. The increase in shovel loading times at Subika of each of the three shovels could therefore be explained. It seems that the shovel loading time can (simply) be improved by improving the fragmentation.

6.1.3. Improving Mill Throughput

Fig. 5.16 shows the days where most feed originated directly from the ROM. The mill performances of these days indicate therefore directly how they behave with a known pre-crushed and post-crushed (VisioRock^{TM}) fragmentation. Table 5.9 summarizes the periods of interest. Period B-E, I and J were compared. Table 6.1 summarizes the design parameters of the mills related to fragmentation.

Table 6.1: Processing Plant Design Characteristics

Capacity	**Primary dry tonnes**	**Oxide dry tonnes**	**Overall**
R.O.M.	5,500,000 per annum	2,000,000 per annum	7,500,000 (73:27)
Primary Crusher	1,187 @ 125mm 1,515 @ 150mm per hour	500 per hour	n/a
Ore Stockpile	56,112	n/a	n/a

An important aspect of understanding the mill throughput is the delay between the ”feed date” and the ”processing date”. Table 6.1 tells (pers.com; 05-2017) that the ore stockpile generally has a capacity of roughly two days worth of production. Since the "feed date" is equal to the date where the ore was fed to the crusher, and the "processing date" is when the ore leaves the stockpile, a delay of two days should be implemented when comparing mill performance.

Table 6.2: Periods of Interest with High Feed from Pit Ratio: Feed Date & Processing Date

Period	Start Date (Feed)	End Date (Feed)	Duration (Days)	Start Date (Processing)	End Date (Processing)
A	06-09-2014	11-09-2014	6	**08-09-2014**	**13-09-2014**
B	10-02-2015	12-02-2015	3	**12-02-2015**	**14-02-2015**
C	20-02-2015	23-02-2015	4	**22-02-2015**	**25-02-2015**
D	25-02-2015	28-02-2015	4	**27-02-2015**	**02-03-2015**
E	09-03-2015	12-03-2015	4	**11-03-2015**	**14-03-2015**
F	16-05-2015	18-05-2015	3	**18-05-2015**	**20-05-2015**
G	10-10-2015	12-10-2015	3	**12-10-2015**	**14-10-2015**
H	16-04-2016	19-04-2016	4	**18-04-2016**	**21-04-2016**
I	25-04-2016	27-04-2016	3	**27-04-2016**	**29-04-2016**
J	13-05-2016	20-05-2016	8	**15-05-2016**	**22-05-2016**
K	14-08-2016	16-08-2016	3	**16-08-2016**	**18-08-2016**
L	30-10-2016	01-11-2016	3	**01-11-2016**	**03-11-2016**

The VisioRock^{TM} data were analysed during the feed times as summarized in Table 6.2 and the following was observed; Some of the data was filtered out with this message "*[-11101] All data events are filtered in summary calculation*". It is unclear why this message is given. During the three years of analysed data, 112 days have been filtered which accounts for 10.2% of the total days. As visualized by Fig. 6.1 these filtered dates occur randomly, expect during July 2014 where the data of 19 days is unavailable. When removing these 19 days from the total of 112 filtered days, only 8.5% of the days outside this period are filtered. The defined periods A - L add up to a total of 48 days. Of these 48 days, 12 days are filtered out, meaning that of the "periods of high interest", 25% of the data is unavailable. This means that the filtered days during the high interest period is 300% more than average. The periods of high interest are visualized in Fig. 6.1. Table 6.3 summarizes the performance of the two mills during these periods.

Table 6.3: SAG- and Ball Mill Performance during Periods of High Interest

Period	SAG Mill kW/t	Ball Mill kW/t	SAG Mill deviate (%)	Ball Mill deviate (%)	Pit Blend
A	14.1	16.5	+28.1%	+24.1%	AM,AW
B	11.9	14.5	+7.5%	+9.2%	AM,AW
C	10.7	14.8	-3.3%	+11.6%	AM,AW
D	9.9	14.3	-10.2%	+7.7%	AM
E	11.9	15.3	+7.4%	+15.4%	AM
F	10.3	12.9	-6.4%	-3.0%	AM,SK
G	11.7	15.2	+6.1%	+14.6%	AM,AW
H	10.1	13.0	-8.9%	-2.0%	AW,SK
I	10.9	13.4	-1.6%	+0.6%	SK
J	11.9	14.0	-8.9%	+5.4%	AW,SK
K	11.5	14.2	+3.8%	+6.4%	AW
L	13.8	15.8	+24.6%	+18.7%	AW,SK

The combination of the information in Table 6.3 and Fig. 6.1 provides an insight in the performance variation of the SAG- and Ball mill based on the post-crushed fragmentation distribution. Periods A, G and L show small spikes in Fig. 6.1 compared to the nearby values. This means that the post-crushed fragmentation was more coarse and this is also clearly visible in Table 6.3, where periods A, G and L show a significantly higher power consumption (kW/t). This shows once again that a good fragmentation is crucial for an efficient production.

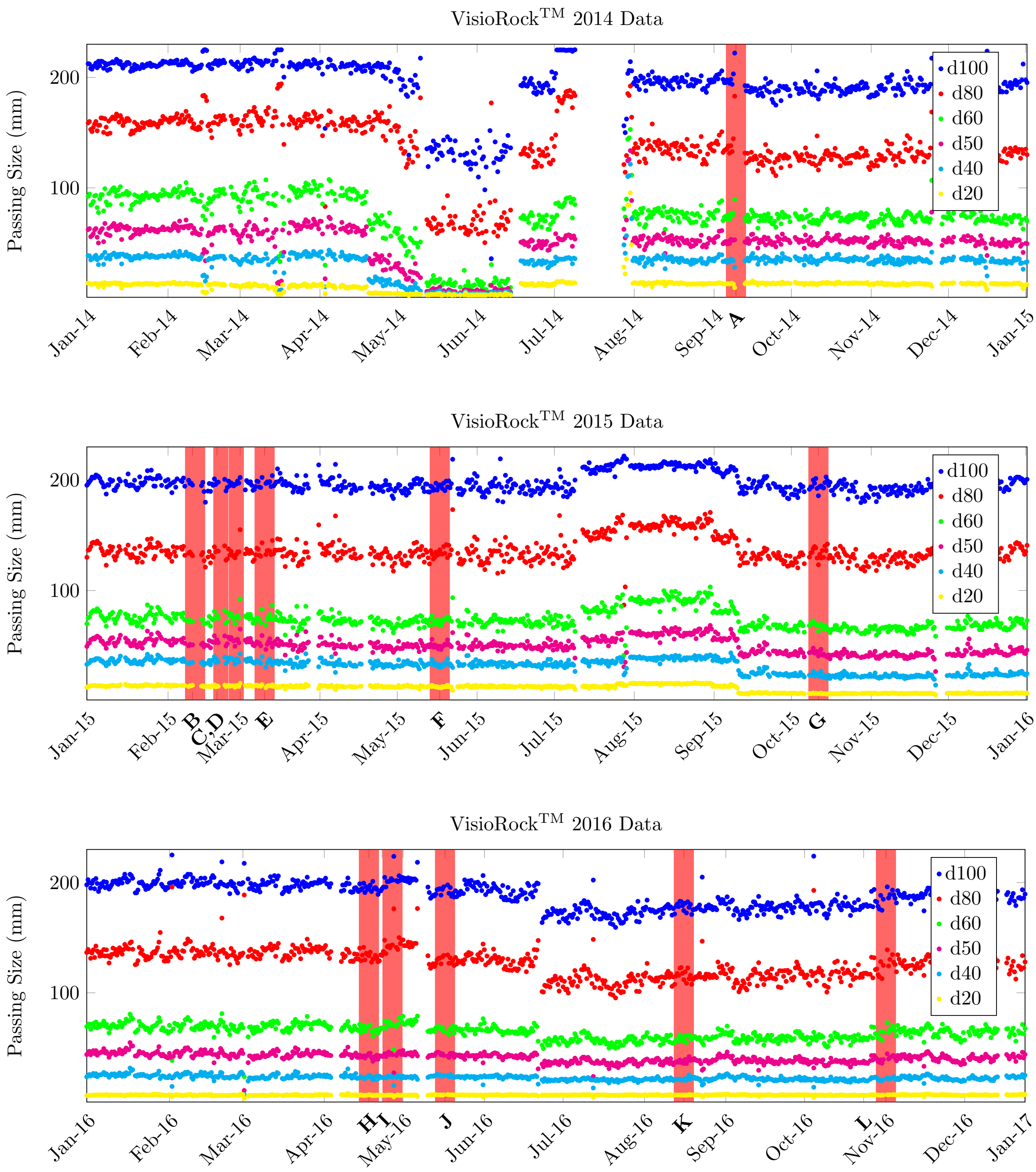


Figure 6.1: VisioRock Fragmentation Data 2014-2016 with Marked "Periods of High Interest"

6.2. Analysis of Production Costs

Financial figures were provided (pers.com; 05-2017) on a monthly basis in order to conduct a cost analysis. These monthly figures were carefully dealt with, since they do not exhibit production changes in a way that makes it possible to draw conclusions from these numbers alone. In other words; monthly cost figures are too comprehensive for a financial analysis. Warehouse management, delays of invoices and constant price changes are factors that contribute significantly to fluctuations of these monthly cost figures. After an extensive search for more detailed financial data, it was concluded that it would not be achievable to obtain such numbers for this research. A general cost analysis was carried out so that an overview of the cost distribution was formed.

6.2.1. Cost Overview

Monthly financial figures were obtained for 2014, 2015 and 2016, giving 36 data points. The costs were separated by production steps and visualized in Fig. 6.2. The mining operations were separated from the processing operations, resulting in the drilling, blasting, loading and hauling operations being combined and the crushing-, secondary drillig & blasting, SAG mill and Ball mill operations being combined. The mining operations account for two thirds of the overall production costs, the processing operations account for a third. Each category encloses monthly operational- and maintenance costs. The overall monthly production costs vary between $10 - 13M US.

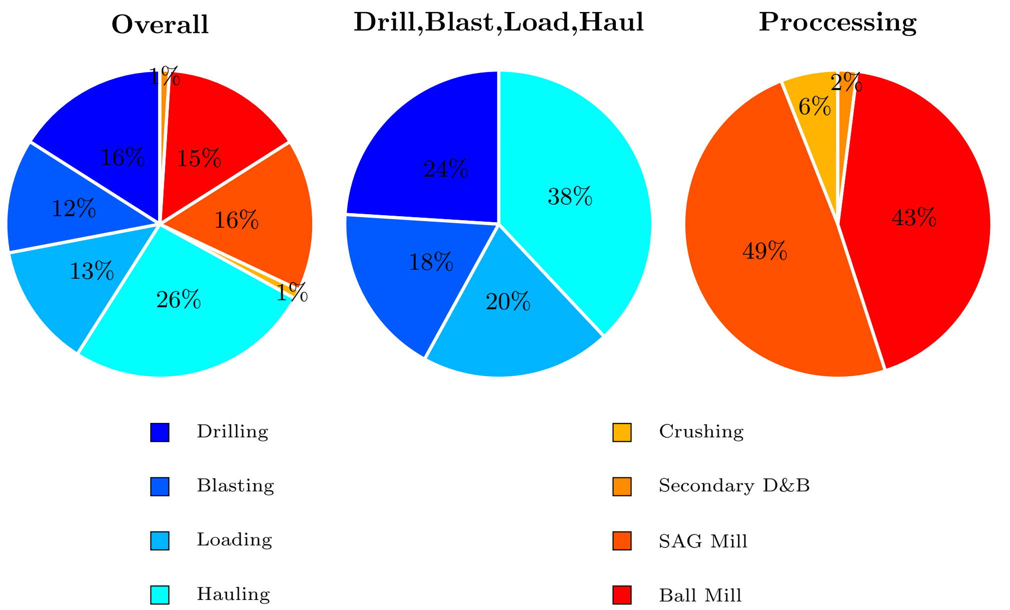


Figure 6.2: Overview of Production Cost

The operation that has the biggest share of the overall production costs is hauling by trucks. Haul truck maintenance accounts for more than a thirds of the monthly hauling cost figure, which is close to $1M US. Much of these maintenance costs is covered by plate works. As discussed in Section 4.5, no detailed is information available on (haul truck) maintenance costs. The two mills account for over 30% of the overall production cost (over 90% of the processing cost), which is mainly covered by the electricity cost.

The leverage ratio between the two main resizing processes, drilling & blasting and milling, is close to 1. The cost of drilling is however quite stable, where the blasting costs are almost fully regulated by the amount of explosives used. When the drill & blast pattern would be narrowed down, the blasting cost would increase significantly. When the assumption is made that a narrowed drill & blast pattern produces a better fragmentation, the crushing-, secondary drill & blast- and SAG mill cost would reduce significantly. The leverage ratio between the blasting cost and the crushing-, secondary drill & blast- and SAG mill cost is equal to 1.2. This indicates that the processing costs are more vulnerable to either an increase or decrease in costs as a result of decision making in pattern change than the mining costs.

6.2.2. Cost Analysis

The American Consumer Price Index (CPI) [19] has been used to correct for inflation, since NGGL is a US$ based company. Fig. 6.3 shows the monthly cost per produced tonne; mining (drilling & blasting, loading, hauling) cost per produced tonne material (ore + waste), processing (crushing, milling) cost per processed tonne of ore. As discussed earlier and stated (pers.com; 05-2017) by a business planning analyst, warehouse inconsistencies should be considered. These could cause significant variations in monthly cost figures. Financial data of 2013 helped to verify that the processing cost peak during early 2014 is an anomaly and that the trend towards the end of 2016 has indeed significantly increased.

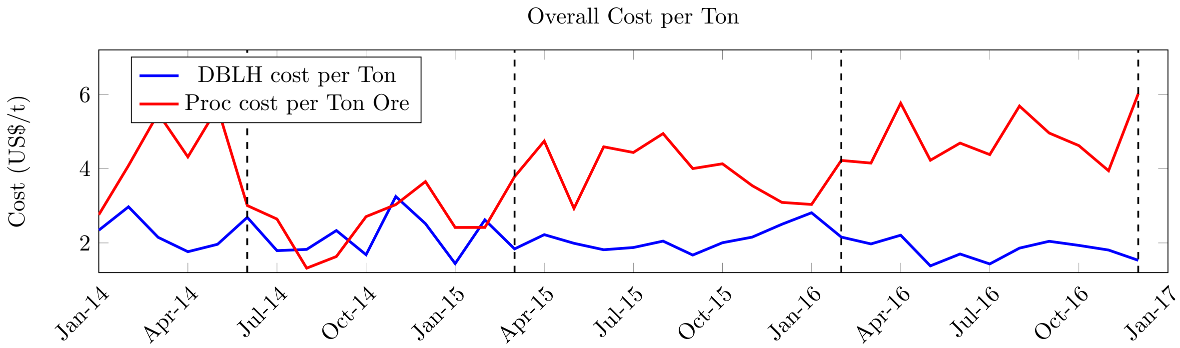


Figure 6.3: Overview of Production Cost over time

The second most costly procedure within the processing costs is the consumption of grinding media. The processing department anticipates on the amount of grinding media that should be added, based on the planned blend. This planned blend is however not commonly achieved (Fig. 5.10 - 5.11). There has been a change in grinding media suppliers over the years. Currently the following sizes and suppliers are used:

- SAG Mill: 125 mm steel ball supplied by SCAW
- Ball Mill: 50mm + 80mm steel balls supplied by West African Forge

Previously (before 2014), the following combinations were used:

- SAG Mill: 125 mm steel balls supplied by SCAW and Comsteel
- Ball Mill: 50 mm + 80 mm steel balls supplied by SCAW and Comsteel

A business planning analyst stated (pers.com; 05-2017) that the prices of the grinding media vary per supplier and per year, no data were available on precise prices. West African Forge has been chosen as a new supplier since they offer better prices. It was stated (pers.com; 05-2017) that there is no quality difference between the suppliers, this has been tested in an independent laboratory. Table 6.4 compares the monthly usage in grinding media from before and after the pattern change in 2015. Fig. 6.3 shows an increasing trend in processing cost per ton. The increasing usage of steel balls contributes to this fact.

Table 6.4: Cost Impact of Grinding Media

Grinding Media	**Monthly Usage Before Pattern Change (tonnes)**	**Monthly Usage After Pattern Change (tonnes)**	**Average Media Price (US$/tonne)**	**Average Yearly Cost Increase (US$)**
SAG Mill	292	329 (**+37**)	1.07	473.000
Ball Mill	231	244 (**+13**)	0.90	138,000

An average yearly cost increase in the usage of steel balls as grinding media is estimated at $612,000 US.

6.2.3. Secondary Breaking Cost

Boulders need to be resized before they can be fed to the crusher. A secondary breakage system is in place to deal with certain boulders, using an excavator (Caterpillar, model not defined) and a rock hammer (Fig. 2.12b). The rock hammer that is used in Ahafo South is a Caterpillar H140E Rockhammer, with a breaking capacity (volcanic rock) of 115-268 m^3 per 8 hour shift [23]. Based on the rock strength (UCS), observed operator competence and circumstances, 150 m^3 per 8 hour shift is assumed be to reasonable for the Ahafo South operations. This means that the rock breaker has a capacity of roughly 6.5 t/h. As stated in Section 1.3, 26,000 tonnes of boulders are produced annually. The rock breaker would need 4,000 hours to break these boulders. Table 6.5 summarizes the corresponding costs, provided by a business planning analyst (pers.com; 05-2017). The operating costs per hour of the excavator and rock breaker add up to $81.53 US. 4,000 Operational hours would cost $325,000 US. In this figure, operator- and maintenance costs are not included in order to calculate only the excessive operational costs as a result of bad fragmentation. It might be essential to purchase a second secondary breaking combination to avoid arrearage.

Table 6.5: Capacity and Cost of Secondary Rock Breaking Equipment

Secondary Breaking	**Capacity 8 hour shift** [23] **(metric)**	**Capacity (tonnes per hour)**	**Hourly Operating Cost (US$)**	**Estimated Annual Cost (US$)**
Rock Hammer H140E s	115-268 m^3	6.5	45.05	180,200
Excavator 324D	n/a	n/a	36.48	145,900

It was observed that the rock hammer requires a lot of maintenance and that the excavator is not always available. There is an integral rock breaking hammer installed at the primary crusher, this installation is however down for the majority of the time.

6.2.4. Cost Summary

NGGL predicted (pers.com; 04-2017) that widening the drill & blast pattern would save $3.2M US. This is an unrealistic figure since the changes in fuel-, explosive- and labour prices are implemented in this number and therefore suggest that these price changes occur as a result of the pattern change. This is not the case, for those prices change every year. Comparing annual prices does not reflect savings as a result of new implementations, but it reflects the change in market price. When these ”price changes” are excluded from the project value, the project would have a value of $2.3M US as a result of lower drilling and blasting costs. Ideally this would be the case, but mining is rarely in line with theoretical numbers. One should look at (historical) actual figures (Fig. 6.3).

The mining fleet can be managed more efficiently (double bench drilling & blasting for example), which would result in the reduction of fuel usage, labour hours and consumables. Ideally this would be the case, but again; mining operations are rarely in line with theoretical numbers, due to site and organizational specific characteristics. One should therefore be careful when making financial assumptions.

Detailed monthly information was obtained with regards to the cost of explosives and accessories in the form of Excel files. In contrast to what could be expected, every monthly cost figure was completely different. Some were equal to zero, some were unknown and where some were given in US$, others were given in GHS (Ghanaian cedi). Each excel file has a different layout and organization, making it unfeasible to analyse this data.

6.3. Production Cost Reduction

The main objective of this research was to reduce the cost of production at the Ahafo South mining operations owned by Newmont. The previous chapters have summarized the data that were obtained during the research. Combining Fig. 2.8 and Fig. 6.2 provides a schematic overview of the relative cost per tonne per production step. Fig. 6.4 included financial data prior to the pattern change in order to show the financial impact of this change.

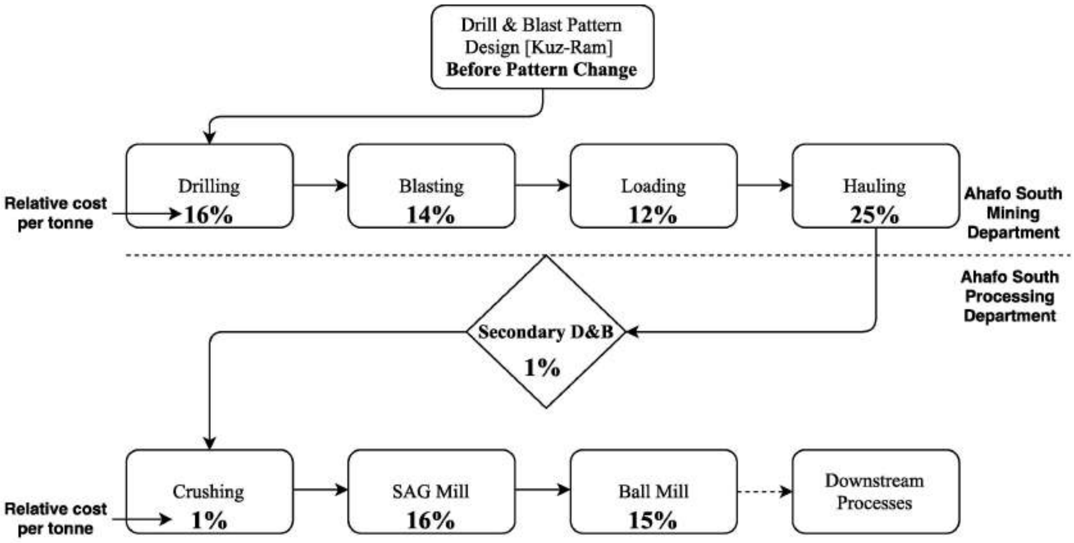


Figure 6.4: Schematic Overview of the Relative Cost per Tonne per Production Step

As visualized by Fig. 6.3, the processing cost per tonne of processed ore increased since 2015 where the mining cost per tonne of material slightly decreased. This can easily be explained by the pattern change during late 2015 and it seems that the desired effect (lowering the mining cost of production) is achieved. The increasing costs of the processing operations is however an issue. Fig. 6.5 shows the impact of the pattern change; financial data after the change were used to recalculate the relative cost per tonne.

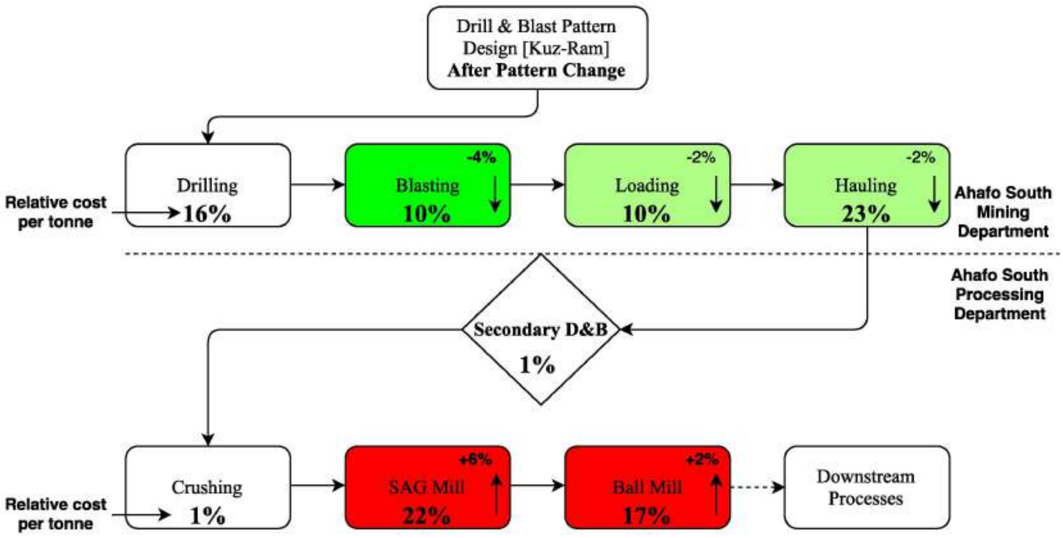


Figure 6.5: The Financial Impact of the Pattern Change in November 2015

It should be noted that no financial data on secondary drill & blast is available. The significant increase in SAG- (6%) and Ball mill (2%) cost is remarkable. There is a small reduction in the loading and hauling costs, where the blasting operation costs have reduced by 4%. The loading and hauling costs have improved as a result of the implementation of a dispatch system and are not considered to have a connection with the pattern change. The excessive amount of boulders are expected to have a negative effect on these costs, meaning that a better fragmentation in combination with the new dispatch system could even reduce the loading and hauling costs further.

7 Discussion

Since the previous chapters extensively discussed the quality and quantity of the data, a brief discussion is held on the reliability of the results. The objectives of this thesis were defined on site, after an extensive training was completed with the aim to get a holistic understanding of the Ahafo South mining- and processing operations. This training on site was advantageous to the process where a specific thesis objective had to be defined with the general topic of: Productivity Improvement and Cost Reduction of the Ahafo Gold Mine. After several audits as described earlier, it was concluded that a topic on blast pattern optimization and fragmentation improvement would be a valuable asset to NGGL.

7.1. Analysis of Fragmentation

There were two main sources available for the analysis of fragmentation; A database that contains the distribution curves, obtained through a manual visual analysis using the software Split-Desktop, was gathered, comprising 584 documented blasts between 01-01-2014 and 31-12-2016. The other database contains the fragmentation distribution of post-crushed feed which is constantly monitored by a VisioRock^{TM} system. The data had to be understood, cleaned and filtered before it could be visualized. It was observed that the density of the data on fragmentation in the Amoma pit after blast is rather sparse, however there is a period where the data is dense, which made it therefore possible to analyse the Amoma pit ROM. The fragmentation in the Subika pit was less favourable and it is therefore assumed that most of the boulders originate from this pit. It is important to realize that the Split-Desktop software just estimates a distribution curve based on a few pictures. These pictures never fully reflect a complete representation of the fragmentation distribution, since one can not assume that the size distribution is completely homogeneous. The heterogeneity of the fragments size distribution is determined by the efficiency of the blast (design). The results of this visual analysis method should therefore be interpreted with care. The results from the VisioRock^{TM} system were expected to have a higher accuracy, since the post-crushed ore is continuously scanned. Each fragment is therefore included in the estimation of the post-crushed fragmentation distribution curve. The VisioRock^{TM} data does however show some interesting features, where all values suddenly drop (Fig. 5.19; Period A, D) or rise (Fig. 5.19; Period C) on a given date. A whole month of data is missing in July 2014, and a sudden systematic two-step decrease in values was observed (Fig. 5.19; Period D). Another remarkable feature is that after Period C, the passing of the fines (D20) significantly drops and never recovers to its original value. There was no clarification found for these features, therefore it was assumed that these observations can be attributed to calibration errors. There has of course been some variation and change in the feed characteristics and ROM fragmentation, but these can not explain the sudden systematic drops or rises of the post-crushed fragmentation distribution. The D100 and D80 do however show an increasing trend after Period C. A correlation between the increase of boulders in the ROM, an increase in crusher delays and this trend was assumed.

7.2. Analysis of Shovel Loading Time

The first fragmentation related issue that was encountered at Ahafo South was a discussion between the primary mine advisor and an operator on systematic delays at the shovels due to boulders. This triggered a search for more information, resulting in the shovel loading time analysis that was executed. The dispatch system monitors the average shovel loading times per blast, grade polygon, hour and date. The daily shovel loading time average was used for a statistical analysis in order to remove irregularities such as varying shift change delays and ”red-alerts”. All available daily averages were visualized in a scatter plot, which made the spread of the data clearly visible. The overall average was well above the target time of 2.4 minutes and some clear ”ups” and ”downs” could be observed over time. Where the average times were decreasing, and therefore improving, during 2014, an increase occurred during 2015 and 2016. Only Shovel 7 performed well within, and even below, the accepted target interval. The data for the Subika pit is relatively sparse compared to the Amoma pit data, which is why a (level 1) sigma analysis was applied to show the overall trend. This trend encompassed 68% of the data, which was accepted as ”the majority of the data”. In an ideal situation, all shovel loads would take exactly 2.4 minutes, which would result in a perfect symbioses between all planned mining operations. Since it is common for a mining operation to experience many site-, equipment- and situation specific variations, it is obvious that this ideal situation will never be achieved.

It was stated that a constant interval of 40 seconds (2.4 min $\pm$ 20 s.) should include at least 68% of the data. The variety of the data was visualized together with the target interval, where the majority of the data was expected to fall within the target interval. Shovel 6, 7 and 8 were operating in the Subika and Amoma pit during 2014 - 2016. During 2014, Shovel 6 and 8 operated for a few weeks in the Awonsu pit; the data that was obtained during this period, was added to the Amoma data since these two pits are assumed to have identical rock properties and could therefore be used to analyse the ”3A” (Apensu, Amoma, Awonsu) average shovel loading times and trends. The Subika average shovel loading time analysis showed that none of the three shovels have produced within target when taking the average of the whole three years. Shovel 6 shows the least positive results, where Shovel 7 and 8 are significantly closer to the average target of 2.4 minutes. The Amoma analysis shows that Shovel 6 made significant improvements and this is promising for the remaining time in Amoma. When Shovel 6 was moved back to Subika, the improvement unfortunately disappeared. Shovel 7 performed very well in Amoma, and Shovel 8 showed just like Shovel 6 a promising decreasing trend during late 2014. These improvements were however nullified during late 2015. By the end of 2016, all shovels were operating in the Subika pit and showing an increasing trend in average loading times.

7.3. Analysis of the SAG & Ball Mill Throughput

An analysis of the feed was essential before the performance of the SAG- and Ball mill could be analysed. The feed determines the performance of the mills, due to the hardness and fragmentation distribution of the feed. Based on the blending data provided by the processing department, the throughput of the mills could be analysed. There were two sources available that indicated the content of the blend fed to the primary crusher; A planned blend and the actual blend, separated by source (pit). The documentation of the feed made it possible to separate feed that originated directly from the pit, from stockpile material. This possibility was used to visualize the blend where material originated directly from each of the pits that were in production at that time. The Subika, Amoma and Awonsu pit have been in production during 2014, 2015 and 2016. In order to optimize the throughput, a blending model was designed. The planned blend does not seem to be the product of a blending strategy, the only systematic features that were observed are the high values of Subika blend in early 2014 and the increasing Subika feed percentage in the blend during 2016. The Amoma and Awonsu feed seems to be randomly mixed with Subika material.

The actual blend (Fig. 5.15) showed similar features as the planned blend for Subika material, the Amoma and Awonsu planned percentages are not met. Some big discrepancies were observed for the actual Amoma blending percentages. Where no Amoma material was planned in the blend until November 2014, some significant amounts of Amoma feed where used. All the other values seems to be random and show no relation with the planned percentages. An interesting remark was seen during the period between April and August of 2016, where high Amoma blend percentages were planned.

The actual Amoma percentages are considerably lower during this period, especially when compared to the other Amoma data. The analysis of the Awonsu blend uncovered that some data was erroneous. The Apensu pit has been out of production since long before the start of 2014, where the Awonsu pit only produced sporadically in 2014. Yet does Fig. 5.14 show that according to the data, lots of Awonsu material (and some Apensu material) was fed directly from the pit. It was assumed that there was a mix up with the documentation of the origin of the material, since the acquired data indicated that the Awonsu ”Directly from Pit” data was really mined at the dates as shown in Fig. 5.15.

The quality of the blending data was therefore doubted.

The power usage and throughput data of both the SAG- and Ball mill were analysed. It was observed that the Ball mill power usage is higher than that of the SAG mill and that it is rather stable, where the SAG mill shows varying values. An interesting observation was made of the values during late 2016, where the SAG mill required almost the same amount of energy as the Ball mill. Between November 2014 and July 2015, a strong decrease in power usage and daily throughput was observed. The throughput never recovered to the values of early 2014, while the mills required more energy towards the end of 2016. The power consumption per dry tonne therefore also increased. In an effort to improve the throughput and reduce the power consumption per unit, more grinding media were added, starting from November 2014. Periods with high feed that originated ”Directly from the pit”, were marked and closely analysed. These periods are of high interest when comparing the ”in-pit” fragmentation to the VisioRock^{TM} data and the SAG mill performance. Periods A to L were identified as ”periods of high interest” and analysed. Period B to E proved to be striking since these periods encompass a time span where ”in-pit” fragmentation was relatively bad, and where the VisioRock^{TM} missed a lot of data since it was filtered out. These periods showed an increase in power consumption of the Ball mill, but the SAG mill did not show remarkable results.

7.4. Cost Impact Analysis

The hypothesis of this thesis stated that the cost of production could be reduced by improving both the SAG- & Ball mill throughput and the shovel loading times. These operations were assumed to be fit for improvement through the optimization of the fragmentation by blast pattern optimization. The ultimate goal of the Ahafo Mine site is to safely produce gold as cheap as possible. All operational considerations have therefore only one determining factor besides safety, which are the costs per produced unit of gold. It is therefore important to understand where costs can be saved for each process. As mentioned above, the goal is to produce gold as safe and cheap as feasible. This research focussed on the resizing and loading aspects of the Ahafo South mine site, these include: Drilling, blasting, loading, hauling, crushing and milling. Each of these processes has certain fixed and variable costs, where an optimum production can be expected if all production targets are met. These targets include fragmentation distribution targets such as the pre- and post crushed P80 values, average shovel loading values and mill throughput values. This means that it is essential, from both a financial and operational point of view, to achieve the production targets.

The Ahafo South Mining department decided in 2015 to widen the drilling pattern so that explosive costs could be reduced. It was not possible to gain clear insights in the actual costs that were reduced. The overall monthly cost figures indicated that the cost of the blasting operations were reduced by 4% after the pattern change. The SAG- and Ball Mill costs increased however by respectively 6% and 2%. There were no actual detailed cost figures available on the maintenance- and secondary drill & blast operations. It was expected that the maintenance costs increased as a results of the excessive presence of boulders, resulting in an increased wear and tear on both the shovel buckets and the haul truck dump bodies. These costs were estimated between $500,000 and 600,000 US annually. The secondary breaking operations of the yearly increase of 26,000 tonnes of boulders were estimated at $325,000 annually, where the extra addition after the pattern change of grinding media was estimated at an annual $612,000 US. It was considered to write off the 26,000 tonnes of boulders as waste, but this would not be economical since the value of these boulders (assumed at 1 ppm gold and a price of $1,300 US per troy ounce) is roughly $1,000,000 US.

8 Conclusion

This section elaborates on the conclusions that were drawn from the statistical analyses carried out on the shovel loading time variance, the throughput of the SAG- & Ball mill and the corresponding cost impact as a result of the varying fragmentation during 2014, 2015 and 2016. An overall conclusion that could be drawn is that the Kuz-Ram model currently predicts that the P80 target for the ROM is not met. The whole mine- and processing site is designed around this critical parameters, however it is predicted that only 76% of the material is equal to or smaller than 350 mm. It therefore seems that the issues related to an undesirable fragmentation start directly at the first step of production, namely the planning of the drill & blast patterns. The downstream effect of such a profound change as widening the drill & blast pattern should be intensively examined.

8.1. Improving Fragmentation

It was easily concluded that the fragmentation in the Amoma pit meets the requirement for smooth shovel loading. The fragmentation data shows this with the P80 values. The Subika pit does indicate that there is room for improvement with regards to the fragmentation. The Awonsu- and Subika pit will keep producing until at least 2029, depending on the gold price. The analysis of the fragmentation showed that there is room for improvement in the Subika pit, since the P80 is mostly not met. The throughput model that is used by NGGL predicts that the Awonsu Phase 3&4 material is harder to break than the Subika material, meaning that even more issues can be expected in the Awonsu pit. It was therefore concluded that the fragmentation will lead to many more problems in the near future. The planning of the drill & blast pattern, and therefore the fragmentation, has to be reconsidered.

8.2. Improving Shovel Loading Time

The visualisation of the variance in the average daily shovel loading times proved that it is possible for each of the three shovels to produce within the target interval of 2.4 minutes $\pm$ 20 seconds. Shovel 6 showed potential in the Amoma pit during 2014, Shovel 7 performed well in both pits and Shovel 8 showed promising performances in the Amoma pit as well during 2014. Yet there are several long-lasting periods where the shovels were having trouble with reaching the target of 2.4 minutes per truck load. The big question is whether the fragmentation was better during these periods where the shovels were performing well. The answer to this question is yes; A clear trend of decreasing average shovel loading times is visible for both Shovel 6 and 8 in the Amoma pit, starting short after July 2014. This is also where the fragmentation in the Amoma pit was intensely monitored and this showed that the fragmentation in the Amoma pit was exemplary between July 2014 and January 2015, where the P80 values were well below the target of 350 mm. Unfortunately, the fragmentation after this period was scarcely monitored in the Amoma pit. The increasing average loading time trend of Shovel 8 between July 2015 and March 2016 could therefore not extensively be analysed. The data that was available did however not indicate that the fragmentation got much worse. It is unknown why the intensive monitoring in the Amoma pit stopped after January 2015. The loading times in the Subika pit were slightly worse that the Amoma pit, where the fragmentation in the Subika pit was also slightly worse. A correlation is thus present and it is concluded that the shovels in the Amoma pit performed better as a result of a better fragmentation. It is regrettable that there is no data on fragmentation after September 2016, it would be interesting to see if the increasing average loading time trends of all of the three shovels during the second half of 2016 could be explained by a deteriorating fragmentation. The increasing delays due to boulders at the crusher indicate that this might be the case.

8.3. Improving SAG & Ball Mill Throughput

By combining the VisioRock^{TM} data with the blend- and throughput data, an understanding could be established of the relation between the pre- & post crushed fragmentation, the throughput of the mills and the power required per processed unit of ore. As discussed, there is a discontinuity in the process flow between loading & hauling and crushing, since not all material from the pit is fed to the crusher directly. In order to optimize the mill throughput, a daily blend of different materials is used to feed the crusher and the processing plant, which means that some ore is stored in a stockpile. When ore is stored on a stockpile, all fragmentation related data goes to waste, since everything on a stockpile gets mixed up. The throughput was the highest during (and before) 2014. This can be explained by the addition of saprolite, or oxide. Ahafo South ran out of oxide material and had to invent a new blending strategy, this is what explains the messy period that lasted from November 2014 to July 2015. The Ball mill power usage is relatively constant compared to the SAG mill, this is because the Ball mill gets a relatively constant feed size, since the SAG mill executes most of the coarse grinding work. The SAG mill shows an increasing power usage towards the end of 2016. This has two reasons; the throughput decreases and the power usage increases, this suggests that the feed changed. The actual blending percentages proved that an increasing share of Subika material is being added, starting from July 2016, which corresponds with the increasing power usage. It is known that Subika material is slightly harder, therefore it was concluded that the increasing Subika material in the blend results in a reduced throughput and higher power consumption of the SAG mill. The VisioRock^{TM} data confirms this hypothesis, since a slight increasing trend in the D100 and D80 values was seen, starting from July 2016. This indicates that not only the SAG mill, but also the crusher has issues with processing a higher percentage of Subika material.

8.4. Cost impact of Blast Pattern Optimization

It is evident that a better, or finer, fragmentation is more expensive to produce, since a bigger blasting effort is required to break rock into smaller fragments. This means that more explosives are required in order to acquire a finer fragmentation, which would result in a significant increase in blasting operation costs. One of the leading questions in this research was whether or not such a potential increase in drilling & blasting costs would be paid back through the improvement of productivity. The overall cost per produced unit of gold should go down as a result of these efforts. An overview of this economic impact is complicated to construct since the financials at Ahafo South are not administered in such a way that makes it possible to extract the desired information in detail. An overview was constructed based on monthly overall cost figures, from which could be concluded that the processing costs are more vulnerable to change than the mining costs. In order to get an understanding of the impact of an excessive boulder presence in the ROM, several simplified financial calculations were carried out. The statement made by the mine maintenance superintendent that the fragmentation as present in 2016 resulted in an avoidable cost increase of $500,000 to 600,000 US, is a strong indication that there is room for optimization. It is understandable that the mining department is under pressure to reduce production costs, but these efforts are useless if the money needs to be spent downstream. The excessive boulder production of 26,000 tonnes annually contributes to $325,000 US of avoidable costs, since these have to be broken with a rock hammer. These two inescapable costs already add up to $1M US. Elements such as the excessive damage to the crusher due to boulders, reduced haul truck tire life as a result of a less smooth pit floor and the increasing shovel cost per tonne (due to longer loading times) were not even included in this figure.

The pattern widening saved annually up to $2,3M US according to the mining department of Ahafo South. This figure was hard to verify due to the financial administration. Therefore no hard conclusion could be drawn with regards to the cost impact of blast pattern and rock fragmentation optimization.

A simple calculation shows that improving the drill & blast pattern from 3.7 m x 4.2 m to 3.5 m x 4 m would result in an explosive cost increase of 11%. A pattern with B = 3.7 and S = 4.2 covers 15.54 m^2, where a pattern with B = 3.5 and S = 4 covers 14 m^2. These two areas have a ratio of 1.11 ($\pm$ 11%). The monthly explosive costs vary between $600,000 and 1,200,000 US per month, when taking the average ($900,000 US), this 11% would thus result in a monthly cost increase of roughly $100,000 US. The monthly drilling costs should in this example however also be accounted for. The monthly average drilling costs vary between $700,000 and 1,100,000 US, meaning these costs would also increase by roughly 11% or 100,000 on monthly basis. These two cost figures add up to a monthly increase of roughly $200,000 US or $2,4M US annually. This indicated that the estimation of the value of the pattern widening project at $2,3M US is genuine.

Is it worth spending $2,4M US more on blast pattern optimization? The answer would be yes if assumed that this optimization produces a better fragmentation, since this investment results in a longer equipment life and better production. This means that significant capital investments such as new trucks or shovels can be postponed, resulting in a financial benefit in the longer term.

9 Recommendations

After extensive analytical research on the acquired data during the visit at the Ahafo South mine site, several conclusions were drawn as discussed earlier. Based on these conclusions, several recommendations were conceived. The recommendations are purely based on the results of the research that was carried out within the scope of this thesis as defined in Section 1.4.2. External factors that may influence the operations or contribute to the problem statement outside the scope of this thesis could make these recommendations inappropriate.

9.1. Optimization of the Drill & Blast Pattern

The Kuz-Ram model is a proven methodology to predict the fragmentation distribution if the (geo-) technical properties are well understood and implemented. It was concluded that a widening of the drill & blast patterns results in a coarser predicted fragmentation. The blast pattern was basically already optimized by Hamdani [11], where the predicted fragmentation precisely meets the P80 target of 350 mm. This prediction did however leave out possible drill hole deviations and redrills, which made this prediction unusable since these factors are always present. It also did consider the "old" drill & blast pattern and the wrong explosive characteristics. It is therefore recommended to reconsider the implementation of the "current" Kuz-Ram model. The average borehole deviation W = 0.38 m should be considered in the model in order to obtain a predicted fragmentation that reflects the actual circumstances. As concluded earlier, the P80 target for the ROM should always be met for the sake of a continuous productivity. A blast pattern that would produce a fragmentation with the preferred size distribution would have the following parameters according to the Kuz-Ram model (Section 3.1):

- **Burden** 3.5 m.
- **Spacing** 4 m.
- **Bench Height** 8 m.
- **Hole Diameter** 165 mm.
- **Sub drill** 1.2 m.
- **Stemming height** 3.3 m.
- **Hole depth** 9.2 m.
- **Borehole deviation** 0.2 m.

This suggested design demands that the (average) borehole deviation is reduced to 0.2 m. The average deviation of 2016 was 0.38 m, where this was 0.24 m for 2015. This indicates that there is room for improvement with regards to 2016, it was therefore assumed that the borehole deviation can, with thorough coaching, be reduced to 0.2 m.

9.2. Double Benching

Another improvement possibility is modifying the height of the benches. The physical dimensions of the Liebherr 9400 shovels constrain the maximum mine-able bench height to 8 m, which means that it would be inefficient from a production point of view to change this parameter. However, when applying ”double benching”, this inefficiency would not occur. When a double bench is drilled and blasted, several benefits are gained. The drill & blast teams are relieved for a significant percentage of their work, since they would only have to drill & blast half of the time when compared to the current bench height (8 m.). Another benefit is that the amount of blasts would be significantly reduced, which would help to reduce dust, vibration and noise nuisance to the community. The third major benefit is that the predicted fragmentation with a higher bench height is significantly better. Drilling & blasting 16 m benches instead of 8 m requires extra efforts, however these would still be significantly lower. It is recommended to carry out several tests where double benching is implemented. The equipment is mechanically capable of drilling holes required for 16 m benches without any modification. It would take some extra time to add an extra rod in order to reach the desired depth, which should not lead to any problems since the drill & blast team would have twice the time to set up a blast compared to the current situation. The economic feasibility of this implementation should be considered and it is advised to perform a detailed study on this matter. The suggested pattern would have the following parameters:

- **Burden** 3.7 m.
- **Spacing** 4.2 m.
- **Bench Height** 16 m.
- **Hole Diameter** 165 mm.
- **Sub drill** 1.2 m.
- **Stemming height** 3.3 m.
- **Hole depth** 17.2 m.
- **Borehole deviation** 0.2 m.

The benefit with this design is that the current ”wide” pattern of 3.7 m x 4.2 m would not be changed. It was however assumed that the average borehole deviation is reduced to 0.2 m. It is anyhow recommended to reduce the borehole deviation, regardless of the suggested optimized pattern. The Kuz-Ram model predicts, with the parameters as described above, a fragmentation with a 350 mm passing of 84%. It is also recommended to further analyse the economic impact of deciding between a single charged or double charged blast.

9.3. Data Management & Continuous Surveying Camera System

The gathering of the data (as described in Chapter 4) pointed out that not all production data are neatly processed or stored. Several inconsistencies have been encountered between data sets, which indicated that there is room for improvement with regards to data management. It is recommended to design templates in a software other than Microsoft Excel, to consistently use these templates and to communicate periodical results between the departments.

The current method to analyse the fragmentation through a passive approach using pictures that have to manually entered into an analysis software should be replaced by a continuous surveying camera system. So called ”ShovelCam” systems are sold which automatically and continuously captures pictures which are immediately analysed. This technique makes it possible to get an understanding of the entire fragmentation distribution within a muck pile, as the shovel digs through the material. The current method only considers the boundaries of the muck pile in its analysis, which provides skewed results since a full homogeneity can not be assumed as described in Section 7.1. It is recommended to consider an investment in such a system for each of the shovels.

9.4. Full Mine-to-Mill Survey

The current throughput model as described in Section 4.4 is the only model that provides an indication of the breakability of the different rock types. It is recommended to conduct a full mine to mill survey, where the characteristics of the feed are extensively analysed before it enters the SAG mill. Based on the throughput and power consumption of the SAG- and Ball mill, conclusions can be drawn which can be used to improve the throughput of the processing plant.

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10

Appendices

Overview of Appendices

The following appendices have been included:

- A: Initial Thesis Synopsis
- B: Training & Data Acquisition Plan
- C: DMAIC - Project Charter Proposal
- D: DMAIC - Costumer Value & Demand
- E: DMAIC - Project Charter Revised
- F: Stakeholder Mapping
- G: Stakeholder Management

Appendix A contains the initial synopsis that was constructed in order to obtain the travel visa to Ghana during the application procedure. This synopsis described the intention to conduct a thesis project on mine optimization and cost reduction on the Ahafo Gold Mine.

Appendix B provides the plan that was created to optimize the available time at the mine site.

Appendices C to G include the templates that were used to define the thesis topic.

Appendix C summarizes the problem statement that was initially defined, where Appendix D was used to define the customer value for the loading & hauling operations with regards to the optimization of the fragmentation. Appendix E provides the project charter on which the decision was made to design a thesis around the specified topic. In order to understand and define the stakeholders that are involved, a stakeholder map was made (Appendix F) based on their specific influence, impact and perception of the topic.

Once the stakeholder map was finalized in consultation with the chief mine engineer (pers.com; 04-2017), a stakeholder management plan was designed (Appendix G) which was used to efficiently plan a data gathering strategy.