Development of a 3D Image Analysis Method to Measure Blast-Induced Fragmentation at the Leveäniemi Mine

By

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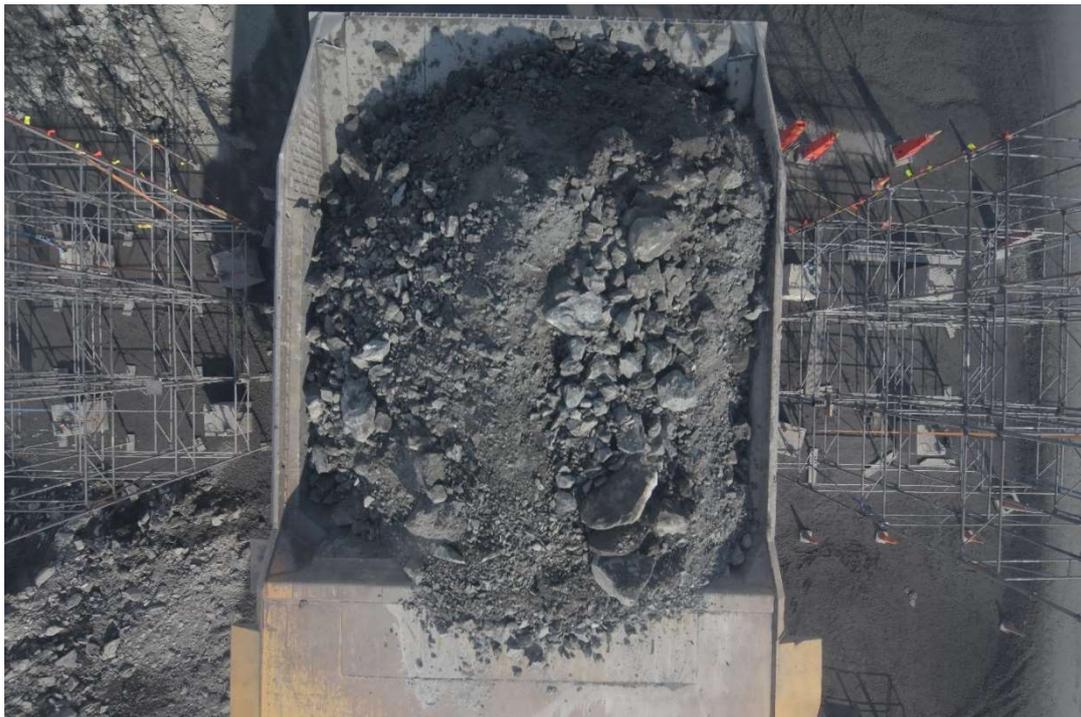# Development of a 3D Image Analysis Method to Measure Blast-Induced Fragmentation at the Leveäniemi Mine

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Abstract

The first size reduction stage in open pit hard rock mining is blasting and is fundamental for mineral resource extraction as it enables transportation of the rock. Consistent fragmentation results are preferable as it can ease the loading, hauling and crushing stages. Fragmentation analysis assists in identifying areas where similar blast results appear when comparable drill and blast designs are used. Subsequently, drill and blast domains can be defined for the Leveäniemi mine to ease the drill and blast design process.

Measuring fragmentation has been continuously researched over the past years. Image analysis methods were developed as it minimised disruption to production and provided a reasonable indirect estimation of particle sizes. So far, research was focussed on 2D image analysis. However, by adding a 3rd dimension, some limitations can be overcome that were experienced when using only two dimensions. Therefore, the potential of 3D image analysis of blasted rock, loaded in haul trucks, is of interest. By evaluating truck loads, the muck pile is better represented in comparison to measuring a whole muck pile. This is one of the few studies done until now on 3D image analysis in open pit mining, analysing material in loaded trucks.

A 3D image analysis field test was executed to measure blast-induced fragmentation in a production environment at the Leveäniemi mine. The aim was to gain a clear understanding of the factors contributing to an optimal blast result and to establish blast domains. The test setup consisted of an image acquisition system, photographing truck loads from above using two cameras that were triggered by a laser. RFID truck markers were combined with Minestar data to identify the origin of the truck. Truck loads were analysed using software developed by LKAB and 3GSM, constructing 3D models and automatically delineating particles to analyse fragmentation. No pre- or post-processing of the images or delineation results have been done. Drill and blast, and muck pile shape parameters were acquired as well.

The results show x_{50} particle sizes ranging from 5 to 56cm and x_{80} ranging from 20 to 150cm. Care should be taken when interpreting these results due to the limited amount of data analysed and bias in the measurements and software. Fines are underestimated and correct particle delineation occurred on average in 42% of each load. The limited amount of data resulted from the practical problems arising during data acquisition. Continuous data acquisition of images was not achieved.

Correlation of fragmentation to drill and blast, or muck pile shape parameters was not achieved due to the challenges faced. 3D image analysis of truck loads proved to have potential but requires many modifications and developments to the system and software to achieve continuous data acquisition. A focus on image quality and the practicalities of the system is recommended. Continuous data acquisition is required when using fragmentation analysis for establishing blast domains.

Comparable and repetitive measurements are the main prerequisites for choosing a method to analyse fragmentation for the purpose of defining blast domains. Hence, other methods like using drones to analyse whole muck piles after blasting should be considered, though it would statistically be less representative. For the Leveäniemi mine, it is recommended to achieve geotechnical domains including joint spacing and orientation before a follow-up study is started on blast domains. Additionally, the development of this method should be finalised, or an alternative is recommended.

Acknowledgements

Contents

Glossary

Abbreviation	Definition
°C	Degrees Celsius
2D	Two-dimensional
3D	Three-dimensional
3GSM	3G Software & Management
AN	Ammonium Nitrate
ANFO	Ammonium Nitrate/Fuel Oil
B	Burden
BH	Bench height
BMX	BlastMetriX
CAT	Caterpillar
CCR	Central Control Routine
d	Distance
D	Hole Diameter
Fe	Iron
Fps	Frames per second
GB	Gigabyte
GPS	Global Positioning System
GUI	Graphical User Interface
HD	Hole depth
J	Subdrill
LHD	Load-Haul-Dump
LIDAR	Laser Imaging Detection And Ranging
LKAB	Luossavaara-Kiirunavaara Aktiebolag
MWD	Measure While Drilling
PSD	Particle Size Distribution
RFID	Radio-Frequency Identification
S	Spacing
SD	Secure Digital
SDe	Stem Deck
TS	Top Stemming
USB	Universal Serial Bus

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1. Introduction

Blasting is fundamental for the extraction of mineral resources because it enables the handling and transportation of rock to the mineral processing plant. It is the first size reduction stage and has many implications on subsequent activities, for example transportation and crushing. It is beneficial to evaluate data regarding drilling and blasting and analyse the blast results in terms of fragmentation. When the blast parameters and results are analysed, blast domains can be identified and used to improve the blasting process.

In section 1.1, the importance of measuring fragmentation after blasting is explained further. The problem statement and hypothesis are described in section 1.2 and 1.3. The research questions and objectives are explained in section 1.4. Section 1.5 and 1.6 provide an introduction of the methodologies used for this thesis and defines what is in and out of scope. The structure of the thesis is summarised in section 1.7.

1.1 Importance of Measuring Fragmentation

Figure 1.1 provides a brief overview of the mining process with respect to factors influencing and affected by fragmentation. During surveying, the slope angles, geological discontinuities and the bench geometry are measured. Rock properties such as strength, mineralogical composition and rock type are determined as well, either while surveying or sampling the drill cuttings. Accordingly, a drill and blast plan can be designed as described in more detail in section 2.1.1.

Having knowledge about fragmentation can provide quality information of the blasting performance and downstream processes. Fragmentation has implications on loading and hauling and the energy required for the comminution processes, generally divided into crushing and grinding. It is also a result from drilling and blasting. To ease this drill and blast design, blast domains can be developed. In the end, controlling and optimising fragmentation is desired at most mining operations.
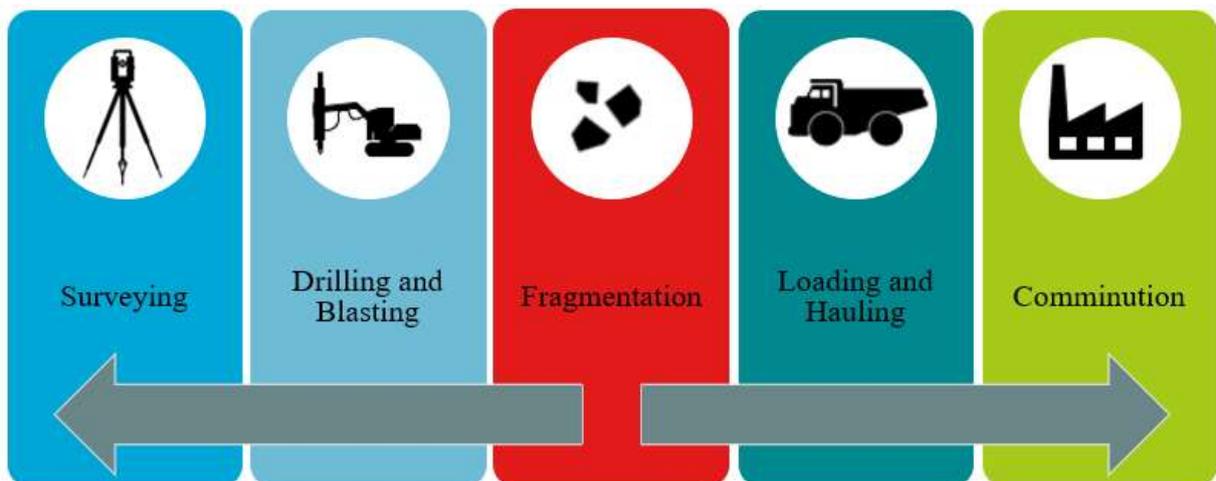
Figure 1.1 – Open pit mining sequence with respect to fragmentation

1.2 Problem Statement

Measuring fragmentation of large-scale blasts is a challenge in the mining industry. Several methods have been developed, as will be explained in section 2.2. However, the challenge remains to develop a method that is highly automated, does not interrupt production and provides reliable results.

To measure fragmentation, 2D image analysis methods have been widely used but remain to have limitations as described in section 2.2.2 (Raina, 2013; Cunningham, 1996). To reduce the amount of limitations, 3D image analysis methods are being developed. 3GSM is one of the companies developing such software, which will be used for this thesis. Images of truck loads will be acquired as it is a better representation of the muck pile than measuring the muck pile straight after blasting (Thurley, Wimmer, & Nordqvist, 2015). The aim is to minimise production disturbances by installing an automated image acquisition system on the haul road.

Not many studies have been done on the use of 3GSM's 3D image analysis software, or any other 3D image analysis to measure fragmentation. The open-pit studies do not measure fragmentation from moving trucks, but rather from the muck pile directly or the loading tool's bucket (Noy, 2012; Onederra, Thurley, & Catalan, 2015; Sameti, et al., 2014). However, some studies on material loaded in Load-Haul-Dump (LHD) buckets in underground mines have been done (Thurley, 2009; Thurley, Wimmer, & Nordqvist, 2015; Stauder, 2018). The main differences compared to this study is that the images will be acquired in an open-air situation where conditions such as lighting are much less consistent, and the climate might provide challenges. Additionally, the picture sets analysed in previous studies were often small and taken statically (Stauder, 2018). This study aims to include a larger picture set and takes pictures as the trucks are driving their regular speed on the haul road.

The software used in this study showed plausible delineation results in a previous study (Stauder, 2018). Even though the Particle Size Distribution (PSD) curves do not show the same results as sieving, it provides useful estimates of the larger size classes (Thurley, Wimmer, & Nordqvist, 2015). Therefore, it can be used as a comparative measure and to define blast domains. It is a challenge to define blast domains in a complex mining setting as many sources of information are required: geological factors, rock structures, blast design parameters and fragmentation. At the Leveäniemi mine, blast domains have not yet been established, hence the fragmentation results will also be used to evaluate the blast results and especially the differences between them.

1.3 Hypothesis

It is expected that 3D image analysis can provide plausible delineation results, provided that the image quality is sufficient. This needs to be achieved by optimising the image acquisition system's settings, which will take some time. From the delineation results, statistical analyses can be done to evaluate particle sizes like x_{20}, x_{50} and x_{80}. Ideally, the image acquisition system on the haul road does not interrupt production. However, since the system is being developed during this work, it is assumed that this can not yet be fully achieved.

The delineation software does not need pre- or post-processing of the results, hence is expected to provide at least partly automated results. The part that cannot be automated yet, is matching the picture groups to the respective origin of the truck. A "matching" tool is aimed to be integrated in the software in the future, but for this project, the existing tool that was used for LKAB's Kiruna mine project will be adapted to suit this study.

Fragmentation results from 3D image analysis and other data sources are expected to assist with defining blast domains. When similar designed blasts around different locations in the mine are executed, similar results should be found if the rock properties are comparable. In that case, the blast locations could belong to the same blast domain. If very different results are found, the locations could belong to different domains. It is expected that some fragmentation data will be acquired. However, since a new method is used, it can become challenging to acquire enough data to conclude blast domains. The data acquisition is also limited by the mine plan, as the plan defines from where data can be acquired.

1.4 Research Questions and Objectives

The aim of the thesis is to gain a clear understanding of the factors contributing towards the blast results with an emphasis on fragmentation, so that blast domains can be identified. The approach is a brief literature study as background, a thorough case study of the Leveäniemi mine and a field-scale experimental imaging acquisition test, including data processing and analysis. Two research questions were defined from the previous sections and followed by four objectives:

1. How can fragmentation measurements automatically and without disturbing production be achieved by 3D image analysis of blasted material in truck loads?
2. Can blast domains be identified using fragmentation results after blasting and how can other data be correlated to fragmentation to assist in the process?

Objective 1: Determining the potential of 3D image analysis of material loaded in trucks in an open pit mining environment.

To measure and evaluate fragmentation after blasting, 3D image analysis of truck loads can be used. The 3D image analysis system used during this thesis has been used in Kiruna's underground mine and will be adapted to suit Leveäniemi's open pit operation. As the environment, operation and acquired data differ from the underground system, the potential and limitation of the system will be investigated. The resulting potential and limitation of the system can help to define if this method can be used to measure fragmentation and to answer the research question.

Objective 2: Estimating the correlation between fragmentation and other defined input or output data.

The fragmentation resulting from 3D image analysis is not the only data acquired. The drill and blast parameters are administrated. Muck pile shape and high-speed video data of the blast is acquired in addition to measuring fragmentation. These methods are introduced in subsequent paragraphs. Correlations between fragmentation and other mentioned data sources will be explored. By discovering correlations, other data sources can potentially be used to predict fragmentation or evaluate blast performance.

Objective 3: Estimating baseline fragmentation for the Leveäniemi open pit mine.

The importance of measuring fragmentation has been explained in section 1.1. The goal is to get information on fragmentation so that a range of expected fragmented particle sizes is known. This will be challenging due to the implementation of the new image acquisition system. However, if it is achieved, it can assist the development of blast domains as different particle size ranges might be measured and thus expected in different areas in the mine.

Objective 4: Defining blast domains using 3D image analysis.

Defining blast domains can ease the drill and blast design process. Evaluating the blast results is a tool to achieve this, as long as the input design parameters are known and used in the evaluation. When blasts with similar design parameters are executed around a variety of locations in the mine, the result can show if certain locations belong to the same blast domain. Additionally, rock properties should be considered as background information, as different joint sets (orientation, spacing) can easily produce different results when blasted similarly.

1.5 Methodology

Blast-induced fragmentation from the material loaded in trucks is measured using a 3D image analysis method. The system is adapted from an underground mining setting, hence time is needed to install and finetune the settings. This method consists of an image acquisition system and software for processing. The image acquisition system includes two cameras that are triggered by a laser when a loaded truck passes them, so that a series of pictures are taken. Additionally, the truck carries a Radio-Frequency Identification (RFID) marker to create a time stamp that can be matched to the right pictures. This allows the pictures to be connected to the right origin, hence blast location, using Minestar data. The pictures are sorted using customised software before further processing.

The set of images from two cameras is then processed to a coloured 3D model and delineated using 3D image analysis software. A study needs to be done on the input parameters of the delineation software and is included in this thesis. From the delineation results, a PSD curve can be established. The fragmentation results will be analysed and compared to the other acquired data, outlined in the next paragraphs. The results could be used to determine blast domains, given that enough data is available. The software is still under development, so some settings must be tested and defined during this thesis. However, in the future this step will most likely be eliminated.

Muck pile shape parameters are measured using Total Station and can serve as easy-to-measure blast performance indicators. The parameters show how far the blast has moved, how high the muck pile is, and how far the muck pile has been pushed away from the bench. These parameters can also be correlated to fragmentation results or drill/blast parameters as often better muck pile distribution means better (and more consistent) fragmentation.

High speed video of blasts and drill/blast design parameters are easy to acquire and can be used as background information. The drill and blast parameters should be known as it is used to scale the muck pile shape parameters to normalised values.

1.6 Scope

The field test is executed at Leveäniemi's mine operation and is therefore operation specific. The scope naturally followed after the case study background was researched and data were acquired. The following data was acquired and considered to be in scope:

- Truck load images
- Muck pile shape parameters
- High speed video of blasts
- Drill and blast design parameters

The truck load images were acquired from certain locations of the Leveäniemi open pit mine due to the mine plan and issues from the image acquisition system. The mine plan reported in section 3.2.1 shows that during the time of data acquisition only a few areas would be mined. An overview of the locations from where image data was acquired is provided in appendix A, where the numbers correspond to specific drill patterns.

The following data was also considered to be acquired, but decided to be out of scope:

- Shovel loading efficiency and diggability
- Time series data
- Systematic face mapping
- Crusher energy consumption
- Measure While Drilling (MWD)

Shovel loading efficiency can easily be extracted through the Minestar system. But during data acquisition, different loading tools were used which complicates the data interpretation. Time series data could not be achieved as data was only acquired for a few months. Systematic face mapping was not executed due to lack of resources. Crusher energy consumption can be monitored easily, but because the mine uses a stock piling system before crushing, the measurements cannot be easily connected to a specific blast. Lastly, MWD was excluded as it was not readily available, and it is hard to correlate to the other acquired data.

1.7 Outline

Chapter 1 introduces why measuring fragmentation is important and for which purpose, the problem statement, hypothesis, research questions, introduction to the methodology, objectives and scope. Chapter 2 includes a literature review about drilling and blasting in open pit mining, the available methods for measuring fragmentation and the introduction of a new approach, 3D image analysis blasted material loaded in trucks. Chapter 3 provides a detailed overview of the case study background and includes a background of the Leveäniemi mine and its mining operation. Chapter 4 outlines the methodology of data acquisition, processing and analysis which resulted from the available data at the Leveäniemi mine. Chapter 5 presents the fragmentation, high speed video and muck pile shape results. Chapter 6 follows with discussing the results in terms of the image acquisition system, the fragmentation results and other data that were acquired. Chapter 7 concludes and recommends the use of the image acquisition system and suggests alternative methods to measure fragmentation.

2. Literature Review

The principles of drilling and blasting in open pit mining are explained in section 2.1. The blast output results in a fragmentation distribution that can be measured using various methods, as outlined in section 2.2. For this research, a relatively new approach is used, which is explained in section 2.3.

2.1 Blasting in Open Pit Mining

To extract hard rock from an open pit mine, drilling and blasting is required. In section 2.1.1 the design parameters that are used in drill and blast design are explained. The result of blasting is a fragmentation distribution of a certain quality, of which more details are provided in section 2.1.2. The definition of blast domains is provided in section 2.1.3.

2.1.1 Design Parameters

When designing drill and blast plans, many factors must be considered (Sharma, 2012). The majority relate to the parameters displayed in Figure 2.1. For example, bench height and angle are often determined by stability of the overall pit slope and the size and type of the loading tool. Most of these factors are interrelated with each other and with the factors displayed in Figure 2.2. For example, when increasing the burden and spacing, the specific charge must be increased to keep a comparable explosive performance. Similarly, when the hole diameter is increased, a lower specific charge is used. The specifics of each parameter are described in the subsequent paragraphs. The explosive performance can be measured by evaluating the quality of the result. Quality assurance could be related to the burden/spacing ratio, actual charging, among other things.

BH = Bench Height
B = Burden
S = Spacing
HD = Hole Depth
J = Sub-Drill
TS = Top Stemming
D = Hole Diameter
SDe = Stem Deck
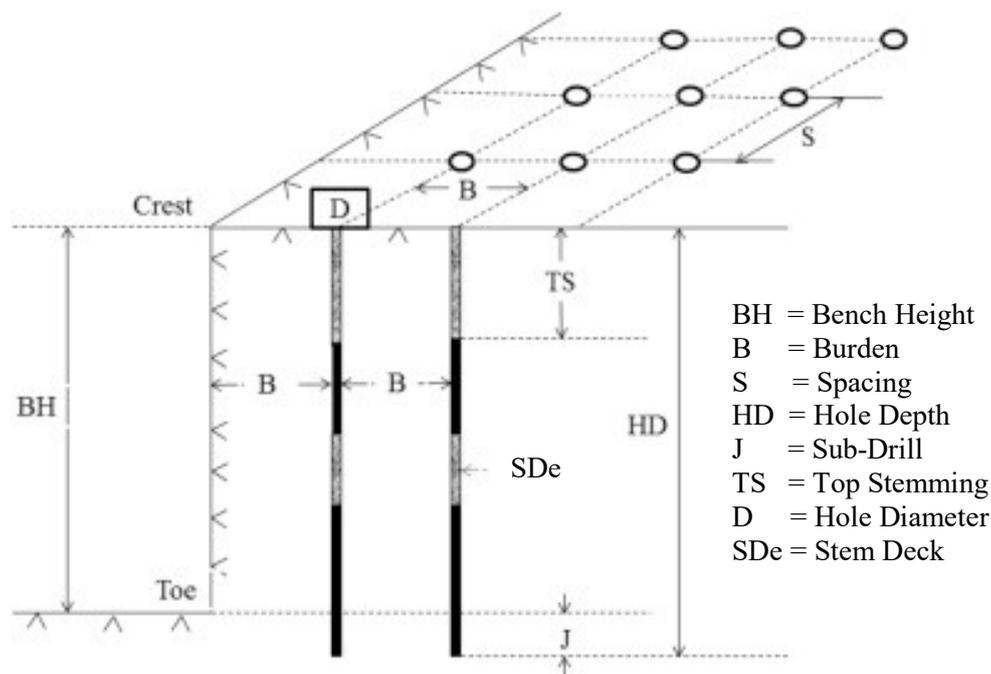
Figure 2.1 – Blast design parameters (Hustrulid, 1999)
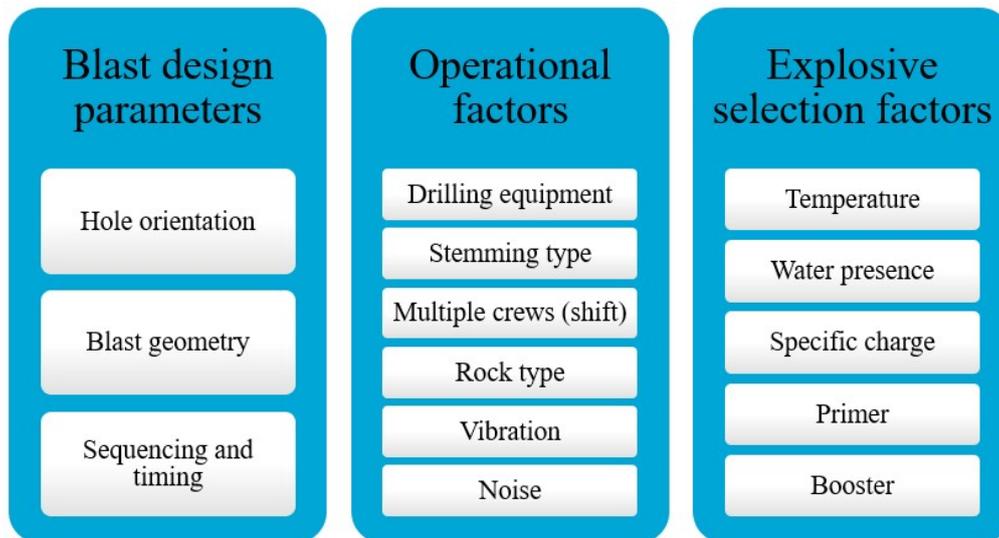
Figure 2.2 – Factors influencing the blast result

Hole Orientation

The hole orientation is related to the dip and orientation of joints, and the bench slope angle. Blast holes can be designed with or against the dip, resulting in different fragmentation. This applies to blasting with joints perpendicular or angular to the face too (Katsabanis P. , 2003). Depending on the pit shape and benches, these factors can be taken into account. The drill hole angle relative to the bench has implications on toe breakage. The toe is the bottom corner of the bench's free face with the pit floor (see Figure 3.5).

Blast Geometry

The blast geometry includes the size, shape and number of free faces. When blasting the first cut to start extracting a lower level, a box cut must be blasted as only the top has a free face. Subsequently, pushback blasts are designed, having the free face on the longer edge (called the free face). Often, one face at the shorter edge is also free (called the free end) when a long bench is blasted in stages, as shown in Figure 2.3. Blasts are generally designed rectangularly to generate a proper explosive energy distribution, to have a free face, and for practical reasons.
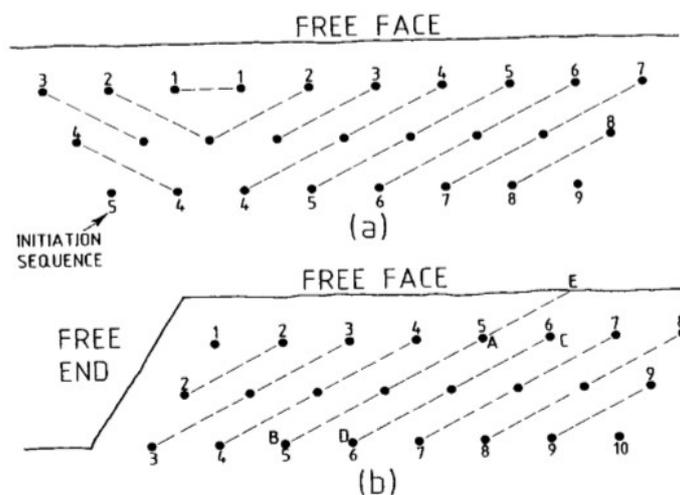
Figure 2.3 – Initiation sequence towards a free face and free end (Katsabanis P. , 2003)

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Sequencing and Timing
Sequencing is designed to start at the location where there is most space for the rock to expand, i.e. at the free face or corner of the free face and free end as demonstrated in Figure 2.3. Sequencing can influence the level of vibrations. The choice for delay intervals is impacted by:

- The burden, if it increases the delay interval should increase too (Katsabanis P. , 2003).
- The time needed for the rock around that hole or row to expand and provide open space.
- The use of down-the-hole delay.

The delay choice can affect fragmentation, control of rock movement, overbreak and fly rock. It has been suggested that the delay time influences the larger sizes of blast-induced fragments and the uniformity of the fragmentation (Katsabanis & Omidi, 2015).

Operational Factors
Before a mining operation starts, equipment is selected and acquired based on initial plans. When the blast drill has been acquired, there are limited options to change the hole diameter because blast drills have a specific range of hole diameters that can be achieved.

Frequently, drill cuttings from blast hole drilling are used as stemming. However, this material is not always optimal as coarser material provides more resistance. Material availability and working costs influence the choice for stemming material. Wet cuttings do not provide much resistance when used as stemming (Katsabanis P. , 2003).

Many mining operations utilise shift work. Multiple crews work during the week, often adopting different working habits. Therefore, there can be deviations in executing production activities. The differences should not be extreme, but it is good to be aware of this factor.

Whether the rock is defined as ore or waste can have implications on blasting. Often, waste does not have to be blasted as optimal compared to ore, because it is not further processed. However, loading and hauling must still be carried out satisfactory, so there are limits. Additionally, the waste dump volume is related to the waste rock fragmentation. Less waste volume is beneficial in terms of required storage area. Note that ore and waste can also occur in the same blast and are separated when the material is loaded.

Depending on the location of the mine, a maximum level of noise and vibration is acceptable, due to regulations, proximity to a community and the environment. Vibration and noise are affected by the charge weight, sequencing, delay and size of the blast. The distance to the blast also affects the level of disturbance. It is important to control these factors to minimise risk and disturbance (Aloui, Bleuzen, Essefi, & Abbes, 2016).

Temperature
Low temperatures can influence the sensitivity and detonation of the explosive. With the development of slurries these problems have almost been eliminated. However, slurry cartridges can become less cap sensitive at extremely low temperatures. More initiation energy is then needed (Jimeno, Jimeno, & Carcedo, 1995). When pumping slurries from an explosives truck, freezing of the hose can occur when temperatures are very low.

Water Presence

When water is present in the holes, some explosives might desensitize and fail (like ANFO). This can be avoided by dewatering the holes, using waterproof cartridge explosives or pumpable slurries/emulsions. The density of slurries and emulsion is higher than water, pushing the water out. Alternatively, holes can be lined to keep the water out. When water in the hole freezes due to low temperatures, charging the hole becomes impossible.

Specific Charge

The specific charge is also called the powder factor, commonly used in the explosives industry, and is directly related to fragmentation (Tosun, Konak, Onur, Karakus, & Tugce, 2013). It is defined as kilograms of explosives required to break a cubic meter of rock (kg/m^3). This is often a leading parameter in blast design, together with hole diameter, burden and spacing. For example, an explosive with the same powder factor combined with small diameter holes spaced close to each other, will generally result in better fragmentation than large diameter holes spaced further apart (Katsabanis P. , 2003). Ultimately, this is a trade-off between blast results and costs.

Primers and Boosters

Sometimes, a primer or booster is required. A primer is necessary when a noncap-sensitive explosive is used to effectively initiate the explosives column when the detonator cannot provide enough energy. A booster is used when additional breakage is needed, like at a hard to pull toe. The booster does not increase the total energy output of the primary explosive. Only the borehole pressure is temporarily increased (Konya & Walter, 1990; Hustrulid, 1999). A detonator is always required for initiation, together with a bulk explosive.

2.1.2 Fragmentation

Fragmentation is the first step of size reduction and a direct result of blasting (Siddiqui, Ali Shah, & Behan, 2009). It results from the response of the rock to the pressure and shock waves from the adjacent explosives. Breaking mechanisms come from many parameters, of which the most important are, but not limited to rock properties, explosives properties, stemming, free face(s), burden and spacing (Katsabanis P. , 2003). Examples of breaking mechanisms are fracturing in tension, fracturing in compression, and spalling.

The free face provides space for the rock to swell and move, which is necessary for fragmentation to occur. To move the rocks into a certain direction, inclined drill holes and adjusted initiation patterns can be used. The number of free faces and location of the blast, among other things, influence the choice for sequencing and timing. These factors effect fragmentation. For example, when a box cut is blasted, the material in the centre must move upwards to a certain extent, to allow the adjacent rock to fall inwards to create a muck pile and space to swell.

Rock structures like joints influence fragmentation significantly, in terms of orientation, filling and spacing (Nur Lyana, Hareyani, Kamar Shah, & Mohd. Hazizan, 2016). When emulsion is used, the explosive can leak into the rock mass, changing the blast result. It might cause a disruption in the explosives columns or it could cause an overcharge resulting in an increased risk of fly rock. Another scenario could be that the explosive energy dissipates into open fractures. For example, if the borehole intersects a fracture, it will open with the strain wave effect and radial cracks in other directions will be limited during the blast. However, if there are fractures parallel and at some distance to the blastholes, they can interrupt the propagation of radial cracks and result in boulders (Jimeno, Jimeno, & Carcedo, 1995).

Fragmentation has many implications on downstream processes (Scott & Mckee, 1994; Kojovic, Michaux, & McKenzie, 1995). It starts when the blasted rock is mucked. A well-swollen and -fragmented muck pile is easier and more efficient to dig. Good fragmentation provides better fill-factors. Additionally, it results in a consistent energy consumption for the crusher. Boulders can be a problem in the crusher as it can choke, reducing productivity. Fines can stick to the sides of the crusher and build up a solid layer, resulting in downtime when it needs to be removed. This is only a selection of implications that fragmentation has on other processes. Hence, for any hard rock mine it is useful to have knowledge about their rock fragmentation as a result of blasting and know the desired fragmentation to suit further processing requirements.

2.1.3 Blast Domains

Some research has been done on the effect of rock properties and structures on blast domains (Bergman P., 2005; Valery & Jankovic, 2011; Dance, Valery, Jankovic, La Rosa, & Esen, 2007). Blast domains are often defined as areas where a specific drill and blast design produce similar fragmentation results. It can be decided if mainly the fragmentation result, mechanical or structural properties of the rock, or the material behaviour after blasting is important in defining blast domains. Generally, a combination of factors is considered.

It is important to keep the blast domaining simple, as the domains are meant to ease drill and blast design processes. Additionally, it should be considered in 3D. When the mine progresses in depth, the domain boundaries might change as well. In this thesis, a blast domain is defined as an area with comparable rock structures and properties, resulting in similar fragmentation distributions if the same drill and blast design is used.

2.2 Review of Available Methods for Measuring Fragmentation

Fragmentation can be measured using various methods. Sieving is a well-known method and is described in section 2.2.1. Image analysis methods are more often used nowadays to measure fragmentation and are grouped in 2D and 3D methods summarised in section 2.2.2. Laser scanning methods are mostly under development and are briefly described in section 2.2.3. The last two methods can be executed either by analysing the whole muck pile, or separate buckets (from loaders or trucks). As some of this will be covered in section 2.3, it is not evaluated for image analysis and laser scanning separately.

2.2.1 Sieving

Sieving has been widely used in the past when evaluating fragmentation on small scale tests. It can also be used to examine image analysis results, especially to measure and correct for fine particles that are hard to detect in images (Cho, Nishi, Yamamoto, & Kaneko, 2003). However, sieving is very costly, time consuming and difficult to implement in mining operations without interrupting production (Sudhakar, Adhikari, & Gupta, 2005). It is therefore regarded unsuitable for this project.

This method could alternatively be used to calibrate another fragmentation measurement system or to evaluate very small fragments that are often undetectable by other systems as described in the previous paragraph. In that case, only a few truck loads would have to be sieved. For calibration, the top layer that is visible for the image analysis or laser scanning equipment should be sieved only, as this compares best to the results. This is very difficult to achieve and since this project uses truckloads of around 200 tons, sieving will still not be used for this purpose as it is simply not practical.

2.2.2 Image Analysis

Digital image processing techniques have been investigated and developed, as this indirect method of measuring fragmentation is a lot easier than for instance sieving (Sudhakar, Adhikari, & Gupta, 2005). Using imaging techniques, reasonable results can be reached while maintaining a practicable approach and spending less efforts. However, it can only be used in a comparative way (Wimmer, Nordqvist, Righetti, Petropoulos, & Thurley, 2015). Additionally, it is fast, inexpensive and generally does not interfere with production (Stauder, 2018). There are several options for 2D fragmentation analysis. For example, Split-Desktop (Split Eng, 2019) and WipFrag (WipWare, 2019) are established 2D image analysis software packages that are widely used in the mining industry. 2D image analysis is limited to only one viewing direction, as it uses a single image and cannot run in automatic mode, meaning that errors need to be corrected by post-processing the results. By introducing a 3rd dimension to the analysis, the constructed PSD curve should become more accurate. Therefore, software companies and researchers have started investing in developing automated 3D image analysis methods for the purpose of measuring fragmentation (3GSM, 2019).

Some 2D image analysis software, like Split-Desktop have functions like automatic, manual and a combination of automatic and manual delineation codes. Correcting automatic delineation provides the most accurate results but are very time consuming. The same counts for the editing of images before they are analysed (Sanchidrian, Segarra, & Lopez, 2006; Righetti, 2014). When both are needed, the system does not suffice the requirement of highly automated as described in section 1.2. Therefore, an investigation into new 3D image analysis software is of interest as this method might have more automatic features. This method is covered in the next section.

Several challenges arose from previous investigation into image analysis techniques and are summarised in Table 2.1 (Raina, 2013; Cunningham, 1996). The table is mostly aimed at challenges related to 3D image analysis, as it is the method used during this study. However, many of the challenges also apply to 2D image analysis.

Table 2.1 –Challenges related to image analysis to measure fragmentation

Challenge	Clarification
Representative sampling size	It is difficult to determine what sample size is representative when analysing a full-size blast. Statistically, a larger sample size betters the accuracy, but is not always practical.
Image quality	The quality of the images is good due to the use of modern cameras. The software is not always capable of handling the pictures or it is very time consuming. If images are acquired in production, motion blur and evaluation time can be more challenging compared to images taken independent from production.
Environmental effects	The image can be affected by e.g. lighting conditions due to weather or dust.
Scaling errors from tilted images	Most software can adjust the tilt.
Errors due to poor edge detection	The possibility of detecting the edge wrong exists, by disintegrating or fusing particles.
Errors from bias to fines	Due to image resolution, software is not able to detect fines smaller than the image's pixels. Only through sieve analysis calibration, a fines correction can be applied.
2D to 3D unfolding models	This is not applicable to 3D modelling.
Errors due to distribution fitting	Most software provide a best fit to the measured PSD curve. If it is a poor fit, the error in predicted sizes and uniformity index might be problematic.

2.2.3 Laser Scanning

There have been first attempts to use laser scanning techniques for measuring fragmentation, as it is supposed to overcome some of the limitations that were experienced when using image analysis. An example is using 3D high-resolution laser scanning techniques to measure fragmentation of the muck pile after blasting (Onederra, Thurley, & Catalan, 2015). Fully automated analysis was possible when the resolution was sufficiently high. However, manual pre-processing was required when the resolution was not sufficient, especially for fines regions. The research showed that this method can be used to evaluate fragmentation instead of image analysis. The same system is now routinely used in an underground sublevel caving mine after calibration and testing (Campbell & Thurley, 2017). Laser scanning equipment was not available and therefore not used to measure fragmentation.

2.3 New approach: 3D Image Analysis of Truck Loads

For this study, a fairly new approach was chosen, 3D image analysis of material loaded in trucks. The image acquisition system originated from LKAB's Kiruna mine where it has been successfully used to evaluate fragmentation from loaded LHD buckets during sporadic testing. Plausible delineation and PSD results were achieved. (Wimmer, Nordqvist, Righetti, Petropoulos, & Thurley, 2015; Stauder, 2018). First, the fundamentals of 3D image analysis are explained in 2.3.1. The advantages and limitations of this method are outlined in section 2.3.2 and 2.3.3 respectively, additional to the challenges reported in section 2.2.2. The details of the methodology are outlined in section 4.4, so this section can be considered general.

2.3.1 Fundamentals

The generation of 3D models is done from multiple 2D images. A minimum of two pictures is needed to generate a 3D model as displayed in Figure 2.4. The more pictures are available, the better the model quality will be. If the distance between the cameras is known, no scale is required in the picture, as is always the case for 2D methods when a single picture is used. For this study, two cameras with known distance between them will be used to acquire pictures. A set of images can then be used to construct the 3D model. Multiple pictures of each camera will be used per truck load.

A specific software for 3D image analysis is used in this project which has been tested last year (Stauder, 2018). Details are provided in section 4.4.3. A general overview of this method is provided in this section. First, a coloured 3D surface model is created from all available 2D pictures, as displayed in Figure 2.4. This results in a point cloud, from which a coloured surface mesh is created using the image's information. From this 3D model, particles can be delineated following an algorithm. By adding spatial information to the model, a better PSD is expected to be achieved when the software reaches its final developed state (Stauder, 2018).
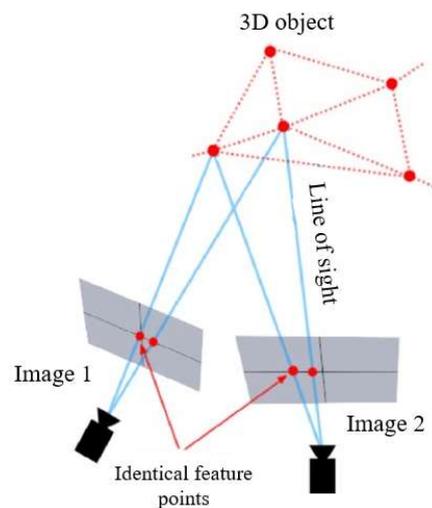
Figure 2.4 – Illustration of the principle of 3D image analysis (adapted from Tokkari, et al., 2017)

Truck loads will be analysed, instead of a whole muck pile. Using truck loads, sampling of the rock fragments is assumed to be more statistically representative, as not only the top view from the blasted pile will be visible. The top of the pile is generally coarser fragmented (Sharma, 2012).

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2.3.2 Advantages

The results of this method can mainly be used in a comparative way. They are reproducible and provide plausible delineation results and therefore provide a robust method (Stauder, 2019; Stauder, 2018). The software does not need any pre- or post-processing of the images, increasing the efficiency and level of automation of data processing (Thurley, Wimmer, & Nordqvist, 2015). A scale is not required as long as the distance between the cameras is fixed and known. Additionally, this system allows to acquire images in production areas. This is an advantage as data acquisition without disturbing production is generally a challenge.

The software ensures that the lens and perspective distortion are corrected when developing the 3D model (3GSM, 2019). It also delineates particles using geometry and colour, which is different from the established 2D software that are currently available.

2.3.3 Limitations

Surfaces from rock fragments (underground) appeared to be smoother and contained more missing data, potentially hindering the delineation process due to the movement of the object to be pictured (Wimmer, Nordqvist, Righetti, Petropoulos, & Thurley, 2015). Similar challenges are expected for the open pit application of 3D image analysis.

It is expected that the image quality can vary due to lighting and weather conditions. Depending on the location of the sun, shadows or reflections can lead to colour differences, wet compared to dry particles for example. This could lead to poor delineation of fragments. Dust from the ground or muck pile can cause bad vision. All factors could influence delineation performance and result in fusion or disintegration of particles (Thurley, Wimmer, & Nordqvist, 2015).

PSDs developed from 3D image analysis provide plausible results (Stauder, 2018). However, segregation is often a problem and leads to different results compared to sieving (Rosata, Strandburg, Prinz, & Swendsen, 1987). Fines are underestimated as they disappear in between larger fragments, especially when trucks cover a significant distance before they are photographed, this is a limitation of both 2D and 3D image analysis methods. The software can also have trouble detecting fines regions. For this reason, fines correction curves have been developed and integrated in certain software to achieve a complete curve.

Additionally, large density differences of the rock could lead to segregation as well. Fines can easily be detected as one large particle if it provides a smooth surface on the picture where no boundaries can be detected. Additional to segregation, overlapping particles can be wrongly detected, but this is more a concern for the software performance.

3. Case Study

The field test was executed at the Leveäniemi open pit mine, located in Svappavaara, Swedish Lapland (Figure 3.1). The iron ore mine is owned and operated by the Swedish mining company Luossavaara-Kiirunavaara Aktiebolag (LKAB).

Figure 3.1 – Location of the Leveäniemi mine (Google Maps, 2019)

The Leveäniemi open pit mine was first operated from 1964 to 1983 and put back in production in 2016 (LKAB, 2015). The reported reserves for 2018 were 98 million tonnes (proven and probable). In 2018, 7 million tonnes of crude ore (25-63% Fe content) were extracted from the Leveäniemi mine (LKAB, 2019). The current pit reaches a depth of about 100 meters measured from the surface, is around 750m wide and 1.3km long. The Leveäniemi iron ore mine consists of several rock types and discontinuities explained in section 3.1. The ore is extracted using conventional drilling and blasting as explained in section 2.1 according to a 0.82 stripping ratio for the current final pit design (currently planned until 2032). The mill feed and pellet product are sold to customers. The site-specific drill, blast, load and haul procedures are summarised in section 3.2.

3.1 Geological and Structural Background

The Leveäniemi mine consists of a large apatite iron ore body containing both high grade (64% – massive magnetite) and low grade (26% – magnetite breccia) iron ore. The main host rock consists of biotite schist, but in some areas, it changes to foliated muscovite schist. The host rock in the central part of the deposit is affected by clay alteration. In this section, the massive magnetite ore is altered to hematite, resulting in a hematite-magnetite mixture having a lower iron ore grade. The contact between the magnetite and breccia ore is mostly distinct (Bergman, Kübler, & Martinsson, 2001). An overview of the geological map can be found in appendix B (SRK, 2014), a plan view of the mineralised zones is displayed in Figure 3.2 and view appendix C for a visualisation of high- and low-grade ore.
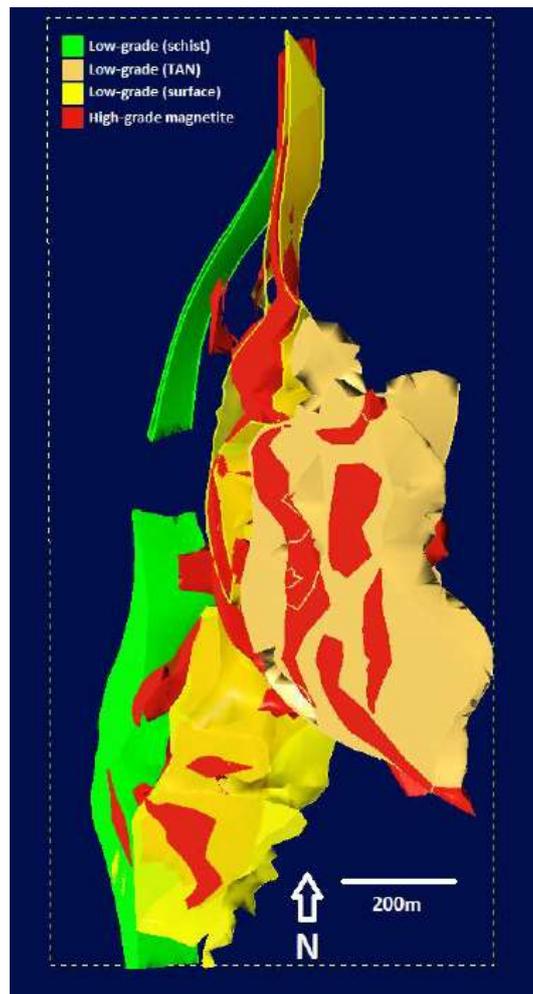
Figure 3.2 – Plan view of Leveäniemi mineralised zone sliced at level 250m (LKAB, 2017b)

The Leveäniemi mine is located in a subarctic climate (Kiprop, 2017). This is characterised by short summers and long cold winters. There is a lot of precipitation in the area as well. The rock is strongly metamorphosed and already geologically complex as described in the previous paragraph. The rock structure gets more complicated when sub-zero temperatures result in the freezing of water-filled fractures and joints. As water expands when it becomes ice, the rock becomes more fractured and weathered.

The mine is situated in an area with a high groundwater table. Additionally, melt water inflow is very high during spring. Both factors result in wet mining conditions, influencing the explosive selection, weathering of the rock and stability of the pit walls.

Geological domains are based on iron type and content, and vanadium content due to processing requirements. The geological domains resulted in eight ore and three waste types. Many domains were altered and differ in their occurrence in terms of orientation, fractures and occurring minerals.

Geotechnical analyses have been carried out to a certain extent, resulting in the estimation of geotechnical domains, illustrated in Figure 3.3. Detailed geotechnical domains are currently being developed. The domains in Figure 3.3 mainly relate to the design criteria of the open pit. For example, all benches will be 30m high, but the bench angle varies from 55° for W, 60° for E and 70° for N, SE and S. The total slope angle is 36° for W and E, 40° for N and S, and 43° for SE. (Bergman A., 2014)
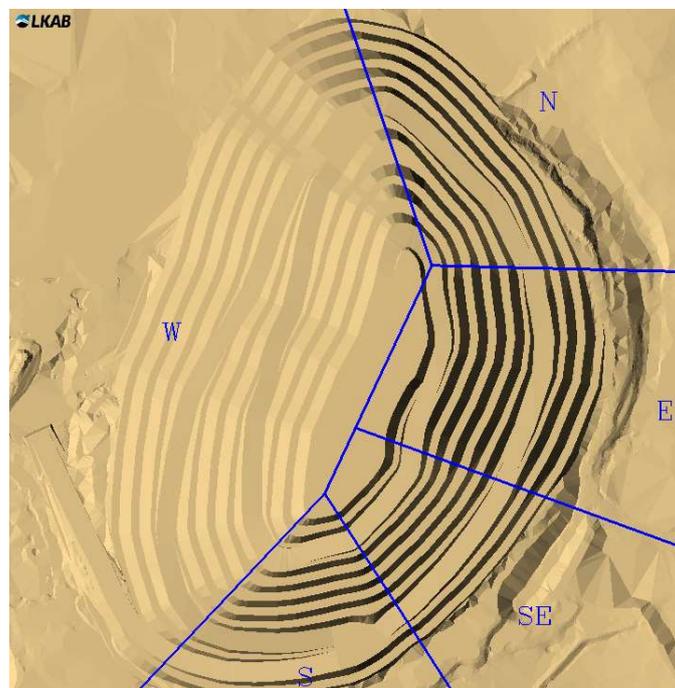
Figure 3.3 – Geotechnical domains based on design parameters (Bergman A., 2014)

3.2 Mining Operation

The mining operation includes drilling, blasting, loading and hauling. Drill and blast design differ depending on the location and purpose of the blast. If a blast is located close to a permanent structure or the edge of the pit, care must be taken to minimise damage. Similarly, fly rock and vibrations should be avoided. Therefore, the explained procedures and parameters correspond to a standard production blast only. Any deviating blast is not discussed in this section. After blasting, the material is removed by truck and shovel before the neighbouring blast can be initiated. In the following paragraphs, mine planning, drilling, blasting, loading and hauling procedures are outlined.

3.2.1 Mine Planning

Mine planning is split up into three timelines at the Leveäniemi mine: long-term, mid-term and short-term planning. Long-term planning decides the life-of-mine plan using the final pit design. Mid-term planning breaks this plan up into three-month periods and short-term planning uses weekly plans. As data was acquired during the period April-June, the mid-term plan is displayed in Figure 3.4. It shows that data can only be acquired from a few locations in the mine.
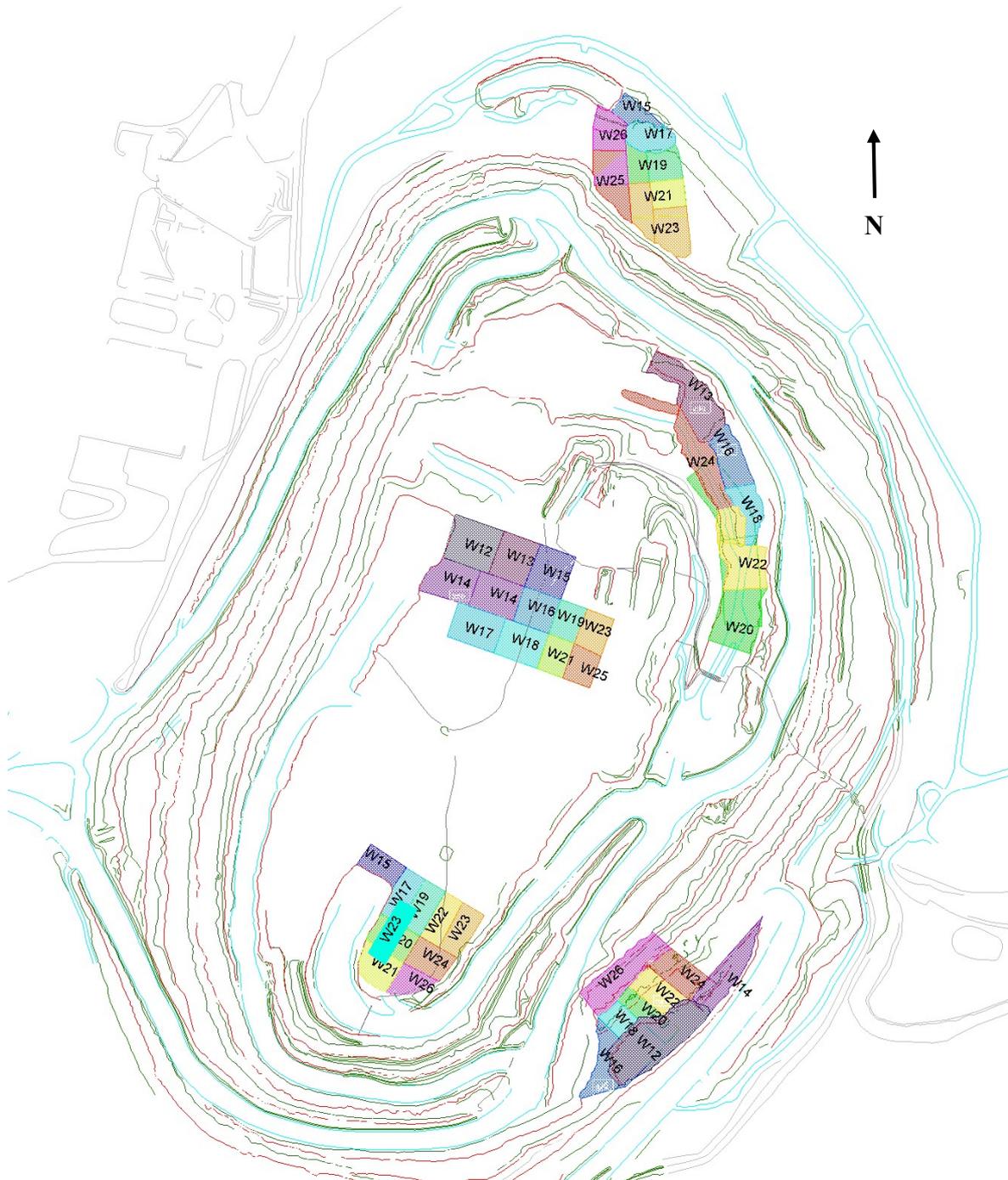
Figure 3.4 – Mine Plan for April–June 2019 (W stands for week number)

3.2.2 Drilling

The parameters of a standard drill pattern design are listed in Table 3.1. These parameters are defined and adjusted by the short-term planning engineer for specific cases. When the production technician designs the drill plan, the coordinates of the bottom of the holes from the above bench must be considered as a safety precaution. Otherwise, the drillers risk drilling into explosive remnants. Additionally, the row of holes closest to the free face is adjusted to the distance between the toe and the bottom of the hole. The hole angle can be adjusted up to a maximum of 20° measured from the vertical due to the equipment's specification.

Table 3.1 – Standard drill and blast parameters corresponding to Figure 2.1 at the Leveäniemi mine

Parameter	Abbreviation	Number	Unit
Bench height	BH	15	m
Burden	B	4.2	m
Spacing	S	4.7	m
Hole depth	HD	16	m
Sub-drill	J	1	m
Top stemming	TS	5.5	m
Hole diameter	D	165	mm
Hole incline	-	5	°
Pattern geometry	-	Square	-

The drillers will use the designed drill plan to drill the 165mm diameter holes using the Epiroc SmartROC D65. There can be collar and alignment deviations due to errors in GPS measurements, equipment, geology, geotechnical structures, operator skills, etc. For example, on average, three drillers work in one crew, each having a different level of experience.

Practical challenges drilling operators face are listed:

- Falling rocks if working close to a wall. Sometimes the hole cannot be drilled.
- Collapsing hole collars, resulting in a lost hole.
- Failing to use drill support, hindering withdrawing the drilling rod(s) and bit from the hole.
- Failing to calibrate, leading to an unknown hole depth and potential mistakes.

3.2.3 Blasting

When the holes are drilled, they are charged by the blasting crew. In consultation with the short-term planner, the explosive columns and top stemming lengths are defined. An overview of a standard blast design is displayed in Figure 3.5 with corresponding explosives parameters summarised in Table 3.2. Electronic detonators are used for improved performance. The bottom detonator will be initiated first. The top detonator is redundant, if the bottom detonation fails.
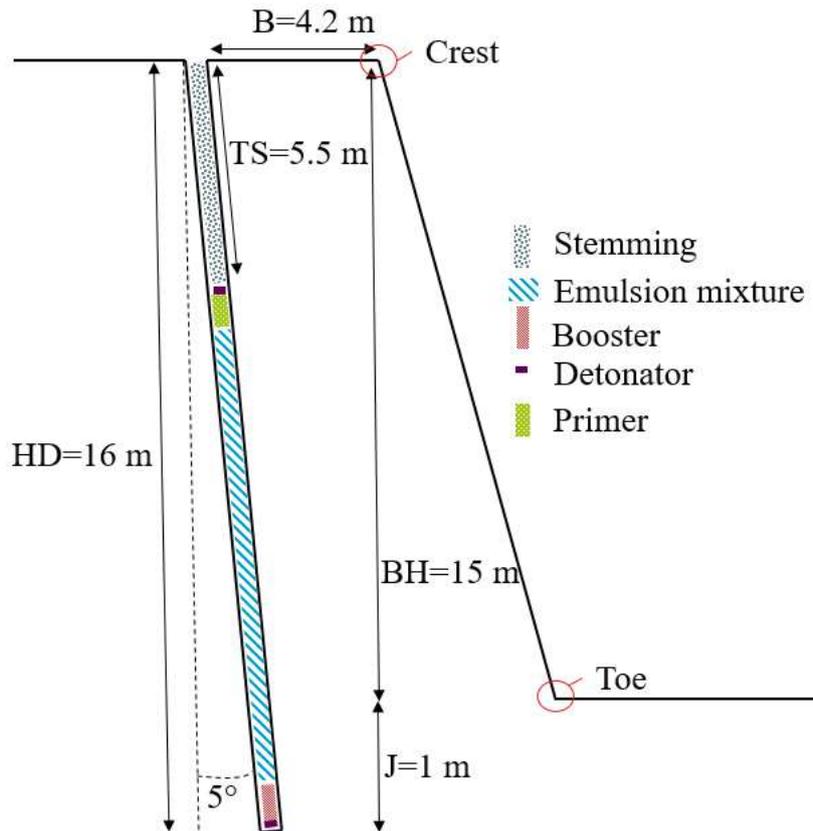
Figure 3.5 – Standard drill and blast design at the Leveäniemi mine (not to scale)

Table 3.2 – Overview of explosives parameters used in Leveäniemi mine

Emulsion mixture	Components	Kimulux SS, AN prills, gaseous liquid
	Emulsion/AN ratio	70/30
	Mixed density	1400 kg/m³
Booster	Pentex 1000	1 piece per hole
Primer	Weight	1385 g per hole
Total blast	Specific charge	0.99 kg/m³
Stemming	Particle size	16-28 mm

Timing and sequencing are also defined by the blasting crew in cooperation with the short-term mine planner. Generally, sequences are defined as explained in section 2.1.1, thus by the presence of a free face and a direction that the muck pile must be thrown into. Timing is also influenced by the location of the blast and the sequencing.

When the charging is finished, the detonators are connected. Each section of connectors will be connected to a bus line, which connects all sections to the blast box. Finally, the holes are scanned to deliver the timing information to each hole's detonator. The blast box is used to initiate the blast.

The blasters can encounter practical problems and deviations when charging the holes:

- Leakage of the emulsion into fractures, resulting in a lost or less loaded hole.
- Frozen water filled holes that cannot be charged, resulting in a lost hole.
- Calibration errors of the emulsion truck leading to inaccurate charging.
- Different timing and sequencing choices due to three-shift blasting crews deciding their parameters in collaboration with the short-term planner.

3.2.4 Blast Domaining

This project was initiated because official blast domains do not exist in the Leveäniemi mine. However, drill plans are already adjusted based on the location of the blast block in the pit and the purpose of the blast. If a final wall is blasted, sometimes a pre-split is used. A pre-split is a row at the final wall location which is loaded with low-power detonator cords to prevent damage to the pit wall. As each blast is separately designed, it could be argued that unofficial blast domains exist to some extent. An investigation into the possible existence of unofficial domains is excluded from the scope of the thesis.

3.2.5 Loading and Hauling

After blasting, the material is hauled to the right location: waste dump or ore stockpiles. This is done by a large-scale or small-scale fleet. The large-scale fleet is used in areas where the main haul road can be reached and consists of nine 220-ton CAT793 trucks, which are loaded by either a CAT6060 front loader or CAT994 wheel loader, displayed in Figure 3.6. Some areas are only accessible with small 60-ton Komatsu trucks, hence smaller sized excavators are used for loading in these areas. This is needed to convert the re-opened mine to a modern operation.

Figure 3.6 – A CAT793 truck in Leveäniemi with a CAT994 on the left, and a CAT6060 on the right (Eliasson, 2015; LKAB, 2017a)

The stockpiling system for the ore is necessary due to the complexity of the iron ore deposit. Iron and vanadium grades vary significantly and must be mixed when it is loaded into the crusher due to further processing requirements. Therefore, the blasted material is not directly tipped into the crusher.

4. Methodology

Various data acquisition methods were evaluated, considering the purpose and availability of the data. First, data documentation is outlined in section 4.1 following with a summary of unavailable data in section 4.2. The last sections cover the measured data. As background, the drill and blast parameters were administrated according to section 4.3. 3D image analysis was the main method to evaluate fragmentation and is described in section 4.4. For further analyses, the muck pile shape and high-speed video data were utilised as described in respective sections4.3 4.5 and 4.6.

4.1 Data Documentation

The administration of data uses the codes that are used in the mine site's documentation system. First, the Minestar loading block codes are explained, then the drill plan codes and lastly the model identification is explained. The Minestar loading blocks are used to determine which sections of the muck pile must be transported to which destinations. The destinations vary from stock piles with different grades to the waste dump. As displayed in Figure 4.1, the first two inputs are always the same for this mine site. The levels show the bottom and top of the bench. The blast block is a unique integer corresponding to a certain level and increases as the number of blocks that are blasted on that level increases. A "M" means Malm and a "G" means Gråberg (ore and waste in Swedish, respectively) for the loading zone. The following number is an integer to differ between several zones within one blast.
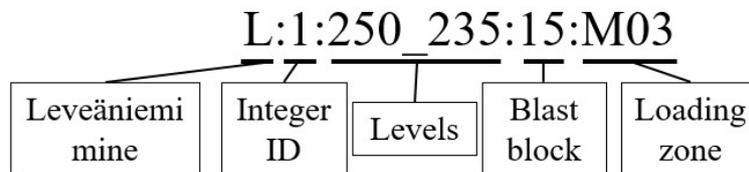
Figure 4.1 – Code used for Minestar loading blocks

The drill plan codes displayed in Figure 4.2 consist of the level on which the collar is located. It is followed by unique integers that increase as more drill plans are designed and connected. The drill plan codes are administrated with the Minestar loading blocks to enable matching them. The number of drill plan ID's can vary. Sometimes drill plans are made at once, but it can happen in stages when the crest and toe from the previous adjacent blasts are known only a short time in advance. This allows drillers to start drilling for new blasts before the adjacent one has been initiated.
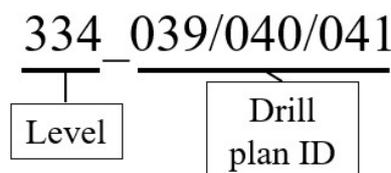
Figure 4.2 – Code used for drill plans

An example of the codes used for model identification is shown in Figure 4.3. Date and time were used to save the models. It eases to find picture groups after processing. Date is in month/day format and time is in hh:mm.
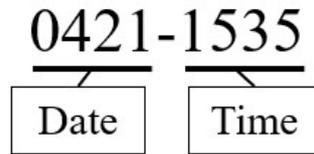
Figure 4.3 – Code used for model identification

4.2 Unavailable Data

Often, lots of data are measured at mining operations. However, it is not always accessible or straightforward to analyse. Some data had to be excluded to develop a realistic thesis scope and some data was not available due to the mine's operations. Why these data are unavailable and why it might have been of interest is discussed in sections 4.2.1, 4.2.2, 4.2.3, 4.2.4 and 4.2.5.

4.2.1 Shovel Loading Efficiency and Diggability

Loading efficiency for shovels can provide information on swell of the muck pile after blasting (Beyglou, 2016). Hence it can be considered a blast performance parameter. Loading efficiency can be extracted from Minestar reports. The Minestar system was only installed for the large-scale equipment fleet. This limits the potential to blasting locations where the CAT6060 or CAT994 is operating. The CAT6060 front shovel broke down during the data acquisition period. It was temporarily replaced by the wheel loader. Loading efficiencies from different loading tools cannot easily be compared. Therefore, it was decided to exclude this.

4.2.2 Time Series Data

It could be of interest to investigate the influence of weather, especially in northern Sweden. However, the experimental setup was newly introduced; hence data acquisition was limited to March, April and May. These months are considered the spring season and consists of many phases of freezing and thawing, potentially affecting data acquisition.

4.2.3 Systematic Face Mapping

Systematic face mapping provides information on detailed structures of the rock that will be blasted. Especially the number of joint sets, their spacing and orientation is of interest. Face mapping was not executed on a regular basis in this operation due to a lack of resources and the complexity of geotechnical structures. An example of such a complex geotechnical structure is displayed in Figure 4.4.

Figure 4.4 – Example of a geotechnically complex bench face (South-East on level 350, facing North-East, 4th of April, for exact location see appendix A)

4.2.4 Crusher Energy Consumption

The crusher energy consumption can be monitored and provides information on the homogeneity and relative particle sizes of the fragmentation distribution (Beyglou, 2016). This could not be tracked at Leveäniemi's operation due to their stockpiling system. Material from the stockpile is loaded into the crusher later, so it is difficult to track from which blast that material originates.

4.2.5 Measure While Drilling

Today, drill rigs are often capable of monitoring MWD data which can provide information on the rock type and geological structures using some drill parameters (Beyglou, 2016). There are three reasons that MWD data is being excluded from this project. Firstly, the information was not readily available. Secondly, it can only be used as a comparative measure (Beyglou, 2016). Lastly, the drill pattern is already designed at the drilling stage, therefore this data cannot be used to change the drill and blast design to improve fragmentation.

4.3 Drill and Blast Parameters

The drilling and blasting parameters were defined by operational staff and is readily available because of Leveäniemi's daily operations. These parameters were saved in their respective software and could therefore easily be extracted and considered as background information. The parameters of interest were saved and are expected to be reliable, but double checks have not been executed.

4.3.1 Data Acquisition

The drill plans are designed in Microstation (Bentley, 2019). The parameters used to generate drill plans are the burden, spacing, hole depth, borehole inclination and collar coordinates. Additionally, the toe and crest of the respective free bench face and uneven bench floors are considered leading to deviations in the set parameters. For example, the holes close to the bench face might be angled more to achieve proper toe breakage as displayed in Figure 4.5. It must be emphasised that drill plans were used to collect data, not the actual drilled holes, as this data was not readily available.
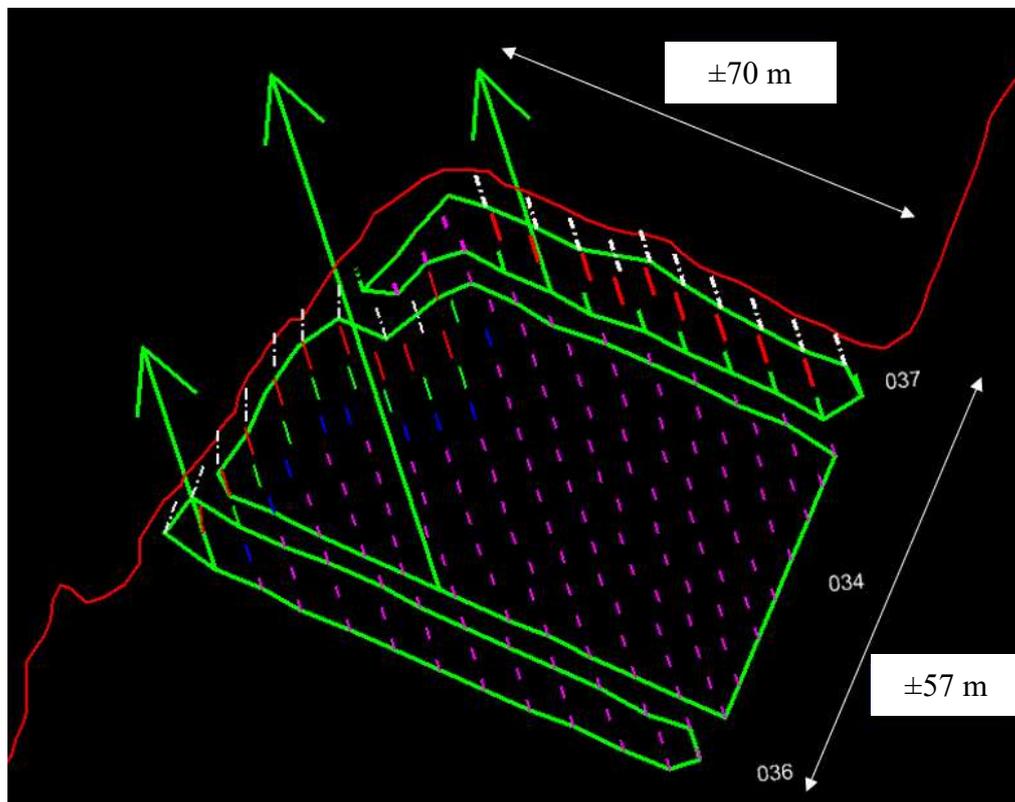
Figure 4.5 – Example for a drill plan for 250_034/036/037 where the colours display various hole inclinations (purple = 5°, blue = 7.5°, green = 10°, red = 12.5°, white = 15°)

Drill plans were designed according to their purpose and bench shape conditions. Therefore, the hole length, burden and spacing often consisted of a range of numbers. Estimating the volume of the blast block was done by multiplying the bench height, width and length of the blast. It could only be considered an estimate, not an exact calculation.

The blasting crew determines the amount of explosives, and the timing and sequencing plan in collaboration with the short-term planner. The total weight of emulsion and primer is administrated due to legislation. When dividing the total emulsion (kg) used per blast by the estimated volume (m^3), the powder factor was estimated.

Additionally, all timing and sequencing plans were saved as displayed in Figure 4.6. The numbers in the circles represent top and bottom initiation time, starting at a delay of 1000ms. As can be observed, for this blast the top and bottom were initiated simultaneously. Generally, the bottom was initiated first. Depending on the crew's working habits, lost holes are considered before or after designing the timing and sequencing. It can be beneficial to adjust the plan when there are a few lost holes close to each other. The parameters were summarised and saved.
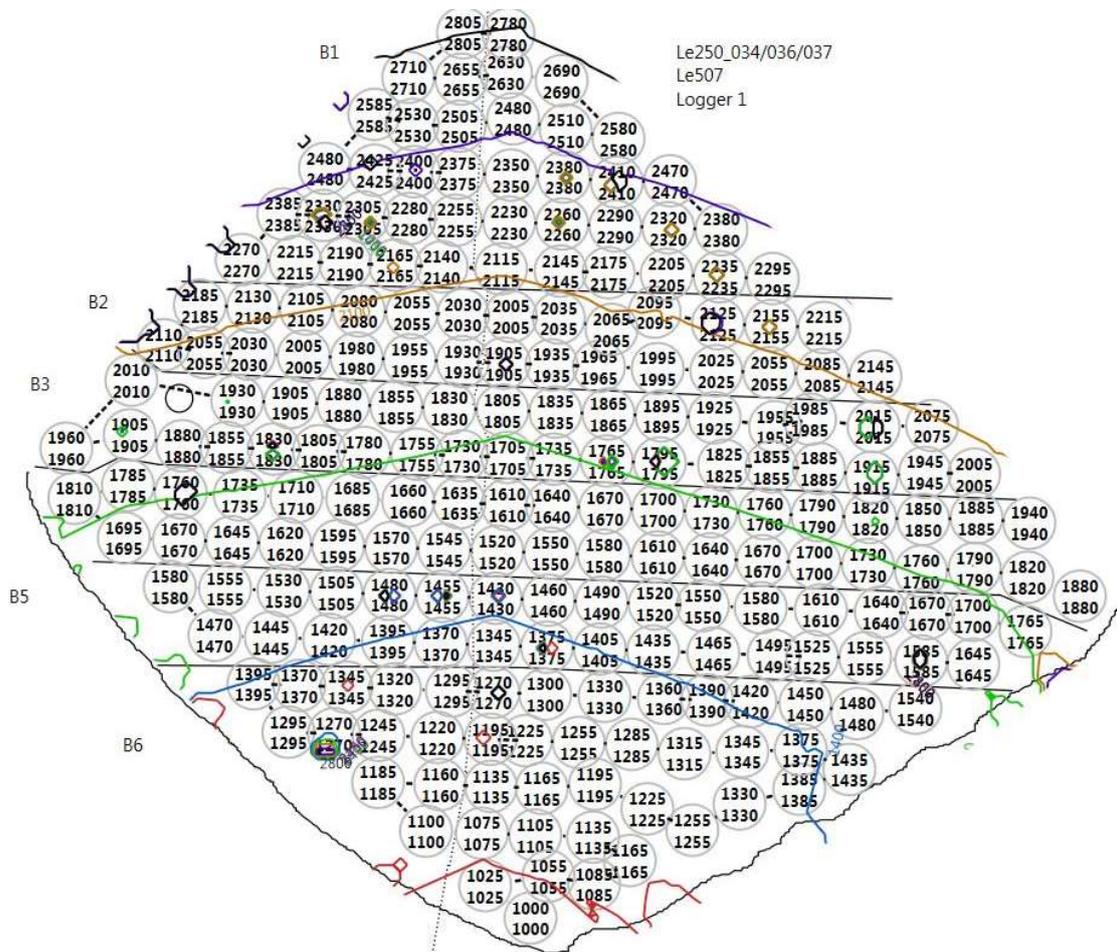
Figure 4.6 – Example of a timing and sequencing plan for blast 250_034/036/037

4.4 3D Image Analysis

3D image analysis is regarded as the main topic of the study. The system takes images from truck loads viewed from above, using two cameras. The set of pictures is used to produce 3D models of the muck pile. This model is analysed in newly developed software and produces a PSD curve. The setup was adapted to suit the open pit environment, as explained in section 4.4.1. How data are acquired from the system is outlined in section 4.4.2 and the data processing follows in section 4.4.3. The fragmentation analysis results had to be validated and evaluated, as outlined in sections 4.4.4 and 4.4.5.

4.4.1 Experimental Setup

The experimental setup consisted of a camera station, laser trigger and Radio-Frequency Identification (RFID) system, all mounted on an arch structure located on the main haul road. The camera station system took photographs when trucks passed, using the laser as a trigger. The RFID was used to identify which truck was passing at which time. The systems are explained in the following paragraphs and Figure 4.7. The truck dimensions correspond to the CAT793 (Caterpillar, 2013). A picture of the system in the field is included in appendix D. All systems were connected to the same electricity supply, except for the RFID truck markers, which ran on batteries.
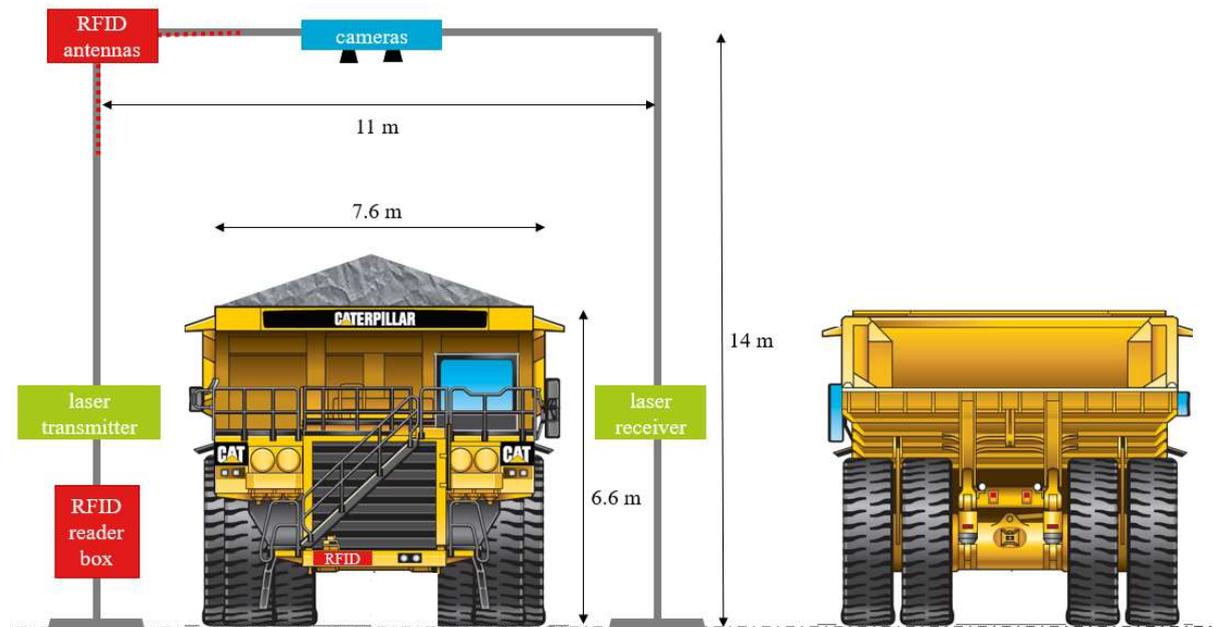
Figure 4.7 – Schematic experimental setup including dimensions (not scaled, red = RFID system, blue and green = camera system) (modified from Caterpillar, 2013)

Camera Station

The camera system consisted of a camera box (Figure 4.8) and laser triggering system (Figure 4.9) which were connected to each other. The laser system had a trigger and receiver, that communicated their signal to the StopShot (Cognisys Inc., 2019). When the laser beam was broken by a passing truck, the cameras shot pictures according to StopShots settings. These settings were used to define how long the cameras should take pictures, with which delay, and how long it should wait before it could take a background picture of the haul road. The input parameters were experimentally found by taking some time measurements at the installation before the laser system is installed and were checked after the first test run to limit the number of empty pictures. The final settings were 10ms delay, 2.4s of shooting pictures and a 2.5s gap until the background picture was taken (explained in section 4.4.2), resulting in 16 pictures per camera. The 16 pictures resulted from a certain frames per second (fps) setting. Additionally, there was a sensitivity setting, which was locked on least sensitive, so that the cameras were not triggered too easily.
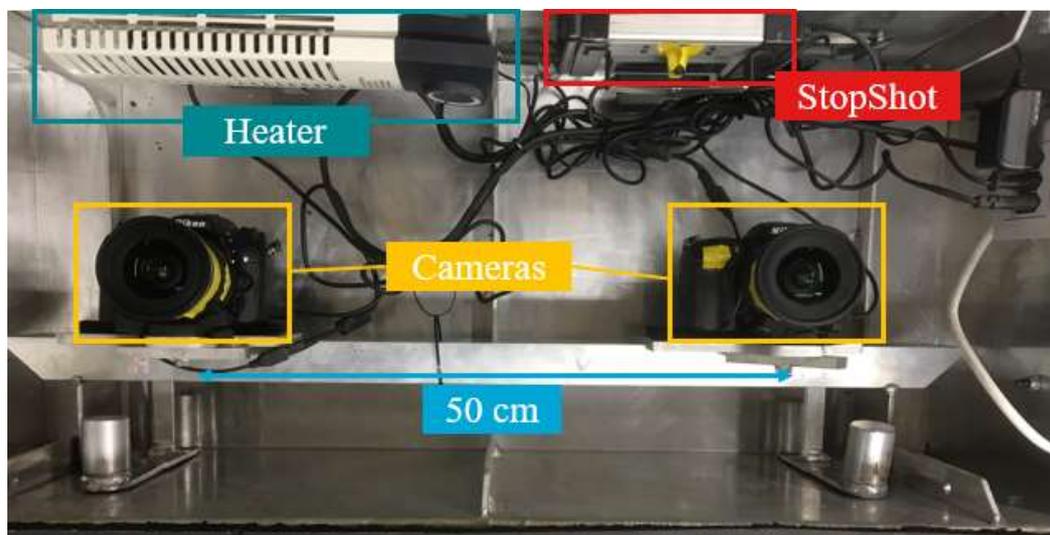
Figure 4.8 – The camera box' content: two Nikon D7200 cameras, a StopShot and heater

Figure 4.9 – The laser receiver (left) and transmitter (right) on the scaffolds

The cameras were connected to the StopShot and took pictures using its locked settings. Manual camera settings were used to generate consistent conditions. The zoom had to be set according to the distance from the muck pile, which was around six meters. It was important that the full truck load would be visible on at least one picture for the software. The distance between the cameras also had to be set proportional to the distance to the objects. The focus was set to infinite, as the distance to the muck pile was about four times larger than the hyperfocal distance of this camera. The aperture and shutter speed were found using field trials and recommendations of 3G Software and Measurement (3GSM), the company that supplied the 3D image and fragmentation analysis software. All settings were locked by tape, so they could not be accidentally changed while acquiring data or by the lens sinking down due to gravity. An overview of the camera's specifics and final settings is provided in Table 4.1.

Table 4.1 – Camera specifications and settings for two calibrated cameras by 3GSM

Type	NIKON D7200
Sensor	APS-C 23.5 mm x 15.6 mm
Resolution (px)	6000 x 4000
Aperture	F8.0
Shutter speed (s)	1/500
ISO	400
Focal length (mm)	11 mm
Distance between (cm)	50

The heater was added to the camera box compared to the underground system because temperature differences are much larger in open-air. The heater prevented frost from growing on the lid of the camera box, as well as protecting the equipment against extremely cold temperatures.

Towards the end of the data acquisition period, two data transmitting cables were added to the installation. They allowed to check the data on the cameras from the ground. It was used to see if the cameras were taking pictures as expected and if enough space was left on the SD cards. Data transmission was not fast enough to download the data from the cameras directly.

Radio-Frequency Identification System

The RFID system was used to identify the passing trucks, to match pictures to their respective origin, the blasted bench. The system consisted of a reader box, antennas and so called "smart markers" (Elexon Electronics, 2019). The markers with unique IDs were mounted on the trucks of interest, as displayed in Figure 4.10, and documented with the truck number. The antennas would pick up any truck marker's signal that passed the camera station and saved the respective time, date and ID in a text file on a SD card.

Figure 4.10 – RFID marker on a CAT793

4.4.2 Data Acquisition

The data had to be gathered from the different sources explained before: Minestar, the cameras and the RFID reader box. The Minestar reports were sent daily by e-mail. The picture data had to be collected manually from the cameras by exchanging the full SD cards for empty ones. When using two 512 GB SD cards per camera, it took about one and a half weeks to fill up. Note that this is specific to Leveäniemi's production rate and the laser trigger settings. The SD cards were acquired using a sky lift. When the cards were changed, they had to be formatted to avoid data writing issues. The SD card in the RFID reader box was exchanged as well. Note that this SD card had to include certain text files to enable the writing of the time stamps.

4.4.3 Data Processing

To facilitate fragmentation analysis of the truck loads, the data had to be sorted and processed to 3D muck models first. An overview of the workflow is provided in Figure 4.11. Only data from chosen blocks and truck IDs was picked up so it was important to update the database accordingly. In the following paragraphs, the software used to sort the pictures, create 3D models and perform the fragmentation analysis are explained.
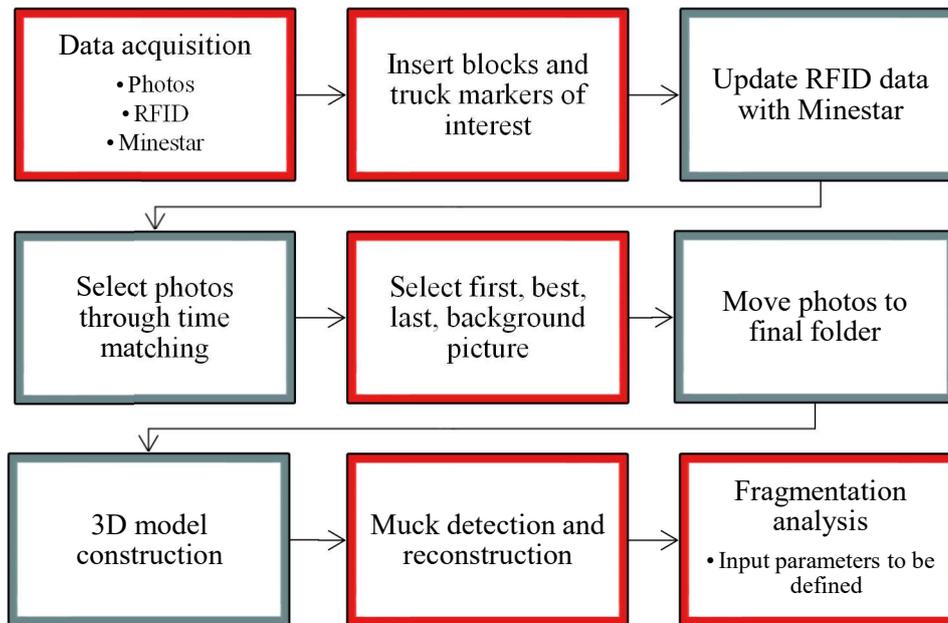
Figure 4.11 – Work flow for data processing (red = manual, grey = automatic)

Selecting Photos

After data acquisition, the blocks and truck markers of interest were inserted to the database. The RFID data was updated with the Minestar data. Only truck time stamps between the start of loading and start of dumping were selected. This was required as empty trucks travelling back were also picked up by the RFID system. Picture groups were matched with the timestamps, so that the group got a truck ID, as shown in Figure 4.12. It can be observed that only few picture groups were of interest and matched to a truck. This is due to the installation of the system and laser trigger. Many pictures of small trucks were taken, but not included in the analysis. Now the location from where the truck loads were originating are known. It must be noted that knowledge of the time format for each system was required to successfully use the sorting tool.
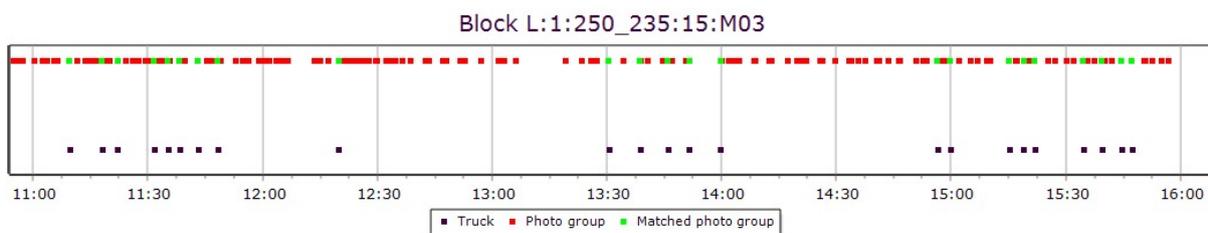
Figure 4.12 – Example of the picture sorting tool where Minestar, RFID and picture data are matched

When the photo groups of interest were selected, the first, best, last and background pictures were manually chosen as displayed in Figure 4.13. Only pictures with at least 60% of the truck load visible were selected to help the 3D model building, so any picture outside of the first and last range was excluded from 3D model construction as demonstrated with the crosses. The background photo was used to help 3D modelling as well. In total, 6-8 pictures per camera were selected for constructing the 3D model. If this step was skipped, there would be a much higher probability of the LKAB CCR crashing when 3D models are constructed. Lastly, the selected photos were moved to a final folder from where the 3D models could be built. The "best" picture was the picture that would be visible in the software and must have had all muck visible. All steps explained in this paragraph were done using LKAB's in-house software, adapted for the open pit camera system.
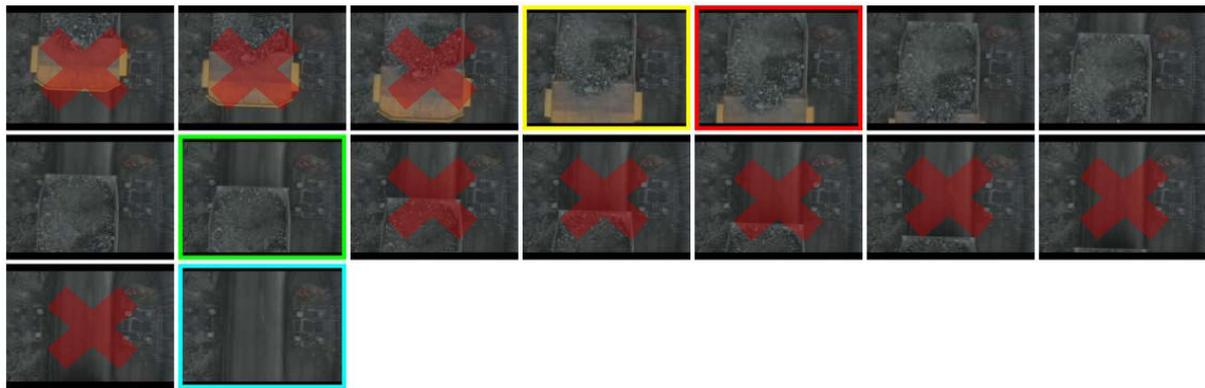
Figure 4.13 – Selection of first (yellow), best (red), last (green) and background (blue) picture for a truck load picture from 24th of May, 12:13 (block L:1:250_235:15:G02)

The fragmentation analyses had to be connected to one blast, which was classified by the drill plan number. In a separate data set, the drill plans were administrated with the Minestar loading blocks. The loading blocks that belong to one drill plan were grouped.

3D Model Construction

The 3D models were reconstructed by batch processing in the LKAB Central Control Routine (CCR) version 1.1.1 (64-bit), a software developed by LKAB and 3GSM. The sorted picture groups were loaded into the program. The software constructed 3D models by computing and scaling a 3D surface model using all available pictures (Stauder, 2018). All computational steps are displayed in Figure 4.14 and include pre-processing, for example improving shading and contrast. For compatibility, the cameras had to be (quasi) synchronised and the distance between the two cameras had to be known (3GSM, 2019). The Graphical User Interface (GUI) is displayed in Figure 4.15. The CCR includes an automatic muck pile detection feature. However, this feature was only developed for the LHDs and finds a similar shape to the LHD bucket. Therefore, the muck had to be detected by hand. The resulting 3D muck models were saved as *.jm3 files and were imported in the BlastMetriX (BMX) Fragmenter, hereafter referred to as the Fragmenter (Stauder, 2018).

Figure 4.14 – Computational steps when generating 3D models in LKAB CCR (green = step completed, blue = step in process, yellow = step to be processed)
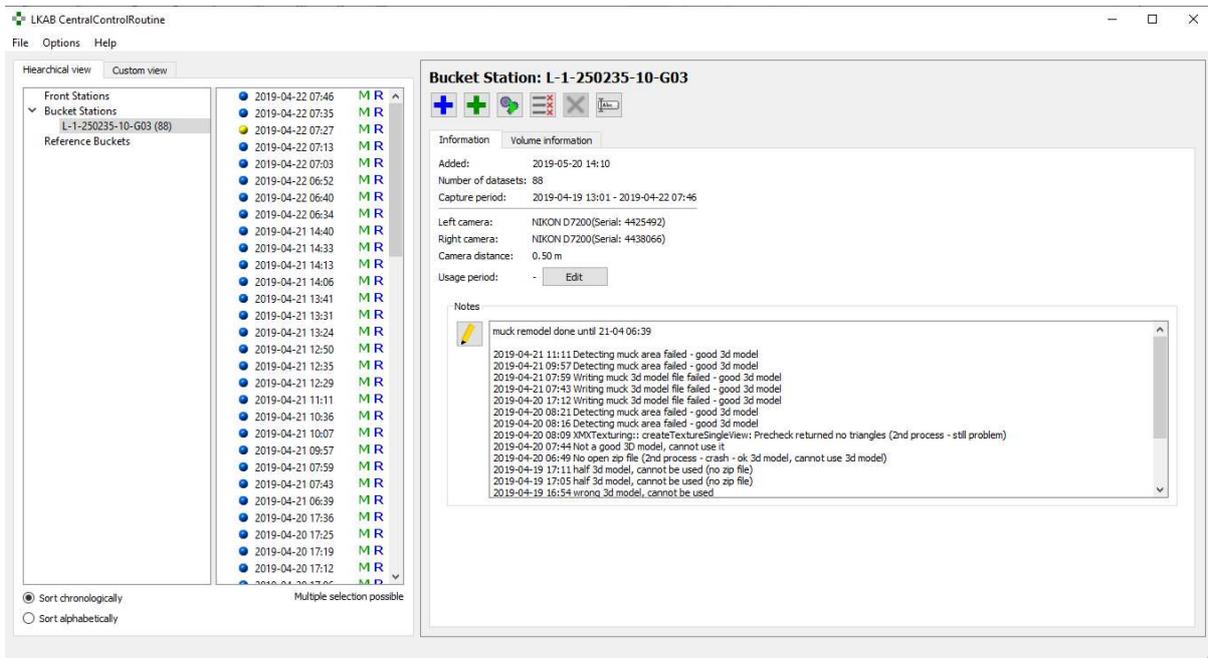
Figure 4.15 – The GUI of LKAB CCR

Fragmentation Analysis

The BMX Fragmenter version 1.2 alpha (64-bit) is a fragmentation analysis software under development by 3GSM and was used to generate PSDs for 3D muck pile models. Figure 4.16 provides an overview of the Fragmenters GUI. The software uses geometry and colour gradients to detect fragments.
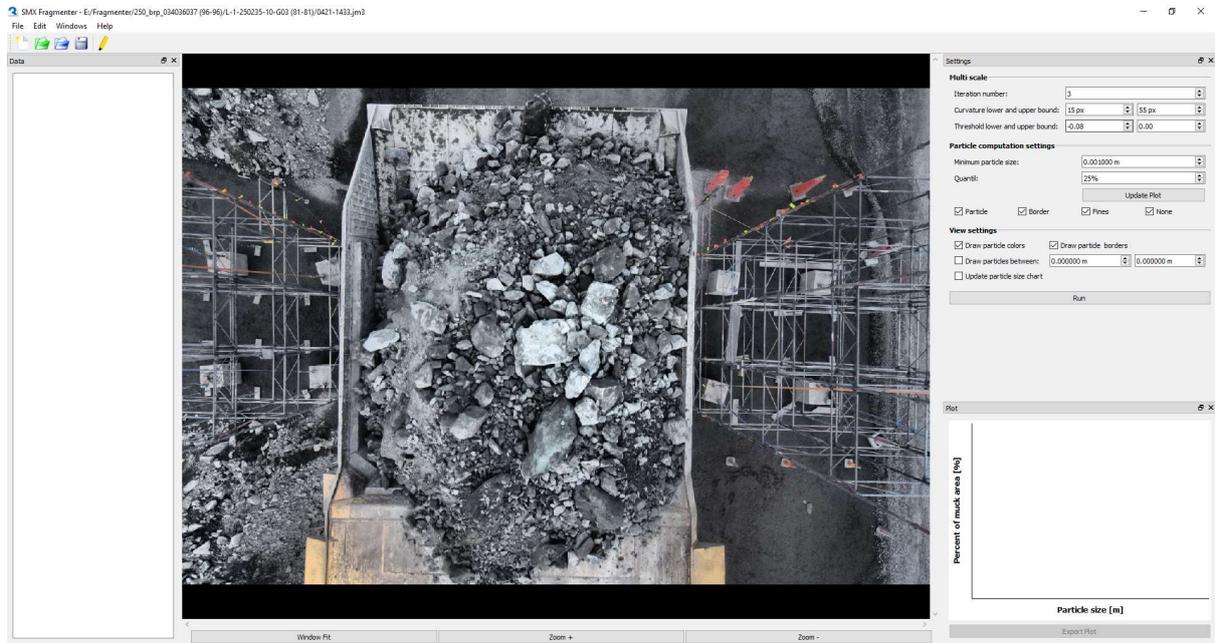
Figure 4.16 – The GUI of the BMX Fragmenter

The parameters that were used to control the results are listed (Stauder, 2018):

- "Iteration number: Changes the iteration number between the lower and upper curvature bound. If the iteration number is equal to one, the upper curvature bound is used for the analysis.

- Curvature lower and upper bound: Smoothens the boundaries of the detected fragments. A higher smoothing radius leads to thicker edges of the particle.

- Threshold lower and upper bound: Defines the curvature threshold. If the curvature is smaller than the lower bound, a boundary is detected. However, a curvature value above the upper bound indicates a fragment.

- Minimum particle size: Is a cut-off value and changes the region of visible fragment sizes. Values lower than the defined minimum particle size are cropped at the PSD.

- Quantil: Defines the threshold to mark fragments below the defined quantil value."

These parameters required investigation before the analyses could be run. Therefore, a parameter study was done. As this was part of the validation process, it is discussed in section 4.4.4.

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The results were shown in the GUI as a semi-logarithmic PSD graph. They were exported to a *.csv file for further analysis. The detected particles were displayed by colour and/or boundary as presented later in Figure 5.6. It was physically impossible to measure a particle smaller than the size of a pixel (Stauder, 2018), leading to generally underestimated fines. As a reference, the acquired images were 6000x4000 pixels and 300 dpi.

The Fragmenter determined the particle size through 3D ellipsoid fitting. From the 3D muck model, the three possible axes of these ellipsoids could be estimated. After evaluating the minor and intermediate axis of the fitted ellipsoid, the software constructed a smallest fitted square around the ellipse, defining the size of the fragment as displayed in Figure 4.17. This principle originated from the mesh size used for screening. It must be noted that this approach can overestimate the particle size. (Stauder, 2018)
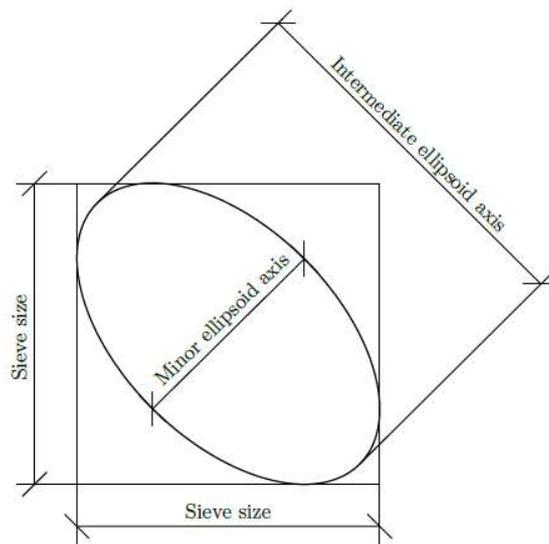
Figure 4.17 – Theoretical minimum sieving mesh size of a detected fragment

4.4.4 Validation

The fragmentation results required validation. No other sources of fragmentation data for these truck loads, like sieving, was available. Hence, visual validation was executed on selected truck loads. Particles were correctly identified, broken up into more fragments (disintegration), or several particles were detected as one (fusion). During the Fragmenter parameter study, the particles were counted and classified accordingly. The settings with the highest percentage of correct detections was used for all analyses. Note that counting the particles only evaluated the correct or false classification of fragments. It did not show the size of the error in which it wrongly detected particles. For example, if a large area of fines was classified as a 50cm boulder, the size of the error was much larger than if three small particles were detected as a 5cm fragment. The classification of correct and false identification was also user dependent. In this case the validation was done by the author of the thesis. Both factors were kept in mind.

Fragmenter Parameter Study

The parameter study for the Fragmenter was required to define the input parameters with which all truck load analyses would be run. The study was run on a homogeneous and heterogenous truck load where the lighting conditions were consistent as displayed in Table 4.2.

The values for the curvature bound, threshold bound, and iteration number were recommended by 3GSM. They experienced the best results with 3 iterations. They advised to not evaluate the curvature bound too narrow. Therefore, a small and large range was selected and two ranges in the lower and higher bounds were selected. Additional ranges would be explored if required. It was recommended to investigate the threshold bound as well, however due to time constraints this could not be achieved. Instead, the program's default was used. (Pötsch, 2019)

For each model and curvature bound setting, the delineation results were investigated. The number of correctly and wrongly detected particles were counted. Wrong detections could be divided into fused and disintegrated particles as explained in the previous paragraphs. (Stauder, 2018)

Table 4.2 – Overview of the values used for each model type in the parameter study

Muck characterization	Curvature bound	Threshold bound	Iterations
Homogeneous; Heterogeneous	21-81	-0.8-0.0	3
	21-41		
	11-51		
	51-91		

4.4.5 Data Evaluation

As described in the previous section, the Fragmenter input parameters that provided the best results would be used to run analyses for all truck loads. Delineation results of the models were visually evaluated. This was subject to user dependency and was only used to disregard extreme outliers. A PSD was regarded an outlier if any extreme wrong detections were spotted visually.

The PSDs was reported and explored per drill plan when not enough truck loads were available for a statistical analysis. A statistical analysis was done for each blast on the following parameters: x_{20}, x_{50}, x_{80} and number of detected particles. The analysis was displayed as a box plot and ore and waste was compared when possible. The number of observations per box plot is reported.

Additionally, the results of this thesis were compared to the outcome of the study "Behaviour of a novel algorithm for fragmentation analysis based on 3D images from photogrammetry" (Stauder, 2018).This study includes some results of the Fragmenter for the Kiruna underground mine case.

4.5 Muck Pile Shape

Measurements of the muck pile shape can be considered a blast performance parameter as the shape of the muck pile straight after blasting has an impact on the diggability of the pile (Choudhary, 2013; Singh & Cheung, 2017). Swell and fragmentation relate to this. As these measurements can be easily done when a simplified approach is used, it is included in the analysis. The throw, drop and spread of the muck pile are measured as displayed in Figure 4.18. The measurement methods are explained in section 4.5. How the data are acquired, processed and evaluated is summarised in the section 4.5.1, 4.5.2 and 4.5.3.
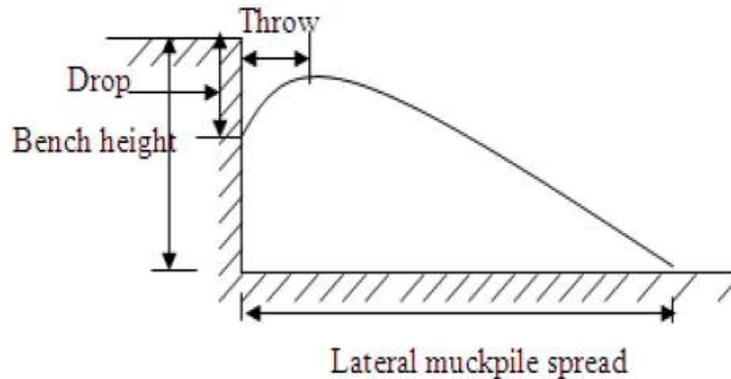
Figure 4.18 – Side view of a muck pile with their shape parameters (Choudhary, 2013)

4.5.1 Data Acquisition

There were two possibilities to acquire data for the throw, drop and spread of the muck pile: drone flying over the muck piles or measuring points using Total Station. As the measurements of the spread had to be done straight after blasting, either the drone flight was scheduled accordingly, or the surveyor with Total Station was on standby. Both methods were tested. The most suitable were the Total Station measurements, and therefore continued for the project's duration. This is explained in more detail in section 5.6 and 0. It must be noted that the drop, throw and spread were measured in the direction of the blast. Therefore, in the case of two free faces, the diagonal was measured as displayed in Figure 4.19.
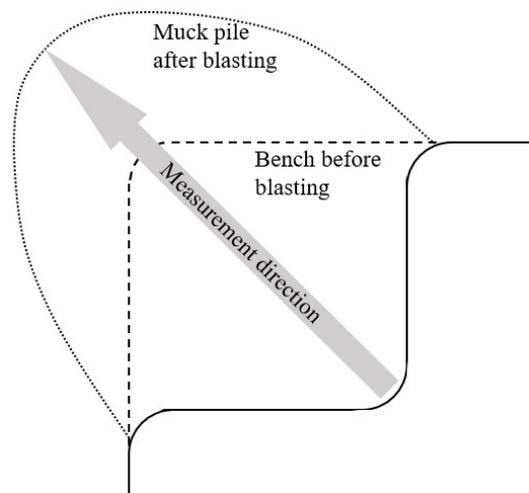
Figure 4.19 – Top view of a bench with two free faces before and after blasting

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In the case of drone flying, some crosses were painted on the ground and marked using GPS so that the drone knew its location. Then a flight was programmed over the respective muck pile. The drone could fly this pattern automatically. Some limitations to drone measurements were that crosses disappeared when it is snowing heavily, there had to be a drone pilot available and the drone's compass could have problems with the iron ore's magnetism.

The surveyors took the Total Station measurements. They examined the muck pile and visually found the best points to measure the throw, drop and spread. Especially the throw was difficult to accurately measure, as the muck pile was often higher than the bench on which the surveyor was positioned. This increased the difficulty of detecting the highest point of the muck pile. A limitation to this method was that there are four surveyors working in rotation, which could lead to measurement deviations due to the human factor.

It was expected that the Total Station measurements are less time consuming, less dependable on weather, but also less accurate than drone flying. These factors are discussed in the subsequent chapters.

4.5.2 Data Processing

First, the drone flight data was processed by the computer. This resulted in a point cloud data set which could be visualised in many programs. To measure the muck pile shape parameters, GPS coordinates of the points of interest were used to calculate the throw, drop and spread using trigonometry and triangulation. The distance (d) between two 3D points (x, y, z) is calculated as follows:

Equation 4.1 – Distance between two points in 3D space

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

It was expected that the drone footage will provide accurate measurements as the point cloud data could be rotated and the muck pile viewed from different angles to find the best coordinates.

The Total Station measurements provided a similar set of points as the drone footage, from which the throw, drop and spread was calculated using Equation 4.1. These measurements were expected to be less accurate than the drone footage, as the points were chosen by a single surveyor in the field. The measurement could not be checked afterwards.

4.5.3 Data Evaluation

The measurements resulted in a throw, drop and spread for each blast of interest. Ideally, it would be investigated if this data was related to PSDs from respective blasts. Additionally, correlations with the powder factor or other drill and blast parameters could be investigated, as they will not have been constant for all blasts. All data and calculations were saved.

4.6 High Speed Video

For background information, some blasts were filmed using a high-speed video camera. Videos of blasts can show if the blast was initiated properly, what the heave looked like, if the stemming functioned properly and where fly rock originated from (Adermann, Chalmers, Martin, & Wellink, 2015). It is a simple measurement, which can help evaluate the blast, especially when any unusual observations are made during the fragmentation analysis. It must be noted that the quality of the measurement depends heavily on the camera. The type of camera used for data acquisition and how the data are evaluated is outlined in sections 4.6.1 and 4.6.2.

4.6.1 Data Acquisition

The data was acquired using a Casio Exilim Pro Ex-F1 high-speed video camera. Previous user experience had shown that the quality of the footages decreased significantly when 600 or 1200 fps were used with this camera. Hence, the videos were shot using 300 fps. The camera was set up on a tripod at the location from where the blasters initiate the explosives. This is due to safety and often provided the best view of the blast. The camera was zoomed and focussed digitally.

4.6.2 Data Evaluation

The footage could be used to identify any deviating behaviour during the blast if corresponding observations were made within the fragmentation analysis. Therefore, it is considered a background analysis if needed. Additionally, observations on fly rock and gas pressures from the blast holes could be made. However, this was not considered to be of interest for this project.

7. Conclusion and Recommendation

This chapter summarises the recommendations and draws conclusions from this study. Section 7.1 revisits the objectives presented in section 1.1 and provides a reflection on the results. Section 7.2 includes recommendations for future development works. It covers the 3D image analysis and suggests alternative methods. Additionally, it recommends investigating additional data.

7.1 Objectives

The aim of the thesis was to gain a clear understanding of the factors contribution towards achieving a good and optimal blasting result with an emphasis on fragmentation. The results are applicable to the Leveäniemi mine and cannot be applied to other operations without taking their differences into account. The defined objectives are repeated and reflected upon as follows:

Objective 1: Determining the potential of 3D image analysis of truck loads in an open pit mining environment.

Achieving fragmentation results prove to be challenging with the 3D image analysis of truck loads in an open pit mining environment. Working in a production environment, the amount of required resources, the unreliable trigger system, and the system shutdowns without a warning system are the main difficulties. Many improvements are suggested to reduce or eliminate these factors, increasing the potential of the system significantly. Most importantly, a continuous data flow should be achieved to acquire data from all locations in the mine. A recurring factor is the bias in the measurements, which cannot be eliminated. Segregation and underestimation of fines remain a problem. But if the system is calibrated, they could be corrected for. Improving the image quality might improve the fragmentation results the most and can be realistically achieved. Additionally, there is potential in further developing the software and improving particle delineation. The study suggests that improvements are investigated and adopted because 3D image analysis is relatively inexpensive and adds colour. To conclude, the potential of the 3D image analysis system has been proven but relies on modifications and developments.

Objective 2: Estimating the correlation between fragmentation and other defined input or output data.

Based on the Leveäniemi case study, it can be concluded that a correlation between data types is not achieved. The mine site is very complex with each blast designed differently, complicating a multivariate analysis. Nevertheless, the types of data that are of interest in such an analysis are identified. Normalised muck pile shape results can in the future be analysed with drill and blast design parameters and fragmentation. This analysis can assist in the definition of blast domains. While muck pile shape results are limited, it provides insights on the relation between the throw, spread and drop. It is therefore recommended to increase the number of observations significantly, both for fragmentation and muck pile shape parameters to achieve a statistically acceptable multivariate analysis. In contrast, it can be concluded that high speed video does not provide insights on fragmentation and should not be focussed on. The study suggests defining geotechnical domains for the Leveäniemi mine in more detail, which is already under development. Joint mapping for each analysed blast is of interest as well as it influences the blast performance significantly. It is concluded that a correlation between fragmentation and other defined input or output data is not achieved.

Objective 3: Estimating baseline fragmentation for the Leveäniemi open pit mine.

Results indicate that x_{20} particle sizes range from 2.5-14cm, x_{50} ranges from 5-56cm and x_{80} from 20-150cm. However, care should be taken when interpreting these numbers, as on average 42% of the particles is correctly delineated and the size of the error is unknown. Calibration is recommended to determine the amount of deviation and correct the results. This can be achieved by sieving but evaluating delineation results in detail could suffice as well. To achieve a statistically representative statement on fragmentation, the sample size should be increased. Practically this means that a truck sampling method should be developed, or that this can only be achieved if the software reaches its final state in which all truck loads can be automatically analysed. At this moment, other fragmentation measurement methods could be considered. The particle sizes mentioned above are a very rough estimate only and it is concluded that they should not be considered as a baseline.

Objective 4: Defining blast domains using 3D image analysis.

To define blast domains, comparable and repetitive measurements from many locations in the mine are most suitable. This research achieved comparable measurements. On the other hand, it failed to acquire data from many locations and did not get repetitive measurements as the sample size is different for each blast. However, developing the system and its software could make this possible. It should also be considered to acquire data with similar drill and blast design, as it would ease multivariate analyses. Drone image analysis could be investigated as it might be sufficient for the comparability and repeatability requirements as well. This study is not able to define the blast domains in the Leveäniemi mine, but it can contribute in defining a follow-up study to achieve this.

Research Question 1: How can fragmentation measurements automatically and without disturbing production be achieved by 3D image analysis of blasted material in truck loads?

Some additional development of the 3D image analysis method that was used during this research is required before it can be used automatically and without disturbing production. The system should be developed so that a continuous data flow can be achieved. The main improvements are aimed at:

- Implementing and developing a warning system for when the image acquisition system shuts down.
- Including an automated data transfer method to recover the images from the cameras, such as implementing a ground station or data transfer through WiFi.
- Improving the triggering system of the cameras.
- Implementing a sorting tool in the software to match pictures of fragmented material to their respective blast location.
- Developing an algorithm for automatic muck detection of truck buckets, as already exists for LHDs.

Using this method, fragmentation can be measured using automatic delineation software where no pre- or post-processing of the image is required. However, the measurements are biased due to segregation and the difficulties of detecting fines. If the actual particle sizes are required, the system can be calibrated. But if the measurements were only to be used in a comparative way, they can suffice.

Research Question 2: Can blast domains be identified using fragmentation results after blasting and how can other data be correlated to fragmentation to assist in the process?

Under a few prerequisites, it is possible to identify blast domains using fragmentation and other data. The considerations are listed:

- The fragmentation results should be comparable. To evaluate this, more investigation on error sizes and types of delineation results is recommended.
- Joint orientation and spacing in evaluated blasts should be known, additional to drill and blast design parameters.
- Enough data from comparable blasts should be available.

Muck pile shape parameters can be used as a blast performance indicator. To evaluate the relationship between fragmentation and these parameters, more data should be acquired for both data types.

7.2 Future Research

The experimental 3D image acquisition system can be used for defining blast domains if further development work is done on the system improvements. Development work includes this thesis project and the project done last year that was referred to throughout this study (Stauder, 2018). Many suggestions already resulted in realistic and practical design change suggestions. However, investigating factors like a robust trigger system and developing a warning system is recommended before executing another field test. Additionally, utilising a wireless server could ease data acquisition significantly and is therefore recommended as well. When the Fragmenter software is finalised, it might be time for another field study. Until then, the image acquisition system is recommended to be used for established and proven software, such as 2D image analysis packages, if the goal is similar to the objectives in this study. Note that the 2D image analysis systems like WipFrag and Split have manual tasks as well to improve delineation results. When the next field test is planned, it is recommended to schedule about one month for installing the system, finetuning the settings and maximising image quality. It is recommended that maximum effort is spent on this, to ease data acquisition on the long term, as the system must keep running for a predefined time-period if the data were to be used for establishing blast domains.

Based on these conclusions, alternative systems should be considered as well. This relates to the goal of the measurements and the costs of the system. It is recommended that there is a focus on 3D image analysis due to the related costs. Models constructed from drone flights can be used for more purposes than the truck loads and is of interest to be further explored. Laser scanning remains to be of interest but only makes sense to investigate if funds allow acquisition of the system and delineation software is available to measure fragmentation.

Further research is required to determine the relationship between contributing factors towards an optimal blast performance. It is recommended to achieve detailed geotechnical domains for the Leveäniemi mine before another study on establishing blast domains is executed. Additional analysis of the drill and blast parameters can be of interest as well. For the Leveäniemi mine, it can be considered to evaluate historical drill plans to find out if some blast domaining becomes apparent, even if there was no intention to use the concept of blast domains.

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