AES/RE/14-07  The application of an underground optical fragmentation analysis method at the Lisheen Mine.

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Acknowledgements

This MSc thesis is the result of a 9 month research project at the Lisheen Mine in the Republic of Ireland, part of Vedanta Resources plc. As part of the curriculum of the Master of Science program of Applied Earth Sciences at Delft University of Technology a student is required to work on a research project at a university or company, in this case The Lisheen Mine. The challenge, applied methodology and results are presented in this document.

I would like to thank Hans de Ruiter for getting me in contact with the Lisheen Mine. I really appreciate the opportunity which the Lisheen Mine has given me by allowing me to do a thesis project.

I owe a lot of gratitude to all of my colleagues in the Technical Service department for making this research possible especially because of the warm welcome during the first month in Ireland. Also I’d like to thank James Town, Phil Brown and Kate Leamy for analyzing some parts of the report. I would like to thank Steve Ridge and Ian Johnstone for helping me get through all the detailed information about the crusher and its electricity costs. Another word of appreciation goes to all the crusher operators, electricians and fitters who have helped me with my research.

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Kilkenny, May 2014

Thomas Waterman
Abstract

Blast fragmentation has an influence on the drill and blast designs, loading, hauling and crushing operations. Previous studies in other mines have shown that by optimizing fragmentation it is possible to save on operational costs. This thesis investigates and applies a method for measuring fragmentation in stopes with the aid of image analysis software at the Lisheen Mine in Ireland. The purpose of this study is to provide an insight to the management of the Lisheen Mine whether or not it is worth to continue to monitor fragmentation.

This research project was based on fieldwork and a literature review and discussion on the locations and errors associated with fragmentation image analysis and it also covers a software comparison of WipFrag and Split Desktop\(^1\) and an accuracy analysis for WipFrag has been carried out.

The findings from this research show that there are many uncontrollable parameters affecting the fragmentation at Lisheen Mine. The most important parameters are the amount of undersize material that bypasses the crusher as well as the difference in geology between the different mining zones. The best location for setting up a permanent automated fragmentation measurement station is at the tipping bay. Errors related to the sampling process are the most significant errors in optical size distribution analysis methods. During this research a preference for using Split Desktop was gained, because the delineations were more accurate for the images which were analyzed for this thesis. The key to measure fragmentation in a safe way is to have proper illumination and have sufficient zoom on both the software and the camera lens. Segregation will always be a major concern while measuring fragmentation at muck- or stockpiles. If the process is not automated time is a major restriction when measuring fragmentation in a production mine. The fragmentation measurements show that the difference in the same stope can be as high as 130.8%. Measurements taken on surface showed a P\(_{80}\) of 137mm for ore which was supposed to be crushed to 150mm.

The accuracy analysis for WipFrag in this thesis has shown that it is more likely (62.3%) to underestimate the fragments, on average it underestimates with 2.09%, outliers were as high as 8.42% and in 0.01% of all the samples the calculated value was equal to its true diameter. The average error was as low as -0.66% over 1000 samples.

The main recommendations for this thesis are that the amount of undersize must first be determined before further research on fragmentation is carried out. In order to analyze the influence of different crews on both day and night shifts fragmentation measurements should be done by more than one person so that the majority of the operation can be successfully monitored.

This research was mainly focussed on the post-blast fragmentation parameters it is advised that more research should be carried out on the pre-blast parameters.

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\(^1\) WipFrag and Split Desktop are two similar image analysis programs used for fragmentation purposes developed by respectively WipWare and Split Engineering.
List of abbreviations

In order of appearance

- LED – Light Emitting Diode
- ABL – Argillaceous Bioclastic Limestone
- RFS – Rathdowney Fault System
- KFZ – Killoran Fault Zone
- DFZ – Derryville Fault Zone
- BFZ – Bog Fault Zone
- UCS – Uniaxial Compressive Strength
- S.G. – Specific Gravity
- IIE – Irish Industrial Explosives
- VOD – Velocity of Detonation
- REE – Relative Explosive Energy
- ANFO – Ammonium Nitrate Fuel Oil
- NONEL – Non Electric
- LP – Long Period
- MSDS – Material Safety Data Sheet
- SSE – Site Sensitised Explosives
- EPA – Environmental Protection Agency
- HSE – Health, Safety and Environment
- PPV – Peak Particle Velocity
- MIC – Maximum Instantaneous Charge
- IR – Infrared
- GPS – Global Positioning System
- DGPS – Differential Global Positioning
- RFID – Radio Frequency Identification
- MTBF – Mean Time Between Failure
- HID – High Intensity Discharge
- JCB – J.C. Bamford excavator
- EDP – Edge Detection Parameters
- EOM – End Of Month
- ISO – International Standards Organisation
- NSAI – National Standards Authority of Ireland
- FAS – Foras Áiseanna Saothair
- MZ – Main Zone
- DV – Derryville
- BZ – Bog Zone
- TMF – Tailings Management Facility
- SAG – Semi-Autogenous Grinding
- SIPX – Sodium Isopropyl Xanthate
- PAX – Potassium Amyl Xanthate
- DCT – Deep Cone Thickener
- MWTP – Mine Water Treatment Plant
- RWTP – Reclaim Water Treatment Plant
- GGBS – Ground Granulated Blast Furnace Slag
- OPC – Ordinary Portland Cement
- OEL – Occupational Exposure Limit
- TWA – Time-Weighted Average
- DPM – Diesel Particulate Matter
- VR – Vent Raise
- RPM – Rates Per Minute
- MCC10 – Underground Material Handling System
- FOGM – Fall Off Ground Management
- 3MRF – 3 Month Roller Forecast
- NATM – New Austrian Tunnelling Method
- CSS – Closed Size Setting
- I-31 – Infrastructure 31

Abbreviations used in appendices

- CMCI – Chevron Mineral Corporation of Ireland
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1. Introduction
The chapter starts with a brief company introduction followed by an introduction to fragmentation and image analysis software. This is then followed by stating the motivation and value of this research. Furthermore the research questions and objectives are stated and these are followed by the report structure and a summary of the scope of work.

1.1.1. Company Introduction
The Lisheen mine is located in county Tipperary on the border with county Kilkenny, between the villages of Templemore in the northwest and Urlingford in the southeast of the Republic of Ireland. Lisheen’s lead and zinc deposit is located in the Rathdowney Trend (See Section 3.3), which stretches 40km between the towns of Abbeyleix to the northeast and Thurles to the southwest. Both the Rossetown and Drish rivers, tributaries of the Suir river, made this region well drained. The Lisheen mine and Thurles are indicated on the figure below (Figure 1) with resp. an A and B.

Figure 1 Lisheen (A) indicated on both images together with Thurles (B), separated by a distance of 14km. Modified images from Google Maps.

A more detailed company profile of Lisheen can be found Appendix B - Detailed company profile of Lisheen.

The Lisheen Mine is an underground mine that produces lead and zinc concentrates and is owned by Vedanta Resources plc. Lead is mainly used for producing batteries but is also used for the production of pigments, chemicals, cable sheathing and many more applications. Zinc is used in the construction, automotive and white goods industries.

1.1.2. Fragmentation Introduction
In order to produce the lead and zinc concentrate the ore first needs to be blasted. After the ore is blasted with explosives it is distributed in many different fragments of varied sizes. Fragmentation is a process of breaking bigger particles into smaller particles. The way these particles are distributed is important for the characterization of blasts.
Blasts that mainly produce undersize fragments use too much explosives whereas blasts with large boulders should use more explosives. Too many fines can cause dust problems, whereas large boulders cause more wear and can eventually cost more time in the material handling at the crusher station. This is because the bigger rocks need to be broken into smaller pieces manually. Not everything can be controlled during the design of a blast, it is therefore important to know the controllable (drill and blast design) and uncontrollable (geological and geotechnical) parameters.

1.1.3. Image Analysis Introduction

For this research fragments are delineated with two different computer programs called WipFrag and Split Desktop. Delineation is a semi-automatic process of drawing borders around the boundaries of particles in an image. Computer algorithms can do this automatically. However, it is often required to manually intervene in this process, because the algorithms make mistakes. First the shape of a fragment is drawn and afterwards the area is calculated. Drawing a best-fitted ellipse around the fragment does this. For the calculation of the shape and area of the fragment the minor and major axis of the best-fitted ellipse are used. Statistical probability functions are then used to add a volume to each fragment.

By applying the algorithms to the image, each particle is assigned a diameter of an equivalent sphere. These diameters of equivalent spheres are then plotted against a range of values representing an actual sieve diameter. The data is then digitally sieved. WipFrag and Split Desktop then use this data to generate a granulation curve. This curve can be used to compare the actual data with the desired data. Its main output is a histogram of which each bin represents a size interval and each bin is assigned a percentage passing.

1.2. Motivation

In mines all of the downstream operating costs are affected by the fragmentation of the blasted material (Maerz & Palangio, 2004). Blast fragmentation has an influence on the drill and blast designs, loading, hauling and crushing operations. For example large boulders can be difficult to load into a scoop or they need to be broken individually by a rock breaker, this is time consuming and can cause extra wear to the machinery. Whereas too many small fragments can indicate that too much explosives are being used in blasts.

At Tarkwa Gold Mine\(^2\) a 10% reduction in loading times has been realized by improving blast fragmentation and secondly it lead to a substantial increase in Tarkwa’s blasted stocks (Amiel, 2008). Whereas at the Morila Gold Mine\(^3\) blast fragmentation monitoring has lead to an incremental increase of 0.2% in the drill and blast costs but resulted in an increase in mill throughput of approximately 10% (Gillot, 2004).

Kojovic et al. (1995) showed that “an increase in the cost of drilling and blasting is swamped by the downstream benefits of improved fragmentation, with the greatest impacts being on excavation costs and crushing costs”. Blasting optimization has been defined critical to overall mining costs and production (Maerz et al., 1987). Therefore this is an area worthy of study. It is because of these reasons the Lisheen mine has asked to investigate and apply a method to successfully measure the fragmentation in stopes. At Lisheen the majority of the production comes from longhole open

\(^2\) Tarkwa Gold Mine is an open pit mine located in Southern Ghana.

\(^3\) Morila Gold Mine is an open pit mine located in Southern Mali.
stoping and it is because of this reason that Lisheen is interested in monitoring the fragmentation in stopes.

By monitoring and analyzing the current distribution of fragments after blasting it is believed that it is possible to save on the downstream operating costs of the mine. This research is focused on a first assessment of an underground optical fragmentation analysis, for which it uses Lisheen Mine as a case study to test the methodology and software.

The purpose of this study is to provide an insight to the management of the Lisheen mine whether monitoring fragmentation should be continued. Lisheen set the maximum investment for this research at 5000 euro. This research was carried out because it has never been done before at Lisheen and therefore the actual level of fragmentation is unknown. With this research more information about the current fragmentation at Lisheen will become available, which can be helpful to save on operating costs such as the excavation and crushing costs.

1.3. Research Questions
Not every underground mine and its associated mined material is suitable for fragmentation image analysis. Analyzing fragmentation in an underground mine raises questions. This research focuses around the following research questions:

1. What is the best location to set up the measuring equipment?
2. What is the most suitable computer program to analyze fragmentation with?
3. What are the most important differences between these programs?
4. What are the major concerns for measuring fragmentation in an underground mine?
5. What is the current fragmentation at Lisheen?
6. How accurate is the optical analysis program?

1.4. Aim and objectives
The overall aim of this research is to advance an understanding of the concept of measuring fragmentation in an underground mine with the aid of image analysis software.

This research has tried to make a first attempt to quantify the fragmentation at the Lisheen mine. The objectives are displayed under each of the six research questions.

1. What is the best location to set up the measuring equipment?
   - Review and discuss different research methods for measuring fragmentation.

2. What is the most suitable computer program to analyze fragmentation with?
   - Compare different software programs measuring fragmentation.

3. What are the most important differences between these programs?
   - Review both software programs and evaluate the differences.

4. What are the major concerns for measuring fragmentation in an underground mine?
   - Identify and discuss fragmentation-controlling parameters.
   - Identify and discuss project, software and operational limits.
5. **What is the current fragmentation at Lisheen?**
   • Evaluate or quantify the current fragmentation in stopes at Lisheen.

6. **How accurate is the optical analysis program?**
   • Evaluate the accuracy of the programs used in this study.

Combining all the answers to the research questions this research consists of a:

- Company profile
- Fragmentation literature study
- Equipment, Software and Accuracy analysis.

For a more detailed overview see Section 1.5. Report Structure and Section 1.6. Scope of work.

### 1.5. **Report Structure**

This thesis will cover the following aspects:

- Description of geology, underground material handling, mining method and drilling and blasting operations at Lisheen. *(Chapters 3-6)*

Their influence on fragmentation is discussed (where possible). Besides a description of the Lisheen Mine this thesis covers a review and discussion on:

- The three different fragmentation analysis methods: sieving, image analysis and field tests. *(Chapter 7)*
- The locations and errors associated with image analysis methods. *(Chapter 7)*
- Both WipFrag and Split Desktop. *(Chapter 8)*
- The limitations of the project. *(Chapter 8)*
- The results obtained from the measurements. *(Chapter 9)*
- An accuracy analysis of WipFrag *(Chapter 10)*

Only WipFrag and Split Desktop were used for this research, because both of these companies supported the academic value of this research. *Chapter 11* provides an observational summary, analysis and discussion on the entire project. The next two chapters provide the conclusions *(Chapter 12)* and recommendations *(Chapter 13)*. All references are listed in *Chapter 14* and are divided into three main categories: personal communication, unpublished material accessed via Lisheen Mine and published literature.
1.6. **Scope of work**

A summary of the scope of work is shown in the table below.

<table>
<thead>
<tr>
<th>Company Introduction</th>
<th>Included</th>
<th>Excluded</th>
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<tbody>
<tr>
<td></td>
<td>Company profile</td>
<td>Economic situation</td>
</tr>
<tr>
<td></td>
<td>Geology &amp; Geotechnical</td>
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<td></td>
<td>Mining methods</td>
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<td>Material handling</td>
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<td>Ventilation</td>
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<td>Drill &amp; blast</td>
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<tr>
<td>Fragmentation Analysis</td>
<td>Literature Study</td>
<td>Sieving</td>
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<td></td>
<td>Optical image analysis</td>
<td>Field-tests</td>
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<tr>
<td></td>
<td>Location &amp; error analysis</td>
<td>Fragmentation prediction</td>
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<tr>
<td>Equipment</td>
<td>Comparison between methods</td>
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<tr>
<td></td>
<td>Camera &amp; lights selection</td>
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<tr>
<td></td>
<td>Equipment engineering</td>
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<tr>
<td>Software Introduction</td>
<td>WipFrag</td>
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<td></td>
<td>Split-Desktop</td>
<td></td>
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<tr>
<td></td>
<td>Underground &amp; Surface Images</td>
<td></td>
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<tr>
<td></td>
<td>Demo-images</td>
<td></td>
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<td></td>
<td>Software &amp; project limits</td>
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<tr>
<td></td>
<td>Software comparison</td>
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<tr>
<td>Accuracy Analysis</td>
<td>WipFrag</td>
<td>Split Desktop</td>
</tr>
</tbody>
</table>

Most of the company introduction can be found in the Appendices B, C and D. Sieving and field tests are not included due to financial limits to the project.

Fragmentation prediction is a completely different area compared to the fragmentation image analysis, however for some parts in this research parameters closely related to fragmentation prediction are discussed and at the end of these sections their relevance to fragmentation prediction is stated.

Only WipFrag and Split Desktop are discussed in this thesis, these two companies were the only two to support this research. An accuracy analysis of Split Desktop is not included as this is due to financial constraints.
2. **Lisheen Mine Cycle and Methodology**

This chapter covers both the specific mine cycle at Lisheen focused on drilling and blasting and the applied methodology for this research.

2.1 **Lisheen Mine Cycle**

After exploration and advanced exploration has completed, environmental assessment will be carried out for new mining areas. A team of mine planners, geologists, geotechnical engineers and drill and blast engineers will develop possible ways to mine the newly discovered resource. Once the decision has been made on how to progress a mine planning engineer issues a ‘noddy plan’. A noddy plan is a general overview of the location, directions and size of the area that will be mined. This noddy plan needs to be signed off before it is distributed.⁴

2.1.1 **Drilling**

After completion of the planning stages, the drill and blast engineer designs the rings for the blast. The following parameters are required for this ring design: drill length, drill angle, direction, the dump angle and the hole diameter. These parameters are also important for fragmentation prediction. Fragmentation prediction is not covered in this research but this research can be used for future studies about fragmentation prediction. A drill and blast engineer then issues a specific drill and blast noddy plan that needs to be signed off before it is distributed to the longhole driller and his supervisors.

2.1.2 **Blasting**

Once the rings have been drilled, the mine captain, drill and blast engineer, geotechnical engineer and the mine planner agree on a firing sequence. The collars are manually designed and the charging length is then calculated. After calculating the charging lengths the holes are manually timed in an Excel-spreadsheet. This spreadsheet will calculate whether the blast does not exceed the limits for vibration (See Section 6.5 Vibration Control). If the vibration limits are exceeded the timings, or the type of explosives need to be changed (See Section 6.2 Explosives) until the vibration limit is not exceeded.

The length of the uncharged collar and the charged length are also important for fragmentation prediction. The maximum vibration is a major constraint for the fragmentation, because it limits the amount of explosives to be detonated at the same time. This makes it an important parameter for fragmentation prediction.

2.1.3 **Monitoring**

After the ore is blasted, the results of the blasts can be seen. This is where this research differs from fragmentation prediction. The image analysis methods as discussed earlier (See Section 1.1.3. Introduction to Image Analysis), can only be used after a blast has been carried out. Fragmentation prediction is carried out prior to a blast. Image analysis is a reactive way of controlling the blasts. Whereas fragmentation prediction models the input parameters of a blast in advance to its preferred

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⁴ A noddy plan is signed off by the originator, mine captain, geotechnical engineer, geologist, drill and blast engineer, ventilation engineer, technical services supervisor and the mine superintendent and the mine manager. It is then distributed to the mine captain, area shift boss, mucking shift boss, geotechnical officer and the grade control officer.
optimum. The methodology described in the following section, explains how the data was gathered and how information was processed.

2.2. Methodology
This research project consisted of the following research steps:

1. Fieldwork, related to drilling, charging and blasting operations.
2. Additional background studies related to the mine, fragmentation and software.
3. Equipment research for camera, lights and software.
4. Imaging blasted & crushed material at various locations.
5. Analyzing images with WipFrag & Split Desktop
6. Comparison between the two different programs.
7. Accuracy analysis of WipFrag.

2.2.1. Fieldwork
Fieldwork consisted of a total of six weeks underground; these weeks were focussed on the areas which are most important for this project, drilling, charging and blasting. Within this time period, it was possible to indentify the different factors controlling fragmentation. Another important aspect was that information could be gained from miners who experienced difficulties with their part of the operation. This information was then taken into account during the research project.

2.2.2. Literature review
All additional background literature can be found in the list of references. Internal notes, presentations and publications combined with personal experience were used to describe the Lisheen mine in more detail. Most papers related to optical fragmentation analysis methods are written by the developers of the software. Of these papers the majority are written by WipWare employees as their company was the first to come up with optical fragmentation analysis methods. The literature review covers a discussion on the location and errors associated with fragmentation analysis methods.

2.2.3. Equipment research
Following the literature review a study of the specific equipment needs of the project was started. This consisted of looking into various camera models, types of lighting and selecting the right software. After selecting and purchasing the right equipment, the construction period began. For this project a Pentax K-5 D-SLR model was used, because it is the most weatherproof camera available of its kind. During this phase the choice for the right image analysis program was made as well, in negotiation with Delft University the choice was made to choose WipFrag as they were the current market leaders in this area of expertise.

After the material is blasted and the areas of interest are cleared from blast fumes and are deemed safe to enter, additional equipment is brought in for taking underground photographs. This involves two LEICA-tripods and one ordinary camera tripod. Each LEICA-tripod has a bar mounted on it which holds up to 4 arrays of light emitting diodes (LEDs). This can be seen on the images below. Each LED array can be switched on or off individually (also the angles of each LED-array can be altered), these lighting bars are connected to two 12 Volt car batteries. While designing the second set, the idea came up to weld a small metal plate to it so the same bar can be used in both horizontal and vertical set-up. The vertical set-up is more advantageous for photographing tipping trucks than the
horizontal setup as the area of interest (the body of a truck), is then positioned vertically. Whereas with muckpiles, the area of interest is over nearly the full width of the muckpile and therefore a horizontal set up is more beneficial.

Before the actual data collection began, a Lux-test was performed; this was done to see if there was any difference in brightness between using the LEDs on 12V or 24V. This test was done underground in a completely dark area. The results can be found in Appendix A – Lux test results. The small difference in the values is due to sensor sensitivity and differences in height and angle of the measurements. The apex angles (angles where the intensity drops to 50% of its peak value) are very small; 4 degrees up and down and 7 degrees left and right (LED Autolamps Europe LLP, 2012), this means these lights are a very concentrated source. Any difference in the angle of either lateral or vertical direction has a huge impact on the amount of lux measured. It was later confirmed by the manufacturer, that the amount of luminous flux should be the same in both 12 and 24 volts because there is a constant output circuit, so the intensities are the same on both 12V and 24V (LED Autolamps Europe LLP, 2012). A comparison between the different types of used lights can be seen in Appendix H – Lights Comparison from Figure 69 up to Figure 73.
### 2.2.5. Data gathering

Twenty five different images were processed:

- 4 test images at the start of the project, these pictures were taken in Main Zone East panel 00 stope 6. (ME00S06).
- A total of 8 images were analyzed underground and these images were taken in Main Zone South panel 08 stope 15 (MS08S15). These pictures can be divided into two separate datasets. The first dataset consists of 5 images photographed within 2 hours of a blast. The second dataset consists of 3 images photographed the day after a blast when mucking operations had removed the first part of the blasted material.
- 3 demo images were analysed to evaluate how the program reacts to photos taken under optimum conditions.
- 10 stockpile images were processed to evaluate how the program reacts to photos taken on surface.

These stopes were selected because Lisheen was developing in these stopes at the time the data had to be gathered. After completion of the project all underground data collection points have become inaccessible due to geotechnical reasons.

It then turned out that taking pictures of underground muck was not very successful due to various reasons which are discussed later on (see section 8.8.). Pictures of demo images (3 images) were then analyzed in order to see how the software works under more optimum conditions. Because the results of this were promising, the Galmoy stockpiles (10 images) were analyzed at various locations (at the bottom of a stockpile) to evaluate the differences between underground and surface images.

### 2.2.6. Data processing and software comparison

After all the required data was gathered and processed in WipFrag, Split Desktop was used during a 30-day trial period. This made it possible to compare the two programs with each other. The user friendliness and differences in results of the two similar programs are discussed in this thesis as well.

### 2.2.7. Accuracy analysis

An accuracy analysis was carried out in WipFrag by comparing the calculated diameter with the ‘true diameter’. The accuracy analysis covers 11 images and a total of 1000 samples, that can be divided into 8 datasets. The complete description of this analysis is detailed in Chapter 10: Accuracy Analysis.
3. Geology
This section starts with stating why it is important to know the local geology and lithology and the associated geotechnical parameters. After this explanation a detailed overview of Lisheen’s geology is given. A geotechnical description of issues and procedures that are in place at Lisheen can be found in Appendix O. Geotechnical Support.

3.1. Influence of geology and geotechnical parameters on fragmentation
Fragmentation has controllable and uncontrollable parameters. Geology and lithology are typical uncontrollable parameters. The following geological features are known to be related to fragmentation (Marton & Crookes, 1999):

- Fractures and joints and faults
- Structure
- Rock strength

The energy of the explosives used for the blast can easily escape in the wrong direction when fractures and joints are present. This can also result in inefficient blasts with poor fragmentation.

The structure of the orebody influences the mining method because the different mining methods use different drill and blast plans it therefore has an indirect link with fragmentation.

Lisheen can be classified as a very wet mine (22,688,036 m³ water pumped away from March 2011 until April 2012, see Table 37) with multiple mining areas which all have different geological conditions. Therefore it is important to know the local geology and geotechnical features of the mine when analyzing fragmentation.

The rock strength is one of the parameters which determines the amount of explosive used in a blast and therefore it has an indirect link with fragmentation and it has a direct link with fragmentation prediction.
3.2. Stratigraphy

The Lisheen deposit is hosted in dolomitized limestones of Courceyan (Lower Carboniferous) age. The stratigraphy of the deposit is quite similar to that recorded across much of the Irish Midlands according to Sevastopulo and Wyse-Jackson (2001) and relates broadly to a northward migrating marine transgression which commenced in the late Devonian and continued intermittently to Upper Carboniferous times (Fusciardi et al., 2003). The sedimentary sequence belonging to this marine transgression was deposited unconformably on Lower and Middle Devonian Old Red Sandstone and Silurian-Ordovician metasediments and volcanics. Phillips and Sevastopulo (1986) state that the pre-Middle Devonian basement was deformed by the Caledonian Orogeny (late Silurian to early Devonian) and the resulting NE-SW structural grain was inherited by the later Carboniferous sequence.

The principal formations which host mineralization in the mine area are shown in the figure below.

![Figure 4 Stratigraphy of Formations present at Lisheen, (Lisheen Mine (2011b)).](image-url)
The stratigraphy of the mine was first described by Shearly (1993) and later summarized by Archer et al. (1996). The sequence starts with Silurian mudstones and fine sandstones unconformably overlain by Old Red Sandstone. Mixed clastic sediments and carbonates represent the start of Carboniferous sedimentation. These sediments belong to the Mellon House, Ringmoylan, Ballyvergin and Ballymartin Formations (Fusciardi et al., 2003). On top of these formations lies the Ballysteen Formation, a sequence dominated by shale, bioclastic limestones and is locally known as the Agrillaceaous Bioclastic Limestone (ABL). Micrites of the Waulsortian Complex, which host the majority of the mineralization, overlie the Ballysteen Formation. The top of the sequence is the Crosspatrick Formation, it consists of cherty, bedded limestones however, these cherty, bedded limestones are not found in the mine area (Fusciardi et al., 2003).

The stratigraphy is relevant for fragmentation prediction models because it uses rock mass description properties, therefore it is relevant to know which formations are present in the mine so that the detailed rock mass properties can be used in future studies that link Lisheen’s stratigraphy with fragmentation prediction models.

3.3. Structure

East-North-East trending folds that mirror the Caledonian strike of the basement which is seen throughout the SE Irish Midlands largely control the gross regional outcrop pattern (See Figure below).

Figure 5 Regional geological map of the Lisheen Mine area (Fusciardi et al., 2003).
The Lisheen mine is situated on the limb of one of these folds and regional bedding dips average 5° to the SE. At Lisheen the outcrop pattern is complicated by a series of E-W to ENE-trending normal faults with throws of 150-200m to the north. Locally, supra-Waulsortian rocks are preserved in the hanging walls of these faults and ABL is exposed in the footwalls. Extensional faults with displacements of approximately 200m are present in the entire mine. These faults are noted to be left-stepping and northerly dipping while displaying en echelon movement. The faulting process is an example of a classic ramp-replay system (Güven et al., 2007).

The shallow en-echelon, ramp-relay fault system is seated on the major NE-SW trending Rathdowney Trend, shown in the image below as RFS: Rathdowney Fault System. The ramp-relay system is shown in the same image as Lisheen Relay. The deposit has developed on the southern dipping limb of the regional syncline. Galmoy (another smaller Lead/Zinc mining operation 10km northeast of the Lisheen mine) is also on the same mineral trend. By using aeromagnetic images it was possible to trace these faults back to towards the Galmoy deposits. Similar en echelon systems have been inferred from airborne magnetic data to the north of the mine area at Barnalisheen (see Figure 5 & Figure 6) (Fusciardi et al., 2003).

![Figure 6 Images after (Carboni et al., 2005) showing the orebodies and the larger extensional ore-controlling faults. Numerous smaller ore-controlling faults extend into the hanging walls of these structures.](image)

Hazlett and Garven (1995) presume that regional folding is related to N-S compression on pre-existing Caledonian-aged structures during the Variscan Orogeny, towards the end of the Carboniferous. Many of the earlier ENE oriented normal faults were reactivated because of this compression. The most common regional structures are sub-vertical, NW, NNW, and NE trending faults. These faults are part of a dextral wrench system which is thought to be post-Carboniferous. The scale of the faults varies in the order of tens of metres but at the mine they are rarely more than 2 metres (Fusciardi et al., 2003).

In the mine the main structural elements can be recognised regionally. These structures record an early period of N-S to NNE-SSW extension resulting in the generation of ENE to E-W trending normal faults (Carboni et al., 2003). This was then followed by N-S compression producing an array of folds and thrusts. Sub-vertical, NW trending strike-slip faults appear to crosscut structures relating to both these events (Fusciardi et al., 2003).
A complex array of normal faults of the same age has been the result of early extensional faulting at Lisheen. These faults can be broadly grouped into two main trends: E-W to ENE trending and NW trending faults. The latter has displacements in the order of 10-20m and these faults are only visible in the underground headings. The first group consists of the Killoran (KFZ), Derryville (DFZ) and Bog Fault Zones these fault zones account for the majority of the 200m extensional displacement (Fusciardi et al., 2003). The Killoran and Derryville Faults are the largest structures in the mine. Each fault zone dips between 50°-60° NNW. A crosssection through the Killoran Fault zone & the Derryville Fault zone can be seen in the figures below.

![Figure 7 Generalised section through the Killoran Fault zone after (Burk, 2011)](image)

![Figure 8 Generalised section through the Derryville Fault Zone (Fusciardi, et al.2003).](image)
A tilted ramp-relay zone between the Killoran and Derryville faults was intersected at the time of excavating the mine decline. Gentle ABL dips in the Derryville Fault footwall were found in the ramp zone, these dips give way to moderate WSW dips. Bedding dips become gentler when the hangingwall is approached from the Killoran Fault. A series of ENE trending normal faults that dip NW at 55°-70° with minor displacements have broken the rampzone regularly. It is thought that these normal faults are splays that link the two main faults. The Lisduff Oolite is locally mineralized where breached by these structures (Fusciardi et al., 2003).

3.4. Mineralization

The mineralization at Lisheen consists of a number of massive sulphide lenses enveloped by a semi-massive, vein and disseminated sulphides. An overview is given in the table below. The general morphology of those lenses is stratiform and pseudo-stratabound. Four economic massive sulphide bodies are known: Main Zone, Derryville Zone, Bog Zone. The fourth zone is the Island Pod which is being developed north of Derryville. Economic ore of the Island Pod is scheduled to be mined by September 2012. Figure 4 shows the stratigraphy of formations present at Lisheen, it also shows where the mineralization is present (4th column from the left).

<table>
<thead>
<tr>
<th>Type</th>
<th>Mineralogy</th>
<th>Ore Texture</th>
<th>Morphology</th>
<th>Occurrence</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Massive Sulphides with <em>Pyrite Cap</em></td>
<td>Pyrite (90%) intercalated (20%) with sphalerite and galena. Pyrite / monorrea often massive.</td>
<td>Cherts and brecciated (probably after BMS) intercalations of pyrite, sphalerite and galena. Coboltom intercalations less common. Massive pyrite developments common.</td>
<td>Forms large lenticular bodies &gt;10m vertical thickness. Sharp hanging and footwall contacts. The former often controlled by BMS or pyrite sulfo-turquoise.</td>
<td>Primarily in south Main and south Derryville Zones close to the Killoran and Derryville Faults. Also occurs in NE Main Zone.</td>
<td>Largely differentiated from Zn-Pb-Fa massive sulphides by High-Pb content.</td>
</tr>
<tr>
<td>(2) Zn-Pb-Fa Massive Sulphides</td>
<td>Pyrite / Manganese veins (Type 2)</td>
<td>Cherts and brecciated (likely after BMS) intercalations of pyrite, sphalerite and galena. Coboltom intercalations less common.</td>
<td>Forms lenticular bodies (average 5m) which further out laterally. Bilaminated lenses are common in Main Zone.</td>
<td>Forms the principal mineralization horizon defining the Main, Derryville and Bog Zones.</td>
<td>Significant variability in Zn, Pb and Fe grades throughout the mineralized horizon.</td>
</tr>
<tr>
<td>(3) Disseminated Sulphides</td>
<td>Pyrite, sphalerite, minor galena.</td>
<td>Occasionally truly disseminated but more commonly mineralization forms pyrite replacements of BMS hosted and veins which intensifies locally.</td>
<td>Forms an irregular discontinuous halo up to 5m above and below the massive sulphide. Is most intensively developed as the lateral extension of massive sulphides.</td>
<td>Occurs throughout deposit.</td>
<td></td>
</tr>
<tr>
<td>(4) Vein/Stringer Style Mineralization</td>
<td>Sphalerite, pyrite, galena.</td>
<td>Forms vein and irregular stringer styles, often metamorphosed into a stockwork, repeating or pointing to more intense massive sulphide mineralization.</td>
<td>Irregular and patchy distribution, proximal to massive sulphides.</td>
<td>Occurs sporadically throughout deposit. Distinct occurrence of galena-rich stockworks in east Main Zone.</td>
<td>Clearly the result of several separate processes including intrusion and tectonic activity.</td>
</tr>
<tr>
<td>(5) ABL-Hosted Sulphides (Plates 8 and 9)</td>
<td>Sphalerite, pyrite, galena.</td>
<td>Massive sulphides commonly seen replacing carbonate-rich facies in topmost ABL. Not laterally extensive.</td>
<td>Pyrite distribution but generally only seen where massive sulphide directly overlies ABL and proximal to tectonic structures.</td>
<td>Occurs generally where massive sulphide directly overlies ABL. Also proximal to faults.</td>
<td></td>
</tr>
<tr>
<td>(6) Oolite-Hosted Sulphides</td>
<td>Sphalerite, galena and occasionally Cu-Na-bearing minerals.</td>
<td>Veinlet/stringer associated with brecciation of the host, grading to massive sulphide locally.</td>
<td>Thin (&lt;1m) and intensively discontinuous.</td>
<td>Seen only in sporadic silting in the vicinity of the Derryville, Killoran and Bog Zone Faults.</td>
<td>Conditioned to be strongly structurally controlled.</td>
</tr>
</tbody>
</table>

In Derryville Zone there is a single sulphide lens above the Waulsortian-ABL contact. Main Zone is more complex, with lens bifurcations and several massive sulphide lenses. The continuity of the massive sulphides decreases northwards away from the major fault zones. A spatial association of thicker massive sulphide and higher Zn-Pb grades with the major normal faults can be seen. There is a minor resource hosted in the Lisduff Oolite adjacent to the KFZ and DFZ (Fusciardi et al., 2003). This zone is called the Oolite Zone and can be seen in Figure 9.

The Oolite Member consists of economic sulphides where normal faults have juxtaposed it with Waulsortian hosted mineralization. Oolite has mineralized on the footwall of these structures (Güven et al., 2007). The Oolite zone is very complex and has multiple mineral phases and is structurally complex. Penalty elements like arsenic, nickel and copper can be found in this zone.
Nickel is present locally mainly as niccolite. The Oolite zone intersects with the Killoran fault, and this is one of the reasons why it is structurally complex and has a rich mineralization. The Killoran Fault and the outline of the Lisheen orebodies can be seen in Figure 6. Tennantite bodies with crosscutting chalcopyrite veins are also present, adjacent to the Killoran Fault. These bodies occur on both sides of the Killoran Fault.

![Figure 9 Mine layout: showing Main Zone to the left, Derryville to the middle and Bog Zone to the right. The Island Pod is situated above Derryville.](image)

The Lisheen carbonate-hosted lead and zinc deposit is a relatively flat-lying massive sulphide orebody at a depth of 160-200 meters below surface, with the bog zone orebody noted to be up to 80m below surface. An overview of the mine-layout is shown in the first image above; and shows the different mining zones. These include the Main Zone to the left, Derryville to the middle and Bog Zone to the right.

When looking at drift scale, massive sulphide lenses\(^5\) are often controlled by variation of argillaceous components in the host rock, with strong evidence for hangingwall definition by shales or stylolytes where sharp contacts occur. The mineralization in Derryville is usually at the Waulsortian-ABL contact, whereas in Main Zone the massive sulphide footwall may be several meters above the Waulsortian-ABL contact. It is common to see disseminated\(^6\) mineralization in the footwall rocks, this can be in the form of true disseminations or often as stringers and veinlets. A complex mineralisation is present, this results in variable grade distributions in various discrete lenses (See Table 2 for overview). The mineralization is polyphase, it shows evidence of varying fluids and fluid pathways and it appears to be strongly influenced by extensional fault structures (Fusciardi et al., 2003).

![Diagram](image)

Hydrothermal breccias, locally known as the black matrix breccia (Hitzman et al., 1992) largely hosts the Lisheen deposit. It is these breccias which allow for mineralization to occur in the host rock. These are developed proximal to the base of a 200m thick massive unit, locally known as the Waulsortian Limestone Formation. This formation is extensively dolomitised. ABL is the lithological footwall to the mineralization. The ABL-layer tends to be laterally persistent. Around 90m below the top of the ABL a 70m thick Oolite Member is found.

\(^5\) The classification of “massive” sulphide is arbitrarily defined as containing >40% of total sulphides (employing the stoichiometric formula: $\text{ZnS} + \text{PbS} + \text{FeS}_2 > 40\%$. (Fusciardi et al., 2003.))

\(^6\) Disseminated sulphides are defined as containing <40% total sulphides.
4. Material handling systems at Lisheen

For this fragmentation research project the type of crusher, feed and crusher settings are important. It is the combination of these parameters that determines the theoretical throughput. This chapter describes the influence of the underground material handling systems on fragmentation, followed by a detailed description of the underground material handling systems at Lisheen can be found in Appendix C – Material handling systems together with details about other material handling systems present at Lisheen.

4.1. Influence of material handling systems on fragmentation

The first step of the material handling system is choosing the right heavy mobile equipment (dump trucks and scoops). For this project the functionality and efficiency of the current mining fleet was not considered. After the material is hauled and tipped it ends up in the 300 ton bin. Oversized rock needs to be broken individually and this is a time consuming process, in mines with fragmentation problems, this could be a bottleneck of the crushing process. Crusher operators at Lisheen have explained that this is not a major issue at Lisheen (Personal Observation, 2012).

It is the combination of different material handling units that finally determines the maximum throughput. Lisheen uses the following combination:

- Roxon Hydrostroke plate feeder type BVE 1655
- Roxon Grizzly type MSV10-1530.16
- Nordberg Primary Jaw Crusher type C140 BS (See Figure 11)

For this research Metso Minerals division of Mining and Construction Technology has been contacted and together with Lisheen’s input a site specific reference has been generated based on a simulation run by Metso Minerals. The results of this simulation can be found in Appendix E – Metso Simulations. The Metso Minerals handbook for Crushing and Screening also provided a table and graph which lists the capacity and technical specification the difference between these figures is that the simulation which was carried out by Metso is adjusted to Lisheen’s input and the graphs and tables in the Crushing and Screening handbook are general numbers. After contacting Metso Minerals it became clear that the theoretical capacity is calculated by only calculating the “crushing time”, this means that the time when the crusher is idle or broken down does not account for the capacity calculations, it also does not take the undersized material in account.

Metso Minerals has determined the theoretical value of the crusher capacity at 1350 tonnes per hour (See Appendix E). The actual throughput of the mine based on a mucking shiftboss’s target averages between 2000-3000 tonnes per 9 hour shift (Tarrant, 2012). Comparing these two values shows the difference between actual and theoretical.

To measure the fragmentation it is desirable to know the amount of material that was crushed, and the amount of material that wasn’t crushed. This information is important to realise whether the amount of explosives used was either too low or too high.

At Lisheen it would be difficult to estimate the undersize (material which bypasses the crusher) because it is not weighed separately. The crushed ore and undersize come together on the same belt and are then weighed afterwards, thus including material which was not crushed. Figure 10 shows the ore before and after crushing. This part of the research raised awareness of the difference
between theory and practice. At Lisheen the values of throughput (crushed + undersize) through the crusher are noted down each hour by the crusher operator, the actual ‘running’ or operating time of the crusher is not directly linked with each hour. Because the throughput is depending on the UCS and s.g. (parameters of the Metso Simulation). It is assumed that these parameters are constant. In fact, this is incorrect, these parameters vary throughout the entire mine, the s.g. is depending on the Zn and Pb grades, whereas the UCS is one of the controlling factors of the ground class. The ground class varies throughout the mine as well. More information about the ground class system can be found in Appendix O – Geotechnical Support.

For this project, the underground material handling energy costs were also analyzed, the details of this analysis can be found in Appendix F – Underground Energy Consumption. It showed that the underground material handling power consumption is only 1.42% of the annual power consumption over the financial year of 2011 (April 2011-March 2012). And therefore it is not worth investigating this issue, as it only has a minor impact on the total operating costs. In reality, it is also difficult to quantify because there is no reasonable estimate for the material which bypasses the crusher.

Fragmentation is the link between the mine and the mill, changes at the crusher which affect the size of the output can be directly seen in the mill. The mineral processing is described in Appendix C – Material handling systems.

Figure 10 The ore before it is crushed is shown on the image to the left and on the image to the right the ore is crushed.
Another important aspect is that it is difficult to compare the actual versus desired fragmentation. Contact with Metso Minerals has resulted in a series of emails discussing the set-up and simulation of the Lisheen underground material handling system. In negotiation with the people responsible for this material handling system at Lisheen it turned out that it is nearly impossible to come up with one single range of desired fragmentation at Lisheen. Mainly because it involves too many unknown parameters. The most important unknown parameter is that the amount of undersize material cannot be determined accurately at Lisheen’s crusher. This means that any changes to parameters affecting fragmentation don’t give information about the fact whether the material was crushed or not. It will only give information about the total material throughput (Personal Observation, 2012).

On the figure above one can see the undersized material falling on the conveyor belt which also receives the crushed ore. There is no quick and easy way for determining the amount of undersized material because it cannot be easily separated from its process. Also some undersized material will end up being crushed because it travels on top of the ‘normal’ feed (feed that is meant to be crushed). The following image illustrates this example.
The red-dashed rectangle illustrates some material which does not need to be crushed, but it will still end up getting crushed. This means that if it is even possible to ‘catch’ the undersize coming from the hydrostroke feeder, this amount would be underestimated. Because some of the material is travelling on top of the ‘normal feed’. (Personal Observation, 2012).

After the material is crushed, the overband electromagnet (see Figure 14) positioned above the accelerator conveyor delivery drum removes ferrous material. The metal detector is positioned in front of the bin feed conveyor receiving section. Between the decline conveyor and the accelerator conveyor there is an intermediate structure of the bin feed conveyor which is suspended from the roof of the crusher chamber and transfers material to a 1000mm wide in-line conveyor (bin feed). The bin feed conveyor then delivers material via a chute to the 1070mm decline conveyor and the material is then discharged onto a stockpile on surface. The decline conveyor, is suspended from the roof, on the receiving section of the decline conveyor material is weighed. Every hour this measurement is recorded on daily report sheets by the crusher operators. The decline itself is 1.7km long and is 7 meters wide and 4.5 meters high and has an angle of -15°. It also acts as a primary intake airway together with other ventilation raises.
5. **Mining Methods.**

Before 2011 three mining methods were used; room and pillar, drift and fill and longhole open stoping. From 2011, drift and fill mining is more or less lumped in with longhole open stoping. The table below shows the preferred mining method based on two important parameters; ore thickness and geological variability (Morris *et al.*, 2011). This table is specific to Lisheen and is displayed below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Geological Variability</th>
<th>Preferred method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin (&lt;5m)</td>
<td>Low</td>
<td>Drift and Fill</td>
</tr>
<tr>
<td>Medium (5-8m)</td>
<td>Low/Medium</td>
<td>Multi Pass Drift &amp; Fill</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Multi Pass Room &amp; Pillar</td>
</tr>
<tr>
<td>Thick (8-15m)</td>
<td>Low</td>
<td>Open Stoping (uphole retreat)</td>
</tr>
<tr>
<td></td>
<td>Medium/High</td>
<td>Multi Pass Drift &amp; Fill</td>
</tr>
<tr>
<td>Very Thick (&gt;15m)</td>
<td>Low/Medium/High</td>
<td>Open Stoping</td>
</tr>
</tbody>
</table>

This research has been carried out only in underground areas where longhole open stoping was applied. The reason for this is that fragmentation in the other areas was not seen as a major concern (Morris, 2012). The major concern in open stopes was the varied size of rocks in the muckpiles.

The applied mining methods are described in Appendix M – Mining Methods.
6. Drilling and Blasting

As mentioned earlier, fragmentation consists of controllable and uncontrollable parameters. Drill and blast designs are typical controllable parameters. In order to compare this research with future studies, a detailed description of the drill and blast operations at Lisheen is given. The next section states the various personal observations that were made by the author during the fieldwork period as described in Section 2.2.1.

6.1. Influence of drilling and blasting on fragmentation

The following controllable parameters are known to have an effect on fragmentation (Amiel, 2008), (Ndibalema, 2008):

- Drilling parameters such as: pattern, rotational speed, subdrill, burden, spacing, hole diameter, type of drill rig etc.
- Charging parameters such as: type of explosives, powder factor, coupling, # of primers etc.
- Blasting parameters such as: timing and blast direction sequence.

Ideally, one would monitor these parameters and make changes to them and analyze their individual influence (spider-chart). However, making changes to operations that are already working is impractical.

With the current technology available, accurate timings for blast patterns are not an issue at Lisheen as the i-kon\(^7\) system is available when it is required. This is the same for the type of explosives that are used, switching between the types of explosives is not something that often happens. I-kon blasts are more effective for obtaining a desired fragmentation (more uniform size distribution) but they are also more expensive, hence an important decision has to be made when one selects i-kon-detonators.

It is not likely that the type of drill rig (Atlas Copco Simba or Tamrock Solo) in a stope is going to be changed during the drilling process. Drilling is probably the most important factor which determines the fragmentation. This is because it cannot be expected that explosives will give the desired result when the preparation of the face and the drilling of the face has been poor. When faces are drilled poorly, it will result in a muckpile with poor fragmentation and possibly lost production as well.

Often drilling problems occur because of the bad ground conditions which are present at Lisheen. Because some of the zones at Lisheen require heavy geotechnical support, the straps or rockbolts are sometimes in the way of the drilling patterns. Some rockbolts would have angles which interfere with the designed drillhole angles. Because the support is already present, the drillholes angles are modified in a way which suits the drill rig operator. Sometimes a rockbolt is only noted after the drill hole has already been drilled, this results in a drill hole being re-drilled in a different position (Personal Observation, 2012).

The presence of groundwater will reduce the ground quality for drilling purposes, which then causes holes to be re-drilled. The drillholes which have failed due to groundwater will create an extra pathway for explosive energy to dissipate (Personal Observation, 2012). This could result in inefficient blasts.

\(^7\) Orica, Sweden manufactures i-kon. The i-kon system consists of programmable digital detonators and control equipment. See Section 6.2.2 Detonators.
with poor fragmentation. The presence of groundwater is also important for choosing the right type of explosives. Water in a drill hole can mix with the explosive column and can affect the efficiency of the explosive and ultimately lead to a cut-off in the explosive column. At Lisheen this is not an issue because Kemex\(^8\) is used. Kemex is a site mixed bulk emulsion explosive and it is waterproof. Also the presence of water results in slower drilling rates, creating large cavities on the face and loosening broken rock leading to backfilling and poor operating faces (Personal Observation, 2012).

Re-drilled holes have an influence on the fragmentation whether the drillhole was redrilled because of ground support, bad ground or water problems these redrilled drillholes generate an extra pathway for the energy to dissipate. Lisheen is a very wet mine (See Table 37 for 2012’s pumping costs), therefore the water affects the drilling operation as well. Water erodes the face and therefore it can also wash away the visible instructions (e.g. holes which are marked up) for the driller. Eroded faces and mark ups which have been washed away decrease the accuracy in drilling (Personal Observation, 2012).

Differences in drilling can also occur because there is a lack of visibility for the drill rig operator, some drifts and headings are very steep at Lisheen and then the roof blocks the drillers view from the drill rig. Visibility problems cause the operator to sometimes ‘guess’ the desired position of the drill hole. This is also one of the reasons why drillholes are too close or too far away from each other. (Personal Observation, 2012).

Holes which are drilled too close to each other will result in finer fragmentation levels and holes drilled too far apart will result in coarser fragmentation (IM, 2011).

The relatively old longhole drilling fleet which is present at Lisheen is not equipped with the most recent technology, this makes it difficult for measuring the right drill hole angles. Therefore it is likely that there will be differences between the designed and actual drilled angles. Also differences in the designed and actual drilled hole length can occur this is because the system that measures the length of the added drill steels on the drill rig is known to fail from time to time. This will affect the fragmentation because it is possible to drill through unplanned zones or formations which are likely to have different geotechnical properties. (Personal Observation, 2012).

The maximum angle for haulages and areas that will be designed for longhole is +/- 12%. The maximum angles for drifts and areas that will not be used as a platform for longhole drilling is +/- 17%. Gradients greater than +/- 12% result in mucking difficulties, especially when remote mucking is carried out. This can result in ore left behind at the faces, or ore could be blocking the next firing in this area. A gradient greater than +/- 12% in longhole areas also makes blasting difficult as it can cause hangups and it will result in lower recoveries (Lisheen Mine Design Guidelines, 2013).

Another known issue is compression of the drill holes after blasts. This happens to holes which were already drilled but not yet charged. The sketch bellow illustrates this example. The effect is over exaggerated but illustrates the idea of compression of the borehole (ideally the hourglass shape should be more cylindrical). The end of the drill holes are usually cleaned out well and the beginning of the drill hole are always cleaned manually by drill rig operators or charging crews when it is clearly

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\(^8\) Kemex is site mixed bulk emulsion explosives production from emulsion matrix. Emulsion matrix is essentially an aqueous solution of ammonium nitrate emulsified in oil.
seen that some material is obstructing the drill hole. This leads to the fact that emulsion is not equally spread throughout the borehole. The diameter of the borehole is not wide enough in the middle, this will contribute to undercharging the borehole in the middle and overcharging in the bottom and the top of the drillhole. (Personal Observation, 2012).

Sketch: 1 compressed drill holes.

Drill rig operators are dealing with day-to-day production targets that should be met every day and every week when possible. When the performance is below the target or behind schedule, this was occasionally compensated by other factors. For instance the operator would drill some holes faster than optimum or would drill the holes slightly shorter if this meant that a drill-rod did not have to be changed or extended (Personal Observation, 2012). And if that is the case, these holes are drilled less accurate and this will result in deviated drill holes.

Also loose drill steels contribute to deviated drill holes. This can be seen in the sketch below. A loose drill steel can occur when the drill steel is damaged (wear and tear) or during drilling when the rock properties change drastically.

Sketch 2: Deviated drill holes.

The result of a blast is better when drilling went at optimal rates and angles. It is clear that deviated drillholes do not contribute to an optimal blasting operation. Deviated drill holes reduce the chances for a more uniform blast. (Personal Observation, 2012).
More details about the explosives and detonation systems are described in Section 6.2.

6.2. Explosives

All explosives and accessories are supplied by Irish Industrial Explosives (IIE) since the start of the mining operations in 1999. A contract till the end of the life of mine was signed in 2007, which ensures that IIE will keep providing Lisheen with all the necessary explosives and accessories.

The explosives properties are important to fragmentation prediction models and are therefore discussed should any future study apply fragmentation prediction models to Lisheen.

6.2.1. Emulsion

Lisheen uses Kemex, it is a site mixed bulk emulsion explosive which is produced from an emulsion matrix that is pumped into the drill holes as a site-sensitised emulsion. Kemex is the result of mixing the matrix emulsion with the gassing agent. The emulsion matrix is an essentially aqueous solution of ammoniumnitrate emulsified in oil. The emulsion consists of a ammonium nitrate (60-80 weight%) sodium nitrate (5-15weight%) water (8-25weight%) highly refined mineral oil(3-8weight%) and an emulsifier (0.5-5weight%). The gassing agent is N-10 and consists of sodium nitrate (dissolved up to 40weight%), sodium thiocyanate (20-40weight%) and water (40-70weight%)\(^9\).

It is used because it is waterproof and it is a safe explosive as it only becomes explosive after 20 minutes in the shothole after enough bubbles have been formed by the gassing agent. Kemex has a velocity of detonation (VOD) of 3700 m/s and a relative explosive energy (REE) of 88% (ANFO is seen as 100%) and needs to be initiated by a booster or 12g detonation cord. Lisheen mainly uses Kemex underground with 3 Normet Charmec machines, but on special occasions e.g. in very wet conditions where extra blasting strength is required Emugel 2 35mm stick powder is used, this is a cartridge powder explosive which has a VOD of 4900 m/s and a REE of 111%. Both products are emulsion based, the main difference is their difference in VOD.

Small gas bubbles of nitrogen oxide and aluminium powder are added to the packaged emulsion and make the Emugel 2 sensitive to initiation. The detonation wave is transported through these materials, and acts as a hotspot to cause initiation.

6.2.2. Detonators

For the initiation of explosives both non electric (Nonel) and electric systems are used at Lisheen. The Nonel-systems are made of pyrotechnics and the electric systems have a chip in them on which the delay is later programmed.

The Nonel system is the Nonel Long Period (LP); it is mainly used in underground applications and has delay periods from 100ms to 6000ms with tube lengths of 6m. The explosives are connected using either bunch connectors or low energy detonator cords (3.6-5.6 g/m). Bunch connectors are designed to initiate a maximum amount of 20 Nonel-tubes at the same time. A snapline connector block is coupled to a loop of the low energy detonating cord. Bunch connectors are connected to the Nonel Dynoline which is used to initiate the blast; it is a high strength, highly abrasion resistant tubing which transmits the initiation signal. Blasts are fired underground from a safe distance which is usually 200m or more.

\(^9\) Material specifications derived from the Material Safety Data Sheet (MSDS) supplied by Irish Industrial Explosives.
For more complicated blast patterns and vibration restricted blasts Orica’s i-kon electronic detonating system is used. These detonators are individually programmed; a microchip is programmed after all detonators are in place. Every single delay per detonator is entered by hand in the blast-logger by IIE-staff. The i-kon system is more accurate as it does not use pyrotechnics for its timing. This makes it possible to fire a larger number of holes (up to 4800 detonators, 200 per logger and 24 loggers per blast) with unique timings (up to 15 seconds) on a more accurate basis. After all timings are set, a test signal runs through the detonators to see if all of them are still functioning, non-working detonators are checked again and either replaced or reprogrammed. After this test has been run successfully; the shotfirer has a 10-15 minute window to initiate the blast otherwise all of the set delay timings are reset and have to be reprogrammed.

Two different types of boosters are supplied by IIE 20g (diamond nugget) and 151g boosters (green cap DC; both manufactured by Austin Powder Company) for respectively development and production blasts. Boosters are small quantities of high explosive which releases sufficient energy to fire the main explosive in the hole.

6.3. Charging

The water pressure is the most important parameter which has an influence on both charging and fragmentation. This is because the water pressure in drilled holes can cause emulsion to flow away after it has been pumped in the hole.

Lisheen uses the Normet ‘Charmec’ utility vehicles which are equipped with access baskets and carry a Dyno Nobel Mini SSE unit for charging. The gassing agent is mixed with the matrix in the MINI SSE. Each Mini SSE unit carries approximately 1.3 tonnes of matrix. Ten to fifteen minutes after the hole is charged the emulsion and gassing agent form an explosive. The pumping parameters which influence the mixing of the emulsion and gassing agent can be changed on the control system of the mini-SSE unit.

6.4. Production drilling

An Atlas Copco Simba and two Tamrock Solo (now built by Sandvik) units are used for production drilling. Production holes are either 64mm or 76mm depending on the ground conditions. If the ground conditions are bad, drillhole diameters are preferably changed to 76mm as they are easier to drill. For longhole stoping three different stages are designed; the raise, the slot and the rings. A blind raise is drilled using a concentrated pattern of holes vertically in the roof of the drift. This raise is required to provide the free face for the rest of the stope. At Lisheen, currently the longest successful raise was up to 27 meters. After the raise has been drilled a slot will be drilled; a slot has a tighter pattern than the main part of the stope. It is used to create a progressively larger void in preparation for the larger blasts. After the slot is blasted, rings are blasted in different stages, usually between 2 and 5 rings per blast. Additional raises are required if the first raise was not successful; opening raises is crucial for the further development of a stope and is seen as the hardest part of longhole open stoping. For longhole stope blasts a powder factor of 0.35kg/t is used and for room and pillar blasting a factor of 0.55kg/t is used. At Lisheen a standard burden spacing of 1.8 meters is used for longhole blasting.

For longhole operations drill holes greater than 7m in length are double primed and three detonators are used in holes longer than 15m. Room and pillar drill holes are double primed at the
toe and collar for holes longer than 7 meters. A typical pillar dimension at Lisheen is 6m high by 8m long by 6m wide. The size and shape of pillars varies from area to area because it depends on geology, rock support and ground conditions. The first ring of a pillar is the ring which is closest to the free face, and therefore has the lowest delay. Timings increase the further the ring is away from the free face. The pattern seeks to achieve full extraction by adjusting the last 3 rings to the same delay, when free standing pillars are blasted.

The detailed information about charging and production drilling can be required for fragmentation prediction models should future studies link these Lisheen specific properties to fragmentation prediction models.
6.5. Vibration Control

Vibration control is important for fragmentation as it can be an operational limit. Vibration limits are set by the Environmental Protection Agency (EPA) and could obstruct Lisheen from getting the desired fragmentation. The vibration limit is an important parameter for the type of explosives and detonators and the quantities used for a blast. Using the ‘wrong’ type of explosives or detonators could result in exceeding the vibration limits. I-kon blasts often cause less vibration and therefore the vibration limit is an important criterion for picking i-kon detonators.

Vibration control does not directly affect the fragmentation, but it indirectly affects the fragmentation, because it determines the maximum amount of explosives that can be used for a blast in a specific area. This directly relates back to the fragmentation prediction models that are out of scope.

The EPA issued an Integrated Pollution and Prevention and Control License, this is also mentioned in Appendix B, in the paragraph about HSE accreditations and awards. This license not only controls the vibration levels but also noise, dust and water discharges. Vibration is measured by Lisheen’s Environmental Centre. There are 3 permanent noise and vibration monitors set up on Lisheen’s premises, and there is also one mobile noise and vibration sensor which can be used for monitoring specific locations from a location other than the fixed monitoring stations. From these monitoring stations vibration analysis reports showing the peak particle velocity (PPV) are produced. The limits for day time blasting are 8.0 mm/s and for night time the limit is 4.0 mm/s. These limits make sure that there no damage occurs due to blasting as damage to buildings usually only occurs when the PPV is greater than 40 mm/s.

All blasts are carefully recorded and entered in a spreadsheet to control and predict future blast limits. A relationship between the distance from the blast to the monitoring point (D) and the maximum instantaneous charge (MIC) and PPV has been found. The log-log graph below shows this relationship as it plots D/MIC^0.5 against PPV. It helps to predict future PPV for blasts with a particular MIC.

![Figure 15 Lisheen regression line, after Lisheen Blast Design Template.](image-url)
7. Introduction to fragmentation analysis

Currently there are three ways of carrying out a size distribution analysis in mining or quarry operations. The first method is called sieving, the second method uses field tests to measure fragmentation and the third method uses image analysis software to measure fragmentation. Size distribution analysis can be used for fragmentation analysis. It is very important because it has an influence on downstream operating costs (See Section 1.2. Motivation). Fragmentation analysis helps measuring the performance of explosives in breaking rock, blast plans with delay timings, efficiency of crushers and grinders, loading and haulage efficiency. Also, fragmentation analysis can help to reduce the maintenance costs on both trucks and scoops and reduce the amount of wear on the crusher.

The flow-chart (See Section 7.3. Introduction to image analysis) is created as a framework for the literature review. Various papers about fragmentation analysis have been combined and reviewed. This chapter starts by explaining the different ‘blocks’ closest to the yellow block of Fragmentation Analysis (see Figure 16).

Therefore this chapter follows the following structure:

7.1. Sieving
7.2. Field tests
7.3. Introduction to image analysis

7.1. Sieving

Before image analysis methods were available, sieving was often used as a method to determine the size distribution of blasted material. However, the process which was required to collect the data was quite time consuming and impractical. Production had to be stopped, a sample had to be manually collected and then it had to be placed on a series of screens, and finally all the material on each screen had to be weighed. These data points had to be plotted on a granulation curve and then it was possible to analyze the size of material at the time of the sampling operation. In a general this is a very time consuming, expensive, and clumsy way of performing a size distribution analysis. The result can be precise however; the samples which are being used for a sieve-based size distribution analysis are usually very small. That makes this method not a representative method (Maerz & Palangio, 2004).

7.2. Field tests

Another way of measuring rock fragmentation size distribution characteristics is by performing field tests such as boulder counting, time delays for crushing operations, measuring power consumption of a loader or its productivity, and visual inspection (Singh et al., 1991). However these field tests are very subjective and inaccurate (Steckley et al., 1974). Field tests cannot provide particle size distributions and they are expensive and time consuming (Steckley et al., 1974). Steckley et al. (1974) state that fragmentation tests must be carefully designed and performed. Systematic standardizes approaches are required at every stage:

1. Evaluate and select field tests sites through out several stages in the mine.
2. To determine the initial as well as the post-test deformational state of rock
3. Correlate laboratory and field test data
Examples of possible field-tests are: equipment maintenance logs to record possible wear and tear, recording the tyre pressure of dumptrucks, rock break tests, monitoring the wear of conveyor belts, counting the use of the rock-breaker near the crusher over a period of time.

Mechanical properties generally play a more direct role in analysis of rock fragmentation. The following tests may be necessary to evaluate the rock fragmentation properties:

- Compressive strength tests (uniaxial, confined, and three axial)
- Tensile strength.
- Shear strength.
- Flexurual strength.

The amount of energy required to fracture the rock in the stress regimes imposed by each of these tests is an important indicator of the rock’s behavior when subjected to forces that cause size reduction. The “fracture energy” in each of these tests is obtained by measuring the area under a “complete” load deformation curve (Steckley et al., 1974). An important difference with these kind of field tests compared to sieving and image analysis is that these field tests are used to predict fragmentation. Whereas sieving and image analysis measure fragmentation. At Lisheen it was not possible to perform these tests.

### 7.3. Introduction to Image Analysis

The thesis is focused on applying an image analysis method. Therefore it goes into more detail on the following aspects:

- 7.3.2 Quality of the images
- 7.3.3 Image requirements
- 7.3.4 Random or systematic approach.
- 7.3.5 Location
- 7.3.6 Automated fragmentation monitoring

The choice of selecting an automated or manual system was made after the literature review was completed. It turned out that the initial investment for an automated system was close to $80 000 – $120 000 (Harry Watson, 2012). To justify an investment this large for a MSc-thesis is beyond the scope of work and therefore this will not be discussed in detail.

After reviewing these issues the errors related to image analysis are discussed (See Section 7.4 Errors in size distribution analysis methods). These errors can be divided in the following categories:

- 7.4.1 Errors related to the image analysis method
- 7.4.2 Errors related to sample presentation
- 7.4.3 Errors related to the imaging process
- 7.4.4 Errors related to sampling process

After discussing the errors the advantages of image analysis are listed in section 7.5. All options are then compared in the next section 7.6. Chapter 10 covers the accuracy and calibration of the analysis.
This flowchart is the result of combining various research papers, the following sections in Chapter 7 cover the steps of this flowchart in more detail. The references to the papers can be found in the corresponding sections of Chapter 7. The next page starts with explaining the ideas and theory behind image analysis for fragmentation purposes.

Figure 16 Flow chart of fragmentation analysis.
7.3.1. Image analysis theory

Image analysis methods were first proposed by Carlsson & Nyberg (1983) and further research was then carried out (Maerz et al., 1987) which eventually lead to the development of the WipFrag photo analysis system in 1987, this became commercially available in 1996 (Maerz et al., 1996). Size distribution analysis software deals with stereology, a way of extrapolating an extra dimension to the available 2D images. The software analyses images and reconstructs a 3D distribution using geometric probability principles (Maerz, 1996). Basically there are two different distributions which can be measured. The first one is the true size distribution of a body of particles and is expressed as \(H(l)\) and the second one is the observed profile distribution of a section, expressed as \(h(s)\), \(l\) is a measure of the true particle size and \(s\) is a similar measure of the observed particle profile size. Statistical analysis methods are then used to infer \(H(l)\) from \(h(s)\) (Santalo, 1976). This process is called unfolding (Maerz, 1996). Data collected from the image is first converted into a 3D frequency distribution, then a weight percentage is attached to the distribution, the combination of these two conversions results in a cumulative weight percent distribution.

Maerz (1996) states that:

"Unfolding is particularly difficult because the observed profile size of a particle is a function of both the true size of the particle, and of the nature of the intersection between the particle and the sampling line or plane. Because it is impossible to determine whether a small profile is derived from a small particle sampled through its largest dimension or from intersecting a small corner of a larger particle, it is necessary to use geometric probabilities and make a-priori assumptions about \(H(l)\) to reconstruct it.”.

The following sketch illustrates this problem:

Sketch 3: The fragment is in the middle of the box and the sampling line (intersection) is displayed in red.

In both cases the same particle (fragment) is intersected. Without attaching the geometric probabilities the results would be completely skewed. The small circle in the first frame represents a pen (looking from the top), the second frame depicts a pen lying on its side. This is an example that illustrates the situation as described above by Maerz.

However, Maerz & Zhou (1998) state that Cunningham (1996) has suggested that unfolding is not required and that two dimensional measurements should simply be used “as the unfolding function is merely a mathematical transformation” (Cunningham, 1996 cited in Maerz & Zhou, 1999, p. 419). Maerz and Zhou (1998) make the remark that it is intuitively more satisfying to present three-dimensional numbers.

This principle of 2D-analysis has been used for this research, by applying an accuracy analysis in WipFrag (See Section 10), all samples are used for comparison only. This corresponds with the findings of Maerz & Zhou (1998).
Image analysis depends on different parameters, such as quality of the image, image requirements, the location of the image and the required strategy.

All of the above parameters have a certain influence on the error which is related to the image analyses process.

7.3.2. Quality of the images
Not every image is suitable for image analysis, often a series of images is required to analyse a specific area. Images should be positioned normal to the surface of what is being sampled. In case the picture is tilted, an error is induced. Currently image analysis software is capable of minimizing this error by using an angle correction on oblique images. Tests on rotated images of square ruled paper showed that the error caused by oblique images can be minimized by a geometric transformation (Maerz & Zhou, 1998).

Another important aspect of an image is any kind of scale, either a natural part of the scene (e.g. bucket of a loader, box of a truck) or an artificial part (e.g. scale bar) which is placed on the scene. These parts should be placed on the edges of the image, so that they do not interfere with the actual areas of interest. It is advised to use 2 scale bars, instead of one because this helps to correct for oblique angles. The use of balls filled with a gas or liquid should not be used as these balls are not dimensionally stable (i.e. air filled balls can expand or contract) (WipWare Photoanalysis Systems, 2011).

Besides the scale and angle, also the minimum amount of analyzed fragments should be taken in to account. In the case where too few fragments are analyzed the area is not representative. When too many fragments are analyzed, there’s a possibility that not every individual block is picked up by the edge detection algorithms, because the algorithms are limited by spatial resolution constraints.

If possible, a telephoto lens should be used; this results in a minimized perspective error. A telephoto lens flattens out the image and compresses the depth in the image. This can be difficult in underground mines, because there might not always be enough space to stand back at the right distance in a narrow underground drift (Maerz, 1996).

7.3.3. Image Requirements
There are three major parameters which have a direct effect on the image; resolution, lighting and dust.

Each single fragment has to have a certain minimum amount of pixels in order to be detected by the edge detection algorithms. The resolution can be improved while using an optical zoom, but the use of digital zooming functions should be avoided as it reduces the resolution, because it interpolates pixels.

Lighting has three major aspects; the most important one is the lighting uniformity, secondly the contrast and the least important factor is the intensity.

When using lights underground it is important not to use single spotlights, they are usually focussed on the centre of the illuminated surface, this results in a drop of intensity towards the edges.
Software is capable of correcting for this issue; however a better result can be obtained when uniform lighting is maintained (Maerz, 1996).

Images must have a clear contrast, as the edge detection algorithms use the contrast between the relatively lighter coloured fragments and the relatively darker coloured shadows between the fragments (Maerz, 1996). If the contrast is too low, the edge detection algorithms can not distinguish the shadows between the fragments, this will result in fragments that are an overestimation of the actual size. And if the contrast is too high, it means that a single fragments can be broken up into numerous smaller fragments, giving an underestimation of the actual size (Eden & Franklin, 1996).

It is possible to compensate for low intensity on most imaging systems, this makes it the least significant lighting parameter unless it directly affects the other lighting parameters.

Dust, is always a problem when blasting, it usually covers up the surface of a muckpile, which makes it harder to detect the edges of fragments as they are blocked by dust on the photograph. Dust and fines particles will be too small to be picked up by the image analysis software. At Lisheen this is avoided by washing the face prior to face inspections and trucking operations (Personal Observations, 2012).

In general one should always take in mind that images should be representative, so it is better to use a series of images, atleast 5 per location, each image should contain atleast 200 particles and the largest block should not occupy more than 20% of the width of the image. Wide angle lenses should not be used as they have an edge distortion. The best estimate of oversize material can be measured by taking at least 10 full-scale shots (WipWare Photoanalysis Systems, 2011).

7.3.4. Random or systematic approach

As mentioned earlier there are only two options available for selecting a strategy, either random or systematic. The location is the most important parameter for the strategy, at each location a decision has to be made on what section of the area will be sampled. For example, in case of a systematic approach the number of filled buckets after a fresh blasts or the objective distance is pre-determined (e.g. pre-marked spray paint at a specific distance from centreline). Systematic strategies give a greater assurance that spatial variations in size are taken into account, whereas random sampling involves picking different sections of areas using statistical methods. In case, the image analysis system cannot handle the required amount of pictures to fully represent an entire fragmentation surface, random sampling methods should best be used (Maerz, 1996).
7.3.5. Location

The location of the image sampling process depends on the chosen strategy, which is either random or systematic; each location will have different constraints (e.g. lighting, angles, objective distance etc.).

The following locations are available for the image sampling process:

1. Top of a muckpile
2. Front edge or cross section of a muckpile
3. Stockpile
4. Surge bin of a primary crusher
5. Conveyor belt
6. Bucket of a loader
7. Box of a truck

![Diagram showing possible locations](image)

*Figure 17 Possible locations of measuring the fragmentation at various places throughout the mine*

The locations 1, 2 and 6 can be found in any active mining area throughout the mine. Their locations vary from day to day and therefore these locations are not represented in the figure above (Figure 17). The green line points to the the area where the trucks unload during periods when the crusher is unavailable (e.g. downtime) and represents an underground stockpile.

The top of a muckpile is not representative because of the segregation of material. Rocks rolling off a muckpile tend to roll further when they are coarser. Muckpiles are inhomogeneous in general, as it is a very subjective place to take an image. The amount of segregation depends on the side of which the image is taken (e.g. at the top, at the side, in a stockpile). It is hard to quantify this error, because it is very unpredictable. Maerz and Zhou (1998) indicate that the magnitude of this error is the largest of all errors. Another problem with taking image samples from muckpiles or stockpiles is that the surface angle to the camera is most likely to be oblique; this results in a perspective error. Computer software is able to minimize this error.

When a cross section of a muckpile is taken as an image sample, this could cause production problems, as there is only a very small window to take a photograph, it will most likely delay
mucking operations. Another problem which arises when looking into cross cuts of muckpiles, is dust. Because the material is being moved constantly, dust is likely to cover the surface of the muckpile (Maerz, 1996).

Images of muckpiles and stockpiles are likely to have sampling biases and are therefore less suitable. The major reason for this is that the material is not mixed at the time of the image being taken. Finer particles will most likely become hidden behind larger rocks and the larger rocks will roll to the outer edges. Also in surface mining and quarry operations the sun angle and cloud cover are highly variable. Examples of images of muck – and stockpiles can be found in Appendix I – Data collection including processed images.

Surge bins of primary crushers could be a good alternative as the lighting, scale and environment can be well controlled. And there is very little degradation of the material (from loading, hauling and dumping operations). However, when the crusher is jammed, this will result in a repetitive image, therefore it creates many images with the same information, this sampling error makes this location unsuitable (Maerz & Palangio, 2004). Lisheen does not have a surgebine, however the purple line in the figure on the previous page represents the location of the crusher.

Conveyor belts are a good set-up location for image analysis systems, as they tackle most of the issues at the other locations. Artificial lighting can easily be mounted above the belts as well as the camera itself, the width of the belt can be used a constant scale. The sampling bias is minimized as all material will pass the conveyor belt, and gravity segregation can be assumed constant (in case of flat conveyor belts), or can be calibrated out when necessary. However most quarries and mines will not transport their blasted material to a crusher on a conveyor belt, therefore it is most likely that this location is only suitable for post-crusher material analysis (Maerz & Palangio, 2004). This applies to Lisheen as well, the location of the conveyor belt is depicted as a red-dashed line in the picture on the previous page.

Maerz & Palangio (2004) claim that the best way of automated analyses of blasted material is to image the fragmented material while it is being transported from the muckpile to the crushing station in a conveyance vehicle. When the image is taken while the material is in transit, the surface is more mixed up with material from all different sizes; therefore it makes the image more representative.

A relatively easy way is to take pictures of cross sections from the muckpile in the bucket of a loader. A disadvantage is that the photographer must be present during the majority of the loading operation. It is likely that there will be small delays in this operation.

Images of the box of a haulage truck are based on the same principles as images from the bucket of a loader. A photographer should be present during the entire mucking operation and should be positioned on a place where most trucks will pass, preferably the crusher area, which is usually well illuminated. The body of the truck can be used as a natural scale, because its dimensions are known.

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10 Section 8.7 covers Galmoy stockpile images in order to determine if the image analysis software performs better with pictures taken on surface (daylight lighting).
7.3.5.1. Images of tipping trucks

This section illustrates the idea of taking pictures of trucks in the tipping bay (blue arrow in Figure 17 points out to the tipping bay). Three tripods and the lights and the camera were installed near the rockbreaker, behind the actual tipping bay. It was expected to be the best location for taking photographs of trucks. The following series of pictures show the tipping operation (See Figure 18).

![Image of tipping trucks](image1.png)

**Figure 18 The different stages during the tipping process**

It turned out to be very difficult due to dust and movement of the ore to get a good picture of the ore in the body of the truck. The best photography moment would be just before the particles start sliding down. In practice however, this moment is very hard to record, because not all of the material starts to slide on the same time. Ideally one would take a picture when the most particles are visible, which would be when the box would reach his maximum tipping angle. Most of the times the material already starts to slide before the box of the truck has reached its highest point.

It is not possible to use the flash on the camera for this kind of pictures because the flash exposes all the fine particles in the air which can be seen on the image below (Figure 19).

![Image of flash photography](image2.png)

**Figure 19 Flash photography is not suitable for underground photos.**
This photo is taken at the same location of the first photo in Figure 18. The difference and the need of additional lighting are clearly visible. Unfortunately the LED-arrays are blinding the drivers when they are reversing therefore this type of illumination is unsuitable for taking pictures of the tipping process. In order to solve this issue, infrared lighting systems and an infrared camera are required.

7.3.6. Automated fragmentation monitoring system

In 2001 WipWare released a new automated system which can measure fragments automatically, it is named WipFrag Reflex. It consists of two main components a triggering system and a tracking system. The system is based on 10 key steps (Maerz & Palangio, 2004).

1. Sense, the presence of a sample
2. Wake up, from a dormant state
3. Identify, the vehicle and origin of material
4. Determine, whether or not the bucket is full or empty
5. Image, the bucket
6. Discard, any parts of the image that do not show rock material
7. Analyze, the image with an advanced fragmentation analysis system
8. Collect, the information in a comprehensive database
9. Share, the information over a network
10. Sleep, if no further activity is detected.

Various different types of sensors were considered for the triggering system (e.g. laser, IR beam, radar, microwave, motion, pressure, optical recognition, and mechanical) but only ultrasonic, microwave and optical recognition (used as a secondary triggering device) have been integrated in the triggering system which is developed by WipWare.

For the tracking system a number of options were evaluated such as: GPS (Global Positioning System), DGPS (Differential Global Positioning), Active RFID (Radio Frequency Identification), Passive RFID, Line Scanning, Optical Character Recognition. Active RFID was found to be the most suitable tracking system, and was integrated in WipFrag Reflex System. It has low power consumption and high mean time between failures (MTBF), robust and is safe and reliable. Each vehicle is tagged and another tag is placed near the camera, this helps the triggering system as it can be used to prevent other vehicles from falsely triggering the system.

Both triggering, tracking and lighting systems will need to meet certain criteria:

They all need to be:

- Extremely reliable
- Extremely durable
- Waterproof
- Dust tight
- Providing adequate sensitivity at an adequate distance
- Capable of operating at extreme temperatures
- Easily contained
- Low on power consumption
- Non hazardous to personnel
The tracking system will also need to have:

- A long battery life
- A reasonable price
- The possibility to be hermetically sealed
- Resistance to oil, water, dust and impact
- The possibility to be mounted easily on direct metal contacts, without reducing the effective range
- The possibility to handle magnetic ore types

Also the associated lighting system will need to meet some extra criteria such as:

- Provide even illumination
- Provide suitable lumen output
- Provide long bulb life
- Low maintenance costs
- Low operating costs
- Not impair the vehicle operator’s driving skills

Various types of lighting systems (e.g. fluorescent, incandescent, halogen, visible LED, infrared LED, HID based on sodium or metal halide) have been investigated. High intensity discharge (HID) type sodium and HID-type metal halide systems have been found most suitable for surface applications. This is because HID-systems are reasonably efficient, resistant to vibration and have a long bulb life. Also, it is well suited for areas in a heavily industrialized area. Even though it produces some heat and has moderate initial costs it is the most suitable lighting system.

For underground mining operations light emitting diodes (LED’s) array and infrared lighting are the best alternative. This is because their power consumption is low and their resistance to environmental factors (e.g. moisture, vibration, shock, dust and temperature) is good. Also LED’s have an average life time of 60 000 hours (2500 days, nearly 7 years of continues use).

More information about the post muckpile – pre primary crusher automated optical blast fragmentation sizing systems is described by Maerz and Palangio (2004).

7.4. **Errors in size distribution analysis methods**

Maerz and Zhou (1998) have made a distinction between four different types of errors for image analysis systems:

1. Errors related to the image analysis method
2. Errors related to sample presentation
3. Errors related to the imaging process
4. Errors related to sampling process

7.4.1. **Errors related to the image analysis method**

An example of the first type of error has been briefly discussed, in section 7.3.3 Image Requirements, it was first discovered by Eden and Franklin in 1996 and named Disintegration and Fusion (see 7.3.3). Fragments where the colour densities vary a lot can also be problematic, as well
as washed and wet fragments. This gives problems for the edge detection algorithms to delineate fragments. All of these issues contribute to an error which is related to misidentification of the true edges of the sampled fragments.

The image analysis system measures in two dimensions, and measure either the cross section or block areas of a 2D-image. This information is then transformed in a representative 3D distribution. This process is known as unfolding. Cunningham (Maerz & Zhou, 1998) has suggested that this is an unnecessary process, and that the two dimensional measurements can be used. This could be done, however it makes more sense to use all three dimensions. The actual transformation from 2D to 3D is a mathematical function which relies on geometric probability principles. Measurements with only two dimensions can be used when they are used for comparison only.

7.4.2. Errors related to sample presentation

This kind of error deals with the difference of the way the sample is presented to the measuring device whether it is a field test, sieve or image analysis system. The most important aspect is to realise that sieves will measure the minor and intermediate axis of the blocks (Wang & Stephannsson, 1996) whereas image analysis systems will measure the intermediate and major axis of fragments. Because of this, image analysis will give larger measurement results than sieving because different parameters are measured.

Another error which is induced by sample presentation is the lighting variability, not every image is taken with the same intensity. The variability in lighting can cause difficulties in delineating different fragments. To minimize this type of error a constant source of artificial lighting should be installed and the dynamic effects of natural lighting should be blocked (Maerz & Zhou, 1998).

The last error in this category is related to the angle at which the image is taken, compared to the surface. When the surface is oblique to the camera, it results in a perspective distortion. All images should be taken in such a way that the axis of the camera is perpendicular to the surface of fragments, as mentioned earlier in section 7.3.2 Quality of the image, a telephoto lens should be used when possible. Tests have shown that software can reduce this error, with the in-built geometric transformation corrections by using geometric rotations, this reduced to the error to an overestimation of 6% (Maerz & Zhou, 1998).

7.4.3. Errors related to the imaging process

This type of error is related to the fact that not everything is recorded on a single image. Recorded areas with a wide size distribution will require many image samples. The errors arise because large boulders may not fit on a single image, or because of dust particles, which could be too small to be even seen on the image. And even if both of them are present on a single image, the edge detection algorithms can still have difficulties delineating the fragments because of their extremes in size. When small fines or dust particles are missing on the image analysis, it will result in an overestimate of the actual result.

It has proven to be difficult for material with a wide size distribution to quantify this error. Two solutions have been proposed by Maerz (Maerz, 1996; Eden & Franklin, 1996) where the first solution relies on the fact that the errors are systematic and since the optical systems can be used for a relative comparison, the relative error will still be low, but the absolute error can be high. This approach would leave the measured values as they are. The second solution is to analytically or
empirically calibrate the values; this calibration is dependent on the shape of the distribution. Calibration methods will increase the accuracy. In general, the net effect of optical methods is that a measurement is too large. A test with WipFrag software has shown that the minimum discrimination for a single image can be as high as 8%, but with 10 images at various objective distances this error can be reduced to 2% (Maerz & Zhou, 1998).

7.4.4. Errors related to sampling process
Sampling errors are the most significant errors in optical size distribution analysis methods (Maerz & Zhou, 1998). More uniform material will have a lower sampling error than less uniform material.

Sieving methods will require a large amount of material to be characterized in order to be representative as a size distribution analysis method. However, only a small amount can actually be measured with sieving.

With optical systems there are two potential sources for sampling errors, they both deal with spatial segregation of material.

One must take in mind that material that is dumped on a truck is coarse in the beginning and the finer material will be located on top. As well as with muck and stockpiles, where the coarser material tends to roll further away. The location where the image was taken has a huge influence on this type of error. By taking pictures of all the material, at different locations this error can be minimized.

When image analysis systems are used they measure in-situ fragmentation (e.g. muckpiles, box of a haulage truck, conveyor belts) every image being taken will have overlapping fragments. Meaning, the image will only measure its surface. When there is segregation, fines will drop in and get behind coarser material, and this information will get lost during an optical measurement. Whereas traditional sieving deals with fragments individually. Partially overlapped fragments will be measured without the information of what part of the fragment is overlapped. This will result in an underestimation. Geometric probability functions can minimize this error, if the model is based on the idea that the overlapping part is more a less constant (Maerz, 1996a).

7.5. Advantages for image analyse systems
Nowadays, more and more companies have started to use digital image processing systems instead of sieving. Image analysis has the following advantages when compared to traditional sieving methods (Maerz et al., 1996).

- Image processing is quicker than sieving; multiple images can be taken quickly, and can also be analyzed faster than a second sieving sample.

- Because the measurements can be automated it reduces the expenses of an operator and the sampling bias associated with the operator (Maerz & Zhou, 1998).

- Image processing, because of its speed does not interfere with or disrupting production.

- Because image processing is inexpensive and fast, many samples can be analyzed when the system is automated and this makes sampling errors less significant.
• The sheer quantity and variability of blast fragmented rock make screening entirely impractical, whereas image processing is not limited by size or volume of the rock.

• Image analysis is non-destructive, which makes it suitable for measurements on weak rocks such as coal or gypsum.

Although image analysis is time consuming when manual intervention is applied, it is still faster than traditional sieving. Split-Online’s practical beltcut procedure (Split Engineering, 2005) suggests that:

• Four people are needed to collect the belt cut and coarse rock samples and this will take less than one hour
• Screening the coarse rock will take four people less than one hour
• To prepare and screen the belt cut sample will take four people approximately three hours.

This whole procedure should also be supervised (Split Engineering, 2005). It suggests that three people are employed full time for a full day to process a sample. Their duties are to set up equipment, collect samples and carry out the sieving. Similar actions are required when one wants to sieve material which is not sampled from belts but sampled from truck loads or scoop loads. One would also require several skilled operators to operate some of the heavy machinery on surface such as trucks transporting samples on surface and JCB’s to help lifting the heavy material. It can be seen from this example that it would take one person on its own longer than several hours of image analysis on a sample. Based on these circumstances it is fair to assume that image analysis is a lot less labour intensive.

Automated image analysis does reduce the time of an operator as no data needs to be acquired manually, but this research was not automated and therefore an operator was still a necessity. The difference in costs between the two different systems (automated and non-automated) was the main reason for selecting the manual system.
### 7.6. Comparison

In the next table a comparison between different locations and different parameters is given. The locations and parameters will be discussed in this section.

**Table 4 Comparison of different factors and locations, Investments costs acquired February 2012.**

<table>
<thead>
<tr>
<th>Image Acquisition</th>
<th>Muckpiles or stockpiles</th>
<th>Trucks while tipping</th>
<th>Scoops with loaded bucket</th>
<th>Belts</th>
<th>Surge Bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred mode</td>
<td>Manual</td>
<td>Automated</td>
<td>Manual</td>
<td>Automated</td>
<td>Combination</td>
</tr>
<tr>
<td>Triggering control</td>
<td>Simple</td>
<td>Very complex</td>
<td>Less complex</td>
<td>Complex</td>
<td>Simple</td>
</tr>
<tr>
<td>Location</td>
<td>Simple</td>
<td>Complex</td>
<td>Less complex</td>
<td>Very complex</td>
<td>Simple</td>
</tr>
<tr>
<td>Sampling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Representative</td>
<td>Poor</td>
<td>Good</td>
<td>Average</td>
<td>Very good</td>
<td>Very poor</td>
</tr>
<tr>
<td>Number</td>
<td>Low-Very low</td>
<td>High</td>
<td>Low-Very low</td>
<td>Very high</td>
<td>Average</td>
</tr>
<tr>
<td>Lighting Quality</td>
<td>Low</td>
<td>Good</td>
<td>Low</td>
<td>Very good</td>
<td>Normal</td>
</tr>
<tr>
<td>Error</td>
<td>High</td>
<td>Low</td>
<td>Normal</td>
<td>Very low</td>
<td>Very high</td>
</tr>
<tr>
<td>Safety</td>
<td>Normal</td>
<td>Very good</td>
<td>Low</td>
<td>Very good</td>
<td>Very low</td>
</tr>
<tr>
<td>Investment Costs</td>
<td>Low</td>
<td>Very high</td>
<td>Low</td>
<td>Very high</td>
<td>Low-average</td>
</tr>
<tr>
<td></td>
<td>(2-3K€)</td>
<td>(80-120K€)</td>
<td>(2-5K€)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scooploads cannot be measured automatically, because their location changes many times. As discussed earlier (See Section 7.3.5) cameras near the surge bin have a larger sampling error because the material which is being photographed or recorded can be jammed. Therefore the image could have a lot of fragments which are similar to previously recorded images. This requires a lot of manual monitoring as well, because duplicate images must be discarded.

The trucks and belts can be automatically monitored by a certain camera setup; the main reason for this project not to go for this option is because the costs are too high for the purpose of this research project.

When manually taking pictures the triggering control is not the hardest part, simply because the operator can control it, a remote shutter and tripod for both the camera and the additional lights will be sufficient. The triggering system for trucks is the most complex of all locations, because the location of the material needs to be identified as well. Scoops have a slightly easier approach for determining the location of the mined material as the person who would be taking a picture has to be near the mined area. The actual data gathering is a bit more complex because the scoops are working in an area with continuous movement of heavy machinery. There would be very little time available to go in and take a picture of the bucket of a scoop, this is what makes the triggering process difficult. Belts have difficulties when the system is stopped for short intervals, these pictures need to be discarded. An operator can take pictures near the surge bin, when manually taking pictures, this makes it easy for the triggering process.

The location is closely related to the safety aspect. A remote area, where heavy machinery is not present is more convenient and safer compared to areas where work is in progress. Trucks pass the tipping point each time during the loading/hauling cycle. Therefore the location is always the same for every truck as long as there is only one tipping point. Because the location hardly ever changes it
makes it a good reference point for data comparison. Each time the truck passes with the same lighting conditions. The location where you can photograph scoops is a bit more difficult as scoops are bound to headings and they do not need to travel much during their shift at a certain heading or stope. The only moment available for taking pictures of scoop loads is when the truck is driving back and forth from the tipping point. Belts are usually a good location; they are safe and just need a camera above the belts. However, at Lisheen the crushed ore does not travel on a conveyor belt to the crusher, it only leaves the crusher on a conveyor belt; therefore it could be used to determine if the crusher functions to its design. This research is focussed on the pre-crusher particle size and therefore this part is neither monitored nor analysed. Lisheen has a bin as well it is known as the 1000ton bin. It is not possible to take a picture if the loading hopper (also known as the 300ton bin) is empty. As everything falls right through and then there is no possibility to take a picture. It is not safe to take pictures near the 1000ton bin area, because trucks and scoops are operating constantly in that area.

It is difficult to get representative images from muckpiles, especially because a lot of the muckpile is inaccessible due to safety issues. Slopes of muckpiles are in general not that steep but they are a serious tripping hazard, therefore taking pictures of muckpiles is often restricted to images of the front of a muckpile. Because of the segregation, in general these images would contain too many large rocks because they tend to roll down to the front of the muckpile. Tipping trucks are much more representative, because of the fully mixed load. Scoops are less representative, because in the same time period it is only possible to record scoops at the area where the photographer is photographing. Whereas with tipping trucks; it is possible to record every incoming truck from all locations. Belts are very representative because all material passes on the belt after it is crushed. Surge bins which are feeding directly to the crusher are however not representative, because it is likely to assume that jamming will result in duplicate images (Maerz & Palangio, 2004). If no jamming occurs at the surge bin one would need a fully automated system as well.

By comparing the amount of data shots in a certain time period; the most data shots per hour would be obtained from the belts, as it is a continuous operation. Second to the conveyor belts are the tipping trucks, because this process is also automated and the location is not changed during the measuring process. It is possible to obtain a lot of shots from the surge bin as well, since it can be automated, however the quality of the shots is doubtful. It is only slightly faster to take shots from muckpiles, than taking pictures of buckets of scoops. It would not be possible to take pictures during the loading process because production would be interrupted. Hence pictures need to be taken in the hauling interval before the truck returns to the scoop. If there is more than one truck working together with the same scoop this strongly reduces the time-window for taking a picture of a bucket of a scoop.

Lighting is an issue for all locations related to underground photography; the only reason that tipping trucks and belts are ranked higher is because it is easier to maintain constant lighting parameters in those areas. The surge bin near the crusher already has some additional lights installed as well; however they are not all pointed in the right direction. Because the lights light up the area in all different directions it creates a lot of artificial shadows. This can cause problems for the software. For this project additional lighting bars with LEDs have been constructed, these lights can be placed on a tripod in both horizontal and vertical direction.
The types of error in relation to the location have already been discussed in section 7.4. and briefly in this section.

The final parameter taken in to account in this comparison, are the investment costs. Because this is a thesis research project, academic licenses can be bought for the use of WipFrag ($8 00) or Split Desktop ($ 500). Besides the software, a camera with the required accessories has been purchased for € 1000. The total value of the 2 lighting bars is estimated around € 300 each. These can be dismantled after the research is finished. The LED lights can be used as reversing lights for the Toyota Hiluxes, and the tripods can be used for geological or geotechnical purposes. Prices mentioned are obtained around February 2012 and can deviate from current market prices.

7.6.1. Safety
Safety and the location are very closely related, automated systems are the safest of all systems. There are different manual methods, but one should always take in mind that all of these methods cannot compromise safety issues. Most care must be taken in to account when heavy mobile machinery is operating, as well as the tripping hazard while photographing muckpiles. Also rocks falling or sliding down from muckpiles are a hazard. When present at a heading this should always be kept in mind.
8. Software Introduction

Measuring particle sizes and shapes is part of granulometry. Not only can this part of science be used for optimizing fragmentation, but also for petrology (microscopic analysis of rock and minerals) and soil mechanics (classification of soils), metallography and powder technology. There are many methods for determining the size of smaller particles, e.g. sieving, centrifugation, sedimentation, or optical microscopy. But none of these methods can be used for determining the size of large particles like rocks and boulders. Hence image analysis has been chosen as a research method for fragmentation analysis in Lisheen’s underground mine. Various different companies have developed image analysis software which can be used to measure fragmentation. Split Engineering LLC and WipWare have developed popular software (Split Desktop and WipFrag). Both companies offer services which allow the customer to send their images to the company where the image analysis is performed by professionals, who work for the software company. For this research a stand-alone software version with academic license was purchased for WipFrag. Split Desktop was used for a 30-day trial period. Both programs consists of various process steps:

1. Open a new image and scale the image
2. Generate a net of fragments.
3. Manually edit the net of fragments.
4. Generate the size-distribution.
5. If necessary, change the width of the distribution bins.

Two different types of input can be used, either a digital camera (lightweight handheld camera) or on-line monitoring, where a fixed video camera focuses on draw points, conveyors etc. This thesis is fully focused on the use of single digital camera as an input for both programs. This is because automated monitoring systems require customized hardware and the investment costs are around a 100 times more expensive (Watson, 2012a). Customized hardware is used for protecting the camera and lighting against dust and blast damage and to avoid image blur when monitoring rock on a moving conveyor.

8.1. Importing images and scaling

Experience has shown that both programs works better with greyscale images instead of coloured images. Wipware suggests that images with a width of more than 1600 pixels should not be used unless really small fines must be detected. When additional scale bars are used it is better to manually adjust these scale bars to one solid colour by using photo editing software (e.g. Gimp or Adobe Photoshop). This can be seen in the image below. If the scale bar consists of more than one colour the software can easily be interpreted as multiple fragments.

Figure 20 Comparison between original (colour) and edited (gray scaled with smoothed scale bars).
Now that the scale bars have been smoothed to one blank colour it is easier to distinguish the scale bar automatically. However, WipFrag still has problems determining the scale bar automatically when you select the option automatically ignore scale. This option simply attempts to erase in a line across the scale line(s) which have been drawn. In some cases this will result in material being ignored because the scale line is overlapping fragments or they are partially hidden by the scale line(s).

![Figure 21 Image is scaled, with dual scale option.](image1)

When scaling images, it is important that two scale bars are used when the analysed area is on a slope. For scaling purposes, balls should be avoided because their dimensions aren’t constant, balls filled with air can contract or expand. When two scale bars used there must be a vertical displacement between the two scale bars. This can be seen in the figure above as well.

### 8.2. Generate and edit a net of fragments

The next step is to generate a net of fragments.

![Figure 22 An auto Edge Detection Parameter (EDP) generated net.](image2)
As can be seen in the image above the auto generated net does not give the desired result. This is where the manual editing comes in. This can be done in 3 ways, changing the edge detection parameters (EDP), manually drawing and erasing lines in the generated net of fragments or finally a combination between these 2 methods. In many cases, the third method is used, by changing the auto EDP parameters you can reduce or increase the amount of fragments, by sliding the 3 main parameters:

- **Threshold** is the difference in intensity (gray tone level, range between a pixel and its window average).
- **Valley threshold** specifies a minimum level of gray tone slope to trigger.
- **Blur** is the strength of the Gaussian smoothing convolution.

An extra two parameters become available when the advanced controls are selected

- **Search dark** attempts to extend the length of a net line. The line will follow the path of pixels with the darkest greytone level until either; the path becomes lighter/brighter, the line closes a polygon or it extends the number of pixels entered as input value.
- **Search radius** also attempts to extend the length of net lines the number of pixels entered as input. The search radius will scan the net in front of the line up to the selected number of pixels. The line will stop searching when it either closes a polygon, or it extends the number of pixels entered as input value (WipWare, 2010).

### 8.3. Manual editing of fragments

After manually editing the previous image, the result looks like the image below.

![Figure 23 Manually edited net of fragments](image)
Areas in solid grey (scale bars) are ignored, whereas white areas are determined manually as fines, in the white area, fragments cannot be determined because their particle size cannot be seen. When manually analyzing and processing fragments it is important to check as many fragments as possible. This is done by right-clicking on a fragment. The next image shows the result of a check on a fragment. It shows the outlines and equivalent sphere diameter of the selected fragment.

![Figure 24 Checking on a fragment](image)

In this example it shows that the fragment has a diameter of an equivalent sphere of 174.61mm. It also shows that the particle is closed completely and does not accidently mix with neighbouring fragments. This cannot be seen on this level of zoom but when zoomed in the particle contour can be seen in more detail, this is shown in the image below.

![Figure 25 Zoomed in on the highlighted particle (600%)](image)
Voids can occur because not all fragments are in direct contact with each other. This usually leaves black gaps in between fragments. These gaps are too dark to analyse and consist of no material. Therefore these voids must be classified as ‘ignored blocks’. Manually drawing particles outlines is usually carried out at a level of either 400%, 600% or 800% zoom. This increases the accuracy, but the original high quality image must be viewed next to the processing screen in order to create the best possible outline. Because there is only a limited amount of zoom available in the WipFrag program (800%), the software uses lower quality images (the dimensions of the images are approximately 4 times less than the original image). Two computer screens are required for a better performance, one for using the software and one for viewing the original image. When viewing the original image, one can see the different particles on a much higher zoom level and with a much higher resolution. This can be seen in the next image below.

![Figure 26 Zoomed in on the same particle, but using the original image](image)

### 8.3.1. Manual editing approach

Minor differences can be seen, while comparing the fragments on both the original and processed image. The differences will always be there and are operator biased as well. However, for this research all images have been processed by the same person (the author). The images in this section of the report are the very first images which were processed. During the research project, experience using the software was gained and fragment recognition became easier and less time consuming. Whilst manually outlining fragments a strategy was developed during the image processing.

It mainly consists of the following steps:

- Start in a bottom corner of the image.
• Draw lines which cancel out the floor or sidewalls or any areas which are too dark (usually the top corners of the image).
• Divide a picture in different zones or height levels (such as floor to first scale bar, between the scalebars, next to the scale bars, above the 2nd scale bar).
• Work your way from left to right or vice versa, once completed a height level move upwards in the image.
• Try not to skip fragments on the same height level of the image.
• Focus and outline first on an easy fragment. Easy fragments are either big, have a distinct shape or colour/grayscale. Once delineated such a fragment work your way around the neighbouring fragments.
• When drawing lines which cancel out dark areas or sidewalls one has to remember that fragments touching these lines must be fully visible, otherwise these fragments need to be classified as ignored blocks in case the particle is only partially visible. If they are not classified as ignored blocks they would be falsely seen as smaller fragments, as the lines which were drawn could have cut these fragments into more than one fragment.

8.4. WipFrag example results
The final step is to request the results from all generated fragments which are not manually ignored (solid dark grey and solid white areas).

Figure 27 Sieved fragments; all coloured fragments are taken into account for the distribution graph.

Fragments with the same colour have no relationship; fragments simply have the same colour because there are not enough colours used in the program to give each neighbouring fragment a different colour. Note that all fragments which touch the edge of the image are not taken in to
account in the distribution curve. This is because their net, the blue drawn line, is not fully closed. Therefore the software cannot determine the full size of the fragment.

The final output of the software is shown in the above image. Each time a result is processed the data is stored in a log file. It stores all the parameters which are displayed on the left of the distribution curve and the x and y values. Besides these values it also stores the $P_{10}$, $P_{20}$, $P_{30}$, $P_{70}$, $P_{80}$, $P_{95}$, $P_{99}$ values.

These values give percentile sizes. $P_{90}$ is the 90-percentile, the size at which 90% by weight of the sample is finer and 10% is coarser. When looking at sieving, $P_{90}$ is the size of sieve opening through which 90% by weight of the sample would pass. The $P_{50}$ is the diameter of which half of the sample is finer and half of the sample is coarser. This is also called the median or the 50-percentile.

8.4.1. Merged analysis
A merged analysis is a fragmentation analysis done on more than 1 image. Each single analysis is exported as a .frag file. When dragging more than one .frag file into WipFrag a merged analysis is carried out. This is very useful for doing an analysis on images with a different scale or performing an analysis based on a large area. An example of the test data set is displayed in the image below.
The title of the image is ‘Merged Analysis’ and it shows the amount of images used for this analysis. For this research, all of the single images of the same stope are merged together. This is done by taking pictures along the full width of a stope. The idea is that the full width of a stope represents the bottom part of the visible muckpile. The top part cannot be photographed due to safety reasons.

It is also possible to hide the histogram or to display the ‘% Retained’ on the y-axis. This is shown in the 2 examples below. This can be done for all cases whether it is a merged analysis or not.
The two columns on the right hand side can also be easily copied to the clipboard, by right clicking on the chart and pressing ‘Copy chart data to clipboard’. This is especially useful for copying results to Microsoft Excel.

### 8.5. Exporting images

Results can also be exported visually this is done by printing the images to a .pdf file. It is possible to print either the fragmentation net on its own or combining the net with the background image. Results are shown in the two images below.
The difference between the two images is the background image. Also the fines and ‘ignored blocks’ are displayed in black on the image above.

![Figure 33 Export of the fragmentation net and background image](image)

When the background image is exported as well, the fines and ignored blocks are displayed in white. This can be seen on the image above.

### 8.6. Demo images

The demo images were analyzed to see whether or not the software would work better on images taken on surface. It can be clearly seen that these pictures (see next page) were taken in more optimum conditions. The reason they are discussed in this thesis is to show the difference between an optimal image and an image taken underground. It proves that the edge detection algorithms can work, but the conditions need to be optimal.

In this research period, the images taken underground which are suitable for processing are not picked up well by WipFrag's edge detection algorithms. Wipfrag provided a series of 6 test images as well. A selection of 3 of these examples is shown in this section.

#### 8.6.1. Differences between demo-images and actual images.

There are many differences between the images obtained from this research and the demo images. These are the most important differences:

- The demo images are not taken underground.
- Only 3 of the demo images contain blasted material (they are missing in this section, as they are also not processed correctly with the auto-EDP parameters).
- The material on the demo images is more uniform than Lisheen’s blasted material.
- The demo images are photographed from above and therefore contain only one side of the fragment.
- All fragments on the demo images are on a flat surface and hence use only one scale.
• The 3 different demo images, which can be seen below, are processed close to perfection with the auto generated net of fragments.

The scale (in the bottom right corner) is 65mm for the first 2 images and 35mm for the 3rd image.

All of the 3 demo images are processed fairly correct, only minor manual modifications had to be made, such as drawing several extra contours and removing unnecessary lines.

The charts of the 3 demo images can be found in Appendix G – Demo Charts (Figure 63 up to Figure 68).

Figure 34 Three different demo images containing clear crushed gravel, natural pea gravel and prills.

Figure 35 The corresponding screenshots after processing in WipFrag.

Figure 36 Fragment net of the 3 demo images, after minor manual editing.
8.7. Galmoy stockpile pictures

A series of 10 pictures of the Galmoy ore stockpile have been processed. These pictures were all taken on the same day at random locations near the stockpiles. The entire data set can be found in Appendix I – Data collection including processed images (Figure 100 up to Figure 119). These pictures were processed to see if the software is able to process surface images on site without a significant amount of manual editing. These pictures were processed later than the demo images. It is because of the demo images that the Galmoy surface stockpile images were measured, the demo images showed that these demo images can be processed correctly. It was then attempted to simulate conditions similar to the demo images, this would make it easier to process stockpile images.

By analyzing the stockpile in broad daylight some of the project limitations have been reduced, such as the confined area, and the possibility to blind other drivers of heavy machinery while working with strong underground lighting. It also improved the available working space, because the stockpile area was a more passive working area. The main objective of these stockpile images was to evaluate if WipFrag or Split-Desktop performs better with surface images than it does with images taken underground. The information acquired from these tests was used to compare the actual vs predicted fragmentation.

The image to the right is zoomed in. These pictures are first resized and then modified to greyscale mode, this is beneficial to the image processing, because the delineations are more accurate.

![Figure 37 Images taken of the stockpiles, zoomed image to the right.](image)

![Figure 38 After manual editing in Split Desktop.](image)
At first sight the image above seems fairly accurate. This is because the conditions of the pictures which are taken on surface are closer to the optimum conditions. Split Desktop tends to fill the relatively dark (black) areas with blue lines. Whereas WipFrag enlarges the surrounding particle and averages the darker area over the surrounding particles. It is not safe to walk up the slope of the stockpile and hence limits the possibility of taking photos of the entire stockpile.

8.8. Software limits and project limits

The conditions for taking photos underground are far from optimal. However, the software can be used but there are limitations especially when combined with taking photos in an underground mine. These limits are listed below:

1. Illumination
2. Safety
3. Zoom
4. Muckpile segregation
5. Time
6. Edge detection parameters

8.8.1. Illumination

Even though additional lighting has been used to take photographs underground it will always be one of the most important parameters and limits for similar projects underground. Because if the amount of illumination is not sufficient, images cannot be easily processed.

Figure 39 A clear image of ore being blasted. Examples of limits can be seen in the picture.
The dashed red lines in the figure above indicate examples of pathways of sliding rocks which are now covered by fines. The orange lines indicate the roof and sidewalls, the area between the red and orange solid lines is seen as either the roof, the sidewall or it is simply too dark to analyse. The area between the orange and green lines covers either the floor or is covered up with fines and dark spots which also cannot be analysed. The area surrounded by the green lines is what remains and is suitable for processing, however also in this part areas can be covered up with fines. The photograph is taken in Main Zone South panel 8 stope 15 and covers nearly the full width of the stope.

8.8.2. Safety
Pictures of muckpiles must be carefully taken as one has to approach the muckpiles to place the scale bars on the muckpile. After the scale bars are placed on the muckpile one can take a photograph at a safe distance from the muckpile. The amount of safety increases when a picture is taken further from the face, but it will also result in less fines being detected by the software.

8.8.3. Zoom
The maximum amount of zoom in WipFrag is 800%, which is relatively low for images taken with high quality cameras. Because larger images take more time to process, images are often rescaled. This reduces the resolution as pixels are interpolated. But it makes it easier and less time consuming to analyse. Another aspect of zooming relates back to the camera used for the data gathering. All images should only contain the blasted material without any other artificial items (except scale bars), also the roof, floor and sidewall should not be photographed. It can happen that the combination of lens and camera and safety distance is not ideal. Because the distance would be too small to safely take pictures without the roof, floor or sidewall. Pictures should then be taken from a safer distance despite the fact that the roof, floor or sidewalls are present on the image.

8.8.4. Muckpile segregation
Larger blocks tend to roll to the front of a muckpile and fines may cover areas where rocks are sliding down the muckpiles. Photos from close by will most likely miss the bigger boulders at the bottom, or pictures from a distance far away will most likely miss the amount of fines (see Figure 39) covering a typical muckpile.

8.8.5. Time
The time is maybe the most important constraint of all for both the software and the data gathering. Lisheen’s mining operation is nearly a 24h operation in contrast to this research, which is only performed during one shift a day (5 days per week). This means that choices have to be made from day to day to see what kind of data can be obtained. It can sometimes also be a problem to gain access to certain areas of the mine as research is never supposed to interfere or delay with production operations. But also when using the software the manual editing process is very time consuming because it can take up to 5 hours (sometimes more) to process a single image, whereas auto generated fragmentation nets are generated within a minute, but they were inaccurate for all the images analysed.
8.8.6. Edge detection parameters

These parameters can be seen in the two images below and their description can be found in section 8.2 ‘Generate and edit a net of fragments’.

These parameters are the base of WipFrag’s edge detection algorithms. It is these algorithms that try to auto detect the individual fragments. The following different stages (see image below) of input are required for WipFrag to generate a granulation curve. Each of the 4 different stages is a limit of its final granulation curve and histogram.

8.8.7. Relationship between project limits

All of the discussed limits have a major influence on the safety aspect and the edge detection parameters. The type of camera and lens together with the type of illumination determine the distance from where the photo can be taken safely. A low quality camera and a lack of illumination will result in problems with the EDP. Because of the segregation in muckpiles one has to stay at a safe distance otherwise it is possible that sliding rocks can either hit the equipment or collide with the person taking the photographs. Time is a very important operational limit. Often there is only a small amount of time available for data gathering. And within this timeslot every action (such as
placing scale bars, and moving the tripods with lights and cameras) has to be performed with sufficient care in a safe way. The amount of time required for data gathering is also related to the quality of the lights and camera. It will take more time to set up the equipment with professional equipment compared to taking images with an ordinary compact camera combined with a mine cap lamp or torch. However the slower method gives considerable better results as the quality of illumination is much better with a professional set-up. This can be seen in Appendix H – Lights Comparison.

Segregation will always take place and therefore it has no direct connection between the other limits (time, camera and illumination).

![Figure 42 Relationships between project limits](image)

### 8.9. Comparison between WipFrag and Split Desktop

Both WipFrag and Split Desktop are fragmentation analysis programs, respectively made by WipWare and Split Engineering. A couple of images have been analysed in both programs in order to evaluate the differences in quality and user friendliness of the programs.

An important difference can be seen in the way the manual editing has to be done. WipFrag has better tools available such as the lasso delete, which enables the user to draw a shape and delete all the points and lines within the lasso. It is also possible to select lasso delete and outline, it will then not only clear the lines in the lasso but it will also create an outline equal to the size of the lasso. This option is quicker than a traditional eraser.

Split Desktop has the advantage that when one is manually editing the particles it automatically shows the boundaries of the particle, they become highlighted. This is useful because in WipFrag one has to manually check if the particle is fully closed, by right clicking on the particle. If a particle is not fully closed in Split Desktop, large yellow highlighted lines appear and they would often occupy the majority of the screen. This makes it easy to spot open ended particles.

While comparing the first automated generated net of fragments in both programs, Split Desktop seems to have more accurate algorithms. Split Desktop’s delineation is a better representation of the actual fragmentation than WipFrag. An example can be seen in Appendix J – Comparing WipFrag and Split Desktop. However both programs need a substantial amount of additional manual editing in order to fully analysis the image.
Another difference is that WipFrag measures the equivalent spherical diameter whereas Split Desktop measures the normal diameter. Both companies are not completely open about the way they calculate these values. This is most likely done to protect their intellectual property. It is possible that these two ‘different’ diameters are in fact calculated the same way. One would have to understand the mathematics behind the calculations and probability functions in both programs in order to verify whether these parameters are in fact in the same.

To calculate the diameter of an equivalent sphere one must know the volume of a particle. Particles in WipFrag are assigned a volume via a statistical probability function. More information about these principles is described in section 7.3.1. Image analysis theory.

The volume of a sphere is calculated via the following formula: \( V = \frac{4}{3} \pi d^3 \), where \( V \) = the volume of the sphere and \( d \) = the diameter of the sphere. Rewriting this formula results in:

\[
D = \frac{3 \sqrt[3]{6V}}{\pi},
\]

this formula is then used to determine the equivalent spherical diameter of a particle. These formulas are used in the unfolding process. It works the same way for a formula in 2 dimensions \( D = 2 \sqrt{\frac{A}{\pi}} \) and \( A = \frac{\pi d^2}{4} \).

In Split Desktop it is not possible to place the histogram and its associated granulation curve in the same image. However, both can be copied separately into any other document. Split Desktop has the option to add reference curves to a graph. This is a useful option when comparing datasets against targets. By generating two different curves it is possible to have a more accurate view on both of the individual graphs.

Another important difference is that WipFrag gives more data output. Compared to Split Desktop WipFrag gives the following extra parameters (based on the default settings):

- \( D_1, D_{2s}, D_{25}, D_{75}, D_{95}, \) and \( D_{99} \)
- for definitions
- \( \text{min, mean, mode, and standard deviation, sphericity} \)
- \( \text{amount of particles} \)

WipFrag does not give a value for \( D_{40} \) and \( D_{60} \). However, Split Desktop allows you to retrieve every single \( D_x \)-value, simply by entering it into a specific field in the results options menu.
8.9.1. Differences in output

The differences in output can be clearly seen on the images below. Split Desktop needs two images whereas WipFrag merges the two images together and has the option to hide the histogram.

The Split Desktop image with the histogram differs from WipFrag’s histogram but that is also because the y-axis is limited to only 50% passing. The table with corresponding data out of Split Desktop can be found in Appendix J – Comparing WipFrag and Split Desktop. This is another difference between the two programs. WipFrag adds the most important data to its image and in Split Desktop it is exported separately.
9. Results

The image below is the final merged result from stope 15 of panel 8 in Main Zone South, the images are taken at the 15th of May and processing was completed at the 21st of May 2012. The merged analysis consists of 5 images that cover the full width of the bottom part of the muckpile. Results and other images of this data set can be found in Appendix I – Data collection including processed images (Figure 74 up to Figure 89).

The image below is the final merged result from stope 15 of panel 8 in Main Zone South, the images are taken at the 16th of May and processing was completed at the 28th of May 2012. The merged analysis consists of 3 images. All other images associated with this data set can be found in Appendix I – Data collection including processed images (Figure 90 up to Figure 99).

![Figure 45 Merged Analysis of MS08S15 15-05-12.](image)

![Figure 46 Merged analysis of MS08S15 16-05-12.](image)
One can clearly see the difference in size distribution when looking at the first fresh blast (Figure 45) and the day after, when the front of the muckpile is removed Figure 46. The difference in $P_{80}$ can be as high as 130.8% ($P_{80}$ in Figure 45 is 330mm and $P_{80}$ in Figure 46 is 143mm). This shows that there is a significant variation between the sizes in the same stope. This can be explained by taking in mind that the front of a blast will contain bigger lumps as it is not shaken up by the other explosives of the same blast and the ore in the first ring has not been (re)cracked yet by previous firings.

The following two figures are derived from images taken from the Galmoy stockpile after processing the images in Split Desktop. A total of 10 pictures were used for this dataset, the pictures and their processed output can be seen in Appendix I – Data collection including processed images (see Figure 100 up to Figure 119).

![Image 1](image1.png)  
*Figure 47 Merged analysis of 10 images of the Galmoy stockpile.*

![Image 2](image2.png)  
*Figure 48 Histogram of the Galmoy stockpile pictures.*
The two previous figures are derived from the following table.

### Table 5 Galmoy dataset first 5 pictures

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<td>99.64</td>
<td>91.67</td>
<td>116.42</td>
<td>111.25</td>
<td>88.04</td>
</tr>
<tr>
<td>P70</td>
<td>112.58</td>
<td>105.09</td>
<td>132.84</td>
<td>128.43</td>
<td>102.14</td>
</tr>
<tr>
<td>P80</td>
<td>127.94</td>
<td>120.53</td>
<td>152.03</td>
<td>150.88</td>
<td>119.34</td>
</tr>
<tr>
<td>P90</td>
<td>149.16</td>
<td>139.82</td>
<td>177.5</td>
<td>184.53</td>
<td>144.33</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>217.4</td>
<td>201.12</td>
<td>253.83</td>
<td>323.47</td>
<td>235.31</td>
</tr>
</tbody>
</table>

### Table 6 Galmoy dataset last 5 pictures

<table>
<thead>
<tr>
<th>% Passing</th>
<th>IMGP0358_bw</th>
<th>IMGP0361_bw</th>
<th>IMGP0387_bw</th>
<th>IMGP0362_bw</th>
<th>IMGP0371_bw</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10</td>
<td>37.94</td>
<td>25.7</td>
<td>22.69</td>
<td>39.04</td>
<td>25.92</td>
</tr>
<tr>
<td>P20</td>
<td>56.51</td>
<td>45.13</td>
<td>39.81</td>
<td>59.92</td>
<td>44.43</td>
</tr>
<tr>
<td>P30</td>
<td>71.42</td>
<td>62.73</td>
<td>55.3</td>
<td>77.03</td>
<td>60.87</td>
</tr>
<tr>
<td>P40</td>
<td>83.76</td>
<td>79.8</td>
<td>70.23</td>
<td>91.68</td>
<td>76.63</td>
</tr>
<tr>
<td>P50</td>
<td>95.17</td>
<td>95.14</td>
<td>83.75</td>
<td>105.12</td>
<td>90.68</td>
</tr>
<tr>
<td>P60</td>
<td>106.85</td>
<td>110</td>
<td>96.81</td>
<td>118.72</td>
<td>104.79</td>
</tr>
<tr>
<td>P70</td>
<td>119.79</td>
<td>126.38</td>
<td>110.69</td>
<td>133.82</td>
<td>119.58</td>
</tr>
<tr>
<td>P80</td>
<td>135.85</td>
<td>145.97</td>
<td>126.76</td>
<td>152.15</td>
<td>137.19</td>
</tr>
<tr>
<td>P90</td>
<td>158.42</td>
<td>174.59</td>
<td>150.66</td>
<td>179.06</td>
<td>159.93</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>252.37</td>
<td>316.66</td>
<td>258.58</td>
<td>274.11</td>
<td>237.09</td>
</tr>
</tbody>
</table>

### Table 7 Merged Results of Galmoy stockpile data (10 pictures)

<table>
<thead>
<tr>
<th>% Passing</th>
<th>Combined Size[mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10</td>
<td>27.59</td>
</tr>
<tr>
<td>P20</td>
<td>46.34</td>
</tr>
<tr>
<td>P30</td>
<td>62.6</td>
</tr>
<tr>
<td>P40</td>
<td>77.36</td>
</tr>
<tr>
<td>P50</td>
<td>90.79</td>
</tr>
<tr>
<td>P60</td>
<td>104.29</td>
</tr>
<tr>
<td>P70</td>
<td>119.1</td>
</tr>
<tr>
<td>P80</td>
<td>137.03</td>
</tr>
<tr>
<td>P90</td>
<td>163.14</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>310.52</td>
</tr>
</tbody>
</table>

---

T.A. Waterman 2014
9.1. Comparing results from WipFrag and Split Desktop

The next three data sets are derived from images taken at Lisheen. The first two tables are related to pictures of the Galmoy Stockpile. The stockpile stores crushed material which should be crushed to a size of 150mm. The $P_{80}$ of the stockpile images should be lower than 150mm.

A total of 10 images have been analyzed in Split Desktop their averaged $P_{80}$ was 137mm. This corresponds to the expectations of a value slightly lower than 150mm. However, when comparing the two programs with each other large differences can be seen in the differences between the $P_{xx}$ values. These differences are quantified in Table 15 Summary of the comparison between WipFrag and Split Desktop. It shows that the $P_{80}$ for the same images is approx. 50mm and 15mm different for respectively IMGP0390 and IMGP0371. That is respectively 36.9% and 11% difference compared to the averaged $P_{80}$ which was measured in Split Desktop over a total of 10 images.

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IMGP0390_bw</td>
</tr>
<tr>
<td>% Passing</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>P10</td>
<td>30.16</td>
</tr>
<tr>
<td>P20</td>
<td>50.89</td>
</tr>
<tr>
<td>P30</td>
<td>69.08</td>
</tr>
<tr>
<td>P50</td>
<td>101.45</td>
</tr>
<tr>
<td>P70</td>
<td>132.84</td>
</tr>
<tr>
<td>P80</td>
<td>152.03</td>
</tr>
<tr>
<td>P90</td>
<td>177.5</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>253.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IMGP0371_bw</td>
</tr>
<tr>
<td>% Passing</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>P10</td>
<td>25.92</td>
</tr>
<tr>
<td>P20</td>
<td>44.43</td>
</tr>
<tr>
<td>P30</td>
<td>60.87</td>
</tr>
<tr>
<td>P50</td>
<td>90.68</td>
</tr>
<tr>
<td>P70</td>
<td>119.58</td>
</tr>
<tr>
<td>P80</td>
<td>137.19</td>
</tr>
<tr>
<td>P90</td>
<td>159.93</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>237.09</td>
</tr>
</tbody>
</table>

These differences occur because of the following reasons:

- Different algorithms
- Scale is not exactly the same
- Different tilt and scale correction in the two programs
- Different manual editing corrections
- Split Desktop takes edge bordering particles in account
- Equivalent spherical diameter vs. diameter
Based on the assumption that the P80 value should be close to 150mm it is likely that the values from Split Desktop are more accurate for measuring the true diameter. These differences are discussed in more detail at the end of this section. The 3rd image was taken underground and here the differences are present as well. The order of the expected P80 value was not clear but it was likely to have a P80 higher than 150mm. Otherwise there would be little to no need for crushing the material. Image 05 can be found on page XXXVIII in Appendix I – Data collection including processed images.

Table 10 IMGP005 in WipFrag and Split Desktop

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>% Passing</td>
</tr>
<tr>
<td>P10</td>
<td>44.33</td>
</tr>
<tr>
<td></td>
<td>P10</td>
</tr>
<tr>
<td>P20</td>
<td>75.72</td>
</tr>
<tr>
<td></td>
<td>P20</td>
</tr>
<tr>
<td>P30</td>
<td>103.72</td>
</tr>
<tr>
<td></td>
<td>P30</td>
</tr>
<tr>
<td>P50</td>
<td>153.73</td>
</tr>
<tr>
<td></td>
<td>P50</td>
</tr>
<tr>
<td>P70</td>
<td>206.03</td>
</tr>
<tr>
<td></td>
<td>P70</td>
</tr>
<tr>
<td>P80</td>
<td>240.00</td>
</tr>
<tr>
<td></td>
<td>P80</td>
</tr>
<tr>
<td>P90</td>
<td>291.91</td>
</tr>
<tr>
<td></td>
<td>P90</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>457.14</td>
</tr>
<tr>
<td></td>
<td>490.50</td>
</tr>
</tbody>
</table>

The P80 is approx. 70mm larger in WipFrag, which is 129% larger than its value in Split Desktop. This makes the customer realize that it is important to know what you are measuring, because the difference between the equivalent spherical diameter and ‘normal’ diameter starts to play a more important role.

The data of the next three tables is derived from the three demo images which can be seen in Figure 34.

Table 11 Natural Pea Gravel compared in Split Desktop and WipFrag

<table>
<thead>
<tr>
<th>Split</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural pea gravel</td>
</tr>
<tr>
<td>% Passing</td>
<td>Size [mm]</td>
</tr>
<tr>
<td>P10</td>
<td>2.83</td>
</tr>
<tr>
<td>P20</td>
<td>3.86</td>
</tr>
<tr>
<td>P30</td>
<td>4.63</td>
</tr>
<tr>
<td>P50</td>
<td>6.39</td>
</tr>
<tr>
<td>P70</td>
<td>8.39</td>
</tr>
<tr>
<td>P80</td>
<td>9.92</td>
</tr>
<tr>
<td>P90</td>
<td>12.49</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>21.57</td>
</tr>
</tbody>
</table>
Table 12 Clear Crushed Gravel compared in Split Desktop and WipFrag

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>% Passing</td>
</tr>
<tr>
<td>Size[mm]</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>P10</td>
<td>1.86</td>
</tr>
<tr>
<td>P20</td>
<td>2.69</td>
</tr>
<tr>
<td>P30</td>
<td>3.33</td>
</tr>
<tr>
<td>P50</td>
<td>4.65</td>
</tr>
<tr>
<td>P70</td>
<td>6.05</td>
</tr>
<tr>
<td>P80</td>
<td>6.89</td>
</tr>
<tr>
<td>P90</td>
<td>8.03</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>13.68</td>
</tr>
</tbody>
</table>

Table 13 Prills in WipFrag and Split Desktop

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>WipFrag</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>% Passing</td>
</tr>
<tr>
<td>Size[mm]</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>P10</td>
<td>0.43</td>
</tr>
<tr>
<td>P20</td>
<td>0.69</td>
</tr>
<tr>
<td>P30</td>
<td>0.91</td>
</tr>
<tr>
<td>P50</td>
<td>1.28</td>
</tr>
<tr>
<td>P70</td>
<td>1.61</td>
</tr>
<tr>
<td>P80</td>
<td>1.79</td>
</tr>
<tr>
<td>P90</td>
<td>2.03</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>2.97</td>
</tr>
</tbody>
</table>

It can be seen from the table that the relative difference between the two programs for prills is even larger than in the previous images. This is most likely related to the scale on the image and to the difference in algorithms. All of the values in Table 15 are above zero. This means that WipFrag gives higher values than Split Desktop for all of the images analyzed in Table 15. One of the most important reasons is the difference in algorithms. An example is showed in the image below.

Figure 49 WipFrag to the left and Split Desktop to the right.
In both programs the same image (prills.jpg) is loaded and the delineation is done automatically and afterwards the images were processed manually to increase the accuracy. The colored rectangles match with both images. It can be seen in the image to the left (WipFrag) that the darker areas (e.g. voids or shades) are averaged over the surrounding fragments, whereas in Split Desktop these voids or shades are filled with darker lines. This sometimes leads to the fact that some darker fragments are incorrectly seen as voids or shades. An example of this can be seen in the green square (see Figure 49). This contributes to the fact that all values measured in WipFrag were higher than Split Desktop’s values.

WipFrag applies this concept for every fragment. However the relative error is bigger when the fragments are smaller, because then the area of a void or shade, which is added to a fragment, takes up relatively more area. This contributes to the fact that the values in WipFrag are nearly 2.5 times higher than in Split Desktop for prills (see Table 15).

Another important factor that contributes to the difference between the two programs is that WipFrag does not account for fragments which are touching the edge of the image (those fragments are ignored as discussed in paragraph 8.4 WipFrag example results. Split Desktop sees an ‘edge touching’ fragment the same way as any other partially overlapped fragment and therefore does use the edge touching particles for their size distribution analysis.

Both programs allow the user to drag a line across the scale bar (or any other scale item) the exact length could be different in the two programs when manually drawing a line. Another difference could be the way the programs account for the angle an in an image when multiple scale items are used.

Because manual editing is carried out on both images it is likely that there will be small differences between the two generated nets. This is because the amount of editing in both images does not have to be the same. It can happen that both programs process certain parts of the same image better or worse than the other one.

The difference between the diameter of an equivalent sphere and normal diameter is not clearly stated by WipFrag. If it was, it was probably easier to relate the two different diameters with each other. When asked to clarify some of the calculations the following answers were received:

WipFrag: “a great chef teases with the ingredients but never reveals the recipe” (Watson, 2012b)

Split Desktop: “Can’t say that the current software is entirely exact to these papers, as things have changed and been edited over the years” (Norton, 2012). This is after receiving papers describing the framework of Split Desktop’s program. The papers were interesting, but did not provide sufficient detail to analyze the mathematics behind the program.
9.2. Relative differences between WipFrag and Split Desktop

The following data is derived from the output of Split Desktop and WipFrag. The $p_{xx}$ values are compared with each other.

An example calculation is included below the table:

Table 14 Comparison of WipFrag and Split Desktop

<table>
<thead>
<tr>
<th>% Passing</th>
<th>Split Desktop</th>
<th>WipFrag</th>
<th>Difference in mm</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10</td>
<td>1.86</td>
<td>2.20</td>
<td></td>
<td>118.17%</td>
</tr>
<tr>
<td>P20</td>
<td>2.69</td>
<td>2.39</td>
<td></td>
<td>88.92%</td>
</tr>
<tr>
<td>P30</td>
<td>3.33</td>
<td>2.63</td>
<td></td>
<td>79.01%</td>
</tr>
<tr>
<td>P50</td>
<td>4.65</td>
<td>2.72</td>
<td></td>
<td>58.49%</td>
</tr>
<tr>
<td>P70</td>
<td>6.05</td>
<td>2.61</td>
<td></td>
<td>43.06%</td>
</tr>
<tr>
<td>P80</td>
<td>6.89</td>
<td>2.45</td>
<td></td>
<td>35.52%</td>
</tr>
<tr>
<td>P90</td>
<td>8.03</td>
<td>2.05</td>
<td></td>
<td>25.53%</td>
</tr>
<tr>
<td>Topsize (99.95%)</td>
<td>13.68</td>
<td>0.52</td>
<td></td>
<td>3.80%</td>
</tr>
</tbody>
</table>

Column 2 and 3 of the table above show the $p_{xx}$ values in both programs. The difference between these 2 values is displayed in the 4th column. The 5th column shows the difference in percentages compared to the first value derived from Split Desktop (example: $(2.20/1.86)*100\% = 118.17\%$).

A total of 6 images have been compared of which 3 were demo images (provided by WipFrag) and the other 3 images were taken at Lisheen.

Table 15 Summary of the comparison between WipFrag and Split Desktop.

<table>
<thead>
<tr>
<th>name</th>
<th>Clear Crushed Gravel</th>
<th>Natural Pea Gravel</th>
<th>Prills</th>
<th>image 05</th>
<th>imgp0371</th>
<th>imgp0390</th>
</tr>
</thead>
<tbody>
<tr>
<td>type:</td>
<td>Demo images</td>
<td>underground</td>
<td>Stockpile</td>
<td>Stockpile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10</td>
<td>118.17%</td>
<td>93.39%</td>
<td>251.86%</td>
<td>29.89%</td>
<td>72.92%</td>
<td>71.49%</td>
</tr>
<tr>
<td>P20</td>
<td>88.92%</td>
<td>74.74%</td>
<td>163.33%</td>
<td>22.48%</td>
<td>36.51%</td>
<td>49.77%</td>
</tr>
<tr>
<td>P30</td>
<td>79.01%</td>
<td>60.60%</td>
<td>99.67%</td>
<td>16.27%</td>
<td>23.82%</td>
<td>33.05%</td>
</tr>
<tr>
<td>P50</td>
<td>58.49%</td>
<td>37.75%</td>
<td>90.86%</td>
<td>18.39%</td>
<td>14.14%</td>
<td>19.17%</td>
</tr>
<tr>
<td>P70</td>
<td>43.06%</td>
<td>23.60%</td>
<td>74.66%</td>
<td>28.04%</td>
<td>8.63%</td>
<td>15.85%</td>
</tr>
<tr>
<td>P80</td>
<td>35.52%</td>
<td>20.77%</td>
<td>67.37%</td>
<td>29.50%</td>
<td>11.01%</td>
<td>33.26%</td>
</tr>
<tr>
<td>P90</td>
<td>25.53%</td>
<td>15.53%</td>
<td>56.70%</td>
<td>38.88%</td>
<td>41.44%</td>
<td>41.58%</td>
</tr>
<tr>
<td>P99</td>
<td>3.80%</td>
<td>6.58%</td>
<td>38.55%</td>
<td>7.30%</td>
<td>23.41%</td>
<td>16.26%</td>
</tr>
</tbody>
</table>

These figures are displayed in charts on the next page.
A total of 25 images have been analysed and 6 of those have been analyzed in both programs.

Two different trends can be seen in the two different charts. The first graph shows a decreasing trend towards the $P_{99}$. The 2\textsuperscript{nd} graph shows a general dip for all images up to the $P_{50} - P_{70}$ and then an increase towards the $P_{90}$ and then a sudden drop again.

It is likely that the difference in the trend for the demo images is caused by the differences in scale. One can clearly see that the difference between the natural pea gravel and clear crushed gravel image is relatively small they are both photographed on the same scale (65mm scale bar), the prills scale bar was 35mm. This would suggest that the error is larger when the scale bar gets smaller. The second dataset of Lisheen-images does not completely justify this as the difference for the demo images starts to become smaller than the Lisheen-images from the $P_{70}$ onwards (see Table 15). This means that the scale bar cannot be the only important parameter causing this trend. Other
differences such as the angle of photographing, uniformity, amount of scale bars in the image must be of influence as well. However, more images should be compared in both programs in order to fully justify this statement. The data, images and charts can be found in Appendix J – Comparing WipFrag and Split Desktop (See Figure 120 up to Figure 129 and Table 38 & Table 39).
10. **Accuracy Analysis**

To determine the reliability of WipFrag an accuracy analysis needs to be performed. Accuracy is defined by the difference between the calculated and the true value. There are various options to determine the accuracy of an optical image analysis program.

- Compare to sieving results
- Calibration of software
- Empirical methods.

In this case, sieving the rock samples wouldn’t be a realistic option, as it is time consuming and the costs for the sieving analysis wouldn’t be covered in the budget. It must be noted that traditional sieving methods and optical image analysis both measure two different aspects of the same fragment. (See Section 7.4.2 Errors related to sample presentation)

WipFrag already has a range of calibrations loaded into the program. In most cases optical image analysis programs use the Rosin-Ramler curve for calibration purposes (WipWare Inc., accessed Feb. 2014). The Rosin-Ramler equation is the following:

\[ y = 1 - e^{-\left(\frac{x}{x_c}\right)^n} \]

Where:
- \( y \) = cumulative percent passing.
- \( x \) = particle size.
- \( x_c \) = is the characteristic size passing, which is at 63.2%.
- \( n \) = is a parameter describing the spread of the distribution.

The formula to calibrate the Rosin-Ramler equation with is:

\[ y = 1 - e^{-\left(\frac{x}{x_c_{\text{adjust}}}\right)^{n_{\text{adjust}}}n_{\text{adjust}}} \]

Where:
- \( x_{c\text{,adjust}} \) = a calibration factor.
- \( n_{\text{adjust}} \) = a calibration factor.

Calibration consists of a few steps (WipWare Inc., accessed Feb. 2014):

1. Take at least 10 pictures that will be analyzed with WipFrag from the same location (different sample each time).
2. Process these images in WipFrag
3. Merge the results, print the distribution.
4. Screen the rock sample and plot the cumulative weight percent distribution with the same axis as on the WipFrag chart.
5. Overlay the two graphs and note the differences.
6. Edit the calibration file, with different parameters \( n_{\text{adjust}} \) and \( x_{c\text{,adjust}} \)
7. Repeat until the differences between the two graphs are minimized.

WipFrag has already some of the different spreads of the distributions loaded in such as: \( n = 0.5, \ 0.75, \ 1, \ 1.25, \ 1.5, \ 2.0 \) and \( 3.0 \). In this thesis the \( n \) values for the fragmentation analysis, were 2.05
and 2.09 these values are close to 2.0 therefore it seems reasonable to use the pre-determined value of 2.0 for non-calibrated analysis. Combine this with the fact that to execute a reasonable calibration the sample still had to be screened (step 4). Sieving the original samples was not an option for this project.

This leaves the empirical method as the last option to determine the accuracy of WipFrag. The idea is to analyze objects that are of a known size and are not likely to deviate from the known size. With this idea, the goal is to gather information about the differences between the measured size and the true size. It raises the question which object is suitable for this analysis. A few objects were suggested such as marbles and coins. Comparing these 2 objects gave the following results:

**Table 16 Marbles vs. Coins**

<table>
<thead>
<tr>
<th>Type</th>
<th>Marbles</th>
<th>Coins (EURO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>1.</td>
<td>Small, easy to transport</td>
<td>Harder to photograph from above</td>
</tr>
<tr>
<td>2.</td>
<td>Low costs to obtain normal marble sizes</td>
<td>Useless after research</td>
</tr>
<tr>
<td>3.</td>
<td>Hard to recognize automatically</td>
<td>Differences in sizes ideal for different datasets</td>
</tr>
<tr>
<td>4.</td>
<td>Breaks or erodes easier</td>
<td>Remains shape and value.</td>
</tr>
</tbody>
</table>

The euro coins were selected for this accuracy analysis. There are 8 different coins, all varying in size (European Union, 1998).

**Table 17 True Diameters of EURO-coins**

<table>
<thead>
<tr>
<th>Coin (EUR)</th>
<th>“True Diameter” (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>16.250</td>
</tr>
<tr>
<td>0.02</td>
<td>18.750</td>
</tr>
<tr>
<td>0.05</td>
<td>21.250</td>
</tr>
<tr>
<td>0.1</td>
<td>19.750</td>
</tr>
<tr>
<td>0.2</td>
<td>22.250</td>
</tr>
<tr>
<td>0.5</td>
<td>24.250</td>
</tr>
<tr>
<td>1</td>
<td>23.250</td>
</tr>
<tr>
<td>2</td>
<td>25.750</td>
</tr>
</tbody>
</table>

The following assumptions were made during this analysis:

1. All coins used in the analysis have the same diameter as when they were manufactured (no erosion or damage present in the sample data).
2. The original diameters provided by the manufacturer are correct (table above).
3. Every coin analyzed in WipFrag is the closest representation of the actual coin.

The 3rd assumption is needed to make clear that WipFrag has not made squares out of circles. All attempts closely represent the true shape (circular) of the coin that has been delineated.
A total of 1000 coins have been analyzed, each different coin (from 0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 euro is analyzed 125 times). The idea was to create an ideal situation for the analysis, so that the amount of errors can be reduced. This would result in a more accurate analysis (minimizing the difference between calculated WipFrag diameter and the “True Diameter”).

- All coins are positioned on either a head or tails side (no coin is sideways e.g. standing up)
- All coins in the picture are analyzed, also the ones bordering the edge of the image.
- All coins are totally visible, no overlapping coins.
- All coins are photographed from an orthogonal angle to the sample (from above).

These steps result in eliminating the following errors (See Section 7.4 Errors in size-distribution analysis methods).

1. Disintegration and fusion. (each individual coins consist of 1 fragment).
2. Wrong unfolding model (all coins can be seen as a 2D fragment).
3. No overlapping fragments (there is no overlap between coins in all images).
4. Sampling window (the entire range is present in the merged analysis).
5. Perspective error is minimized (photos taken from an orthogonal angle).
6. No segregation of material (all fragments are visible).

The results are obtained from WipFrag after completion of the image analysis, only the diameter of an equivalent sphere is noted down for each coin in the image. These diameters are stored in an Excel spreadsheet, within the spreadsheet the calculations are carried out. The results of these calculations are in the following section.

A total of 11 images has been used to gather the information about the diameters measured in WipFrag. This results in 8 different data sets, each with a sample size of 125 and one merged dataset with a sample size of 1000 (the table with the overview is displayed on the next page).
The original images, and results per image as calculated in WipFrag can be found in Appendix P - Accuracy Analysis Images. This appendix also contains the normal and cumulative distribution functions per group.

### Table 18 Overview of coins per image

<table>
<thead>
<tr>
<th>IMG_ID</th>
<th>IMG1</th>
<th>IMG2</th>
<th>IMG3</th>
<th>IMG4</th>
<th>IMG5</th>
<th>IMG6</th>
<th>IMG7</th>
<th>IMG8</th>
<th>IMG9</th>
<th>IMG10</th>
<th>IMG11</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coins/ID</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>SUM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMG_ID</td>
<td>648</td>
<td>650</td>
<td>655</td>
<td>661</td>
<td>664</td>
<td>666</td>
<td>820</td>
<td>821</td>
<td>822</td>
<td>823</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>10</td>
<td>14</td>
<td>28</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td>17</td>
<td>13</td>
<td>5</td>
<td>7</td>
<td>5</td>
<td>125</td>
</tr>
<tr>
<td>0.02</td>
<td>7</td>
<td>14</td>
<td>17</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>15</td>
<td>7</td>
<td>15</td>
<td>5</td>
<td>125</td>
</tr>
<tr>
<td>0.05</td>
<td>5</td>
<td>15</td>
<td>11</td>
<td>15</td>
<td>9</td>
<td>12</td>
<td>8</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>15</td>
<td>125</td>
</tr>
<tr>
<td>0.1</td>
<td>12</td>
<td>23</td>
<td>14</td>
<td>5</td>
<td>10</td>
<td>12</td>
<td>20</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td>0.2</td>
<td>16</td>
<td>16</td>
<td>6</td>
<td>15</td>
<td>15</td>
<td>14</td>
<td>4</td>
<td>15</td>
<td>8</td>
<td>10</td>
<td>6</td>
<td>125</td>
</tr>
<tr>
<td>0.5</td>
<td>4</td>
<td>11</td>
<td>17</td>
<td>20</td>
<td>20</td>
<td>13</td>
<td>5</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>11</td>
<td>125</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>8</td>
<td>11</td>
<td>13</td>
<td>17</td>
<td>12</td>
<td>17</td>
<td>7</td>
<td>25</td>
<td>6</td>
<td>7</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>9</td>
<td>10</td>
<td>14</td>
<td>14</td>
<td>12</td>
<td>19</td>
<td>15</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>SUM</td>
<td>58</td>
<td>105</td>
<td>110</td>
<td>97</td>
<td>92</td>
<td>97</td>
<td>105</td>
<td>100</td>
<td>87</td>
<td>70</td>
<td>79</td>
<td>1000</td>
</tr>
</tbody>
</table>

### 10.1. Accuracy Analysis Results

The following table is obtained by counting whether the value calculated in WipFrag is above or below the ‘true value’. In 1 case the value was exactly equal to the ‘true diameter’.

### Table 19 Over - and Under estimations per coin group

<table>
<thead>
<tr>
<th>Coins/ID</th>
<th>Over</th>
<th>Under</th>
<th>Exact</th>
<th>Coins/ID</th>
<th>Over</th>
<th>Under</th>
<th>Exact</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>36</td>
<td>88</td>
<td>1</td>
<td>0.01</td>
<td>29%</td>
<td>70%</td>
<td>1%</td>
</tr>
<tr>
<td>0.02</td>
<td>49</td>
<td>76</td>
<td>0.02</td>
<td>39%</td>
<td>61%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>48</td>
<td>77</td>
<td>0.05</td>
<td>38%</td>
<td>62%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>33</td>
<td>92</td>
<td>0.1</td>
<td>26%</td>
<td>74%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>50</td>
<td>75</td>
<td>0.2</td>
<td>40%</td>
<td>60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>56</td>
<td>69</td>
<td>0.5</td>
<td>45%</td>
<td>55%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>54</td>
<td>71</td>
<td>1</td>
<td>43%</td>
<td>57%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>75</td>
<td>2</td>
<td>40%</td>
<td>60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>323</td>
<td>623</td>
<td>1</td>
<td>Total</td>
<td>37.6%</td>
<td>62.3%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

The absolute average error is calculated with the following formula:

$$\text{Absolute Average Error} = \frac{\sum_{i=1}^{1000} | \text{Calculated WipFrag Diameter} - \text{True Diameter} | n \text{ True Diameter} \times 100\%}$$

The results of the entire dataset (n=1000) are:
Table 20 Minimum, Average and Maximum error of the entire dataset

<table>
<thead>
<tr>
<th>Type</th>
<th>Error:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.00%</td>
</tr>
<tr>
<td>Abs. Average</td>
<td>1.94%</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.43%</td>
</tr>
</tbody>
</table>

Specified for the 8 different coins it results in the following table:

Table 21 Absolute Average Error per coin group

<table>
<thead>
<tr>
<th>Coins</th>
<th>Absolute Average Difference</th>
<th>Error Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.333</td>
<td>1.99%</td>
</tr>
<tr>
<td>0.02</td>
<td>0.371</td>
<td>1.98%</td>
</tr>
<tr>
<td>0.05</td>
<td>0.512</td>
<td>2.41%</td>
</tr>
<tr>
<td>0.1</td>
<td>0.378</td>
<td>1.91%</td>
</tr>
<tr>
<td>0.2</td>
<td>0.367</td>
<td>1.65%</td>
</tr>
<tr>
<td>0.5</td>
<td>0.423</td>
<td>1.74%</td>
</tr>
<tr>
<td>1</td>
<td>0.418</td>
<td>1.80%</td>
</tr>
<tr>
<td>2</td>
<td>0.511</td>
<td>1.98%</td>
</tr>
</tbody>
</table>

When taking into account that the program is over and underestimating at the same time, the average error when over and underestimation cancel each other out are presented in the table below. The results are calculated using the following formula for each different type of coin (n=125).

\[
\text{Average Error} = \frac{\sum_{i=1}^{n} (\text{Calculated WipFrag Diameter} - \text{True Diameter})}{\text{True Diameter}} \times 100\%
\]

Table 22 Average Error per different coin group

<table>
<thead>
<tr>
<th>Coins</th>
<th>Avg. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-1.05%</td>
</tr>
<tr>
<td>0.02</td>
<td>-0.73%</td>
</tr>
<tr>
<td>0.05</td>
<td>-0.85%</td>
</tr>
<tr>
<td>0.1</td>
<td>-1.09%</td>
</tr>
<tr>
<td>0.2</td>
<td>-0.45%</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.50%</td>
</tr>
<tr>
<td>1</td>
<td>-0.20%</td>
</tr>
<tr>
<td>2</td>
<td>-0.40%</td>
</tr>
<tr>
<td>Average</td>
<td>-0.66%</td>
</tr>
</tbody>
</table>

When looking at the averages of over- and underestimations the following results are obtained:

Table 23 Average Over - and Underestimations

<table>
<thead>
<tr>
<th>EUR</th>
<th>Avg. Over</th>
<th>Avg. Under</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>1.69%</td>
<td>2.22%</td>
</tr>
<tr>
<td>0.02</td>
<td>1.60%</td>
<td>2.23%</td>
</tr>
<tr>
<td>0.05</td>
<td>2.04%</td>
<td>2.64%</td>
</tr>
<tr>
<td>0.1</td>
<td>1.56%</td>
<td>2.04%</td>
</tr>
<tr>
<td>0.2</td>
<td>1.50%</td>
<td>1.75%</td>
</tr>
</tbody>
</table>
When looking at the outliers (the minima and maxima) the following results are obtained:

Table 24 Minima and Maxima per different coin group in %

<table>
<thead>
<tr>
<th>Coins</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.00%</td>
<td>7.46%</td>
</tr>
<tr>
<td>0.02</td>
<td>0.06%</td>
<td>8.43%</td>
</tr>
<tr>
<td>0.05</td>
<td>0.06%</td>
<td>7.76%</td>
</tr>
<tr>
<td>0.1</td>
<td>0.06%</td>
<td>6.21%</td>
</tr>
<tr>
<td>0.2</td>
<td>0.04%</td>
<td>5.69%</td>
</tr>
<tr>
<td>0.5</td>
<td>0.01%</td>
<td>6.45%</td>
</tr>
<tr>
<td>1</td>
<td>0.01%</td>
<td>7.60%</td>
</tr>
<tr>
<td>2</td>
<td>0.02%</td>
<td>4.79%</td>
</tr>
<tr>
<td>Average</td>
<td>0.03%</td>
<td>6.80%</td>
</tr>
</tbody>
</table>

After completion of these statistics the datasets were sorted with ascending values, the average, mean, and standard deviation were calculated. For all eight datasets the data was plotted with corresponding normal distribution and cumulative distribution curves, these can be found in Appendix P - Accuracy Analysis Images.

With this information, two tables were calculated, based on normal distribution functions and their corresponding cumulative distribution functions.

Table 25 Mean, Standard Deviation and True Diameter of coin-groups

<table>
<thead>
<tr>
<th>Coins</th>
<th>True Diameter</th>
<th>μ</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>16.250</td>
<td>16.077</td>
<td>0.379</td>
</tr>
<tr>
<td>0.02</td>
<td>18.750</td>
<td>18.656</td>
<td>0.468</td>
</tr>
<tr>
<td>0.05</td>
<td>21.250</td>
<td>21.104</td>
<td>0.622</td>
</tr>
<tr>
<td>0.1</td>
<td>19.750</td>
<td>19.565</td>
<td>0.441</td>
</tr>
<tr>
<td>0.2</td>
<td>22.250</td>
<td>22.153</td>
<td>0.457</td>
</tr>
<tr>
<td>0.5</td>
<td>24.250</td>
<td>24.153</td>
<td>0.533</td>
</tr>
<tr>
<td>1</td>
<td>23.250</td>
<td>23.146</td>
<td>0.533</td>
</tr>
<tr>
<td>2</td>
<td>25.750</td>
<td>25.567</td>
<td>0.601</td>
</tr>
</tbody>
</table>

The results are displayed in the two tables below, the first one distinguishes between over –and underestimations.

Table 26 Intervals of Cumulative distribution functions (1)

<table>
<thead>
<tr>
<th>Coins / error</th>
<th>[-5% - 0]</th>
<th>[-2.5% - 0]</th>
<th>[-1% - 0]</th>
<th>[0 – 1.5%]</th>
<th>[0 – 2.5%]</th>
<th>[0 – 5%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>63.06%</td>
<td>40.73%</td>
<td>16.51%</td>
<td>13.61%</td>
<td>26.08%</td>
<td>31.92%</td>
</tr>
<tr>
<td>0.02</td>
<td>54.38%</td>
<td>36.79%</td>
<td>15.88%</td>
<td>14.66%</td>
<td>30.58%</td>
<td>40.67%</td>
</tr>
<tr>
<td>0.05</td>
<td>52.24%</td>
<td>32.49%</td>
<td>13.53%</td>
<td>12.50%</td>
<td>26.91%</td>
<td>38.12%</td>
</tr>
<tr>
<td>0.1</td>
<td>62.83%</td>
<td>42.08%</td>
<td>17.39%</td>
<td>14.46%</td>
<td>27.55%</td>
<td>33.35%</td>
</tr>
<tr>
<td>0.2</td>
<td>57.11%</td>
<td>42.69%</td>
<td>19.24%</td>
<td>17.39%</td>
<td>33.96%</td>
<td>41.18%</td>
</tr>
</tbody>
</table>
The second table shows an equal area on both sides of the true diameter.

Table 27 Intervals of Cumulative distribution functions (2)

<table>
<thead>
<tr>
<th>Coins/error</th>
<th>[-5% + 5%]</th>
<th>[-2.5% + 2.5%]</th>
<th>[-1% + 1%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>94.98%</td>
<td>66.82%</td>
<td>30.12%</td>
</tr>
<tr>
<td>0.02</td>
<td>95.05%</td>
<td>67.38%</td>
<td>30.54%</td>
</tr>
<tr>
<td>0.05</td>
<td>90.36%</td>
<td>59.40%</td>
<td>26.03%</td>
</tr>
<tr>
<td>0.1</td>
<td>96.17%</td>
<td>69.63%</td>
<td>31.85%</td>
</tr>
<tr>
<td>0.2</td>
<td>98.29%</td>
<td>76.65%</td>
<td>36.63%</td>
</tr>
<tr>
<td>0.5</td>
<td>97.61%</td>
<td>74.14%</td>
<td>34.86%</td>
</tr>
<tr>
<td>1</td>
<td>96.76%</td>
<td>71.51%</td>
<td>33.12%</td>
</tr>
<tr>
<td>2</td>
<td>95.97%</td>
<td>69.38%</td>
<td>31.75%</td>
</tr>
</tbody>
</table>
10.2. Accuracy Analysis Conclusion

It can be seen from the accuracy analysis, that in 62.3% WipFrag is underestimating the fragments (coins). On average it underestimates with 2.09%. This means for fragmentation analysis, it is most likely that the actual diameter is higher than what WipFrag would calculate, based on this analysis. In 37.6% of the cases WipFrag has overestimated the true diameter, it overestimates on average with 1.70%.

Only one out of thousand coins calculated diameters in WipFrag (0.1% of all 1000 coins) was equal to its true diameter. The maximum difference found between the calculated diameter and the true diameter was 8.43% this was an underestimation. The maximum overestimation was 7.6%.

It seems reasonable to assume that the net effect of over and underestimations cancels each other out, with this assumption the average error over the entire dataset as low as − 0.66%. This is with a sample size of 1000 coins (8*125 coins).

If one assumes that an error is an error regardless whether it is positive or negative the “absolute average error” over the entire dataset is equal to 1.94%.

There were always going to be some errors related to this analysis, the question that remains is: “Are these errors of an acceptable standard?” As mentioned before, the possibility for errors has been reduced, by simulating an ideal situation. Selecting this approach results in knowing exactly what the program measures. Therefore the differences between measured and true diameters are minimized.

These acceptable standards are debatable, however based on this analysis; the level of confidence with 7 out of 8 datasets (0.01, 0.02, 0.1, 0.2, 0.5, 1, 2 euro coins) rounds up to 95% for errors varying from either -5% to +5%. This means that based on these normal distributions, there is a 95% chance that the calculated value lies within 5% (on each side) of the true diameter. In the other case (0.05 euro coin) there is a 90.3% chance that the calculated value lies within 5% (on each side) of the true diameter.
11. Summary, Analysis & Discussion

It has proven to be very difficult to define a single optimal level of fragmentation in an underground mine, this is due to various operating parameters such as:

- Feed variability
- Different ground conditions in different areas in the mine
- Different mining methods in the mine
- Accessibility during operations
- Time
- Differences in drill and blast designs

Determining fragmentation levels with optical image analysis in an underground mine, such as the Lisheen Mine, is made even more difficult because of illumination problems and confined spaces. These two aspects are less of an issue in an open pit or a quarry. The whole fragmentation analysis process is summarized in a flowchart that can be seen in Chapter 7: Introduction to Fragmentation Analysis.

If it were possible to keep conditions the same in a mine, it would mean that data sets could easily be compared with each other. This is important for optimizing the fragmentation, something that initially belonged to the scope of work. However, it turned out to be nearly impossible to monitor changes to drill and blast designs as manual processing of the images takes too much time (up to 5 hours per image in some cases). By the time a full data set would have been analyzed the ore would have been sold.

Manual processing within the software is an aspect that was underestimated at the start of the research. The idea behind this research was to take pictures at various locations throughout the mine and analyze these pictures with the software, which would then come up with a granulation curve. The next step would be to make changes to the original location of the pictures such as changes in different drill and blast areas or compare the different ground classes and their different fragmentation levels with each other. By then analyzing the differences in fragmentation (different granulation curves) it would give a first estimation of the specific influence of that parameter on fragmentation.

11.1. Observational summary

The process described above was thought to be a good approach. These are the reasons why changing the drill & blast parameters and taking data from various locations throughout the mine did not work for this specific project:

- The ore is too colorful. It means that (poly) metallic surfaces light up, even when the image is viewed in gray scale. The software delineates places where the contrast between colors is big. These are voids or shades but can also be differences in color related to mineral content. Some of the particles do not touch each other and therefore they create gaps, these gaps are dark on the pictures and generate troubles for the algorithms. Ideally all fragments should be touching each other.
• In underground mines especially with muckpile sampling it is nearly impossible to image the muckpile at the right angle, which is orthogonal to its surface. This is because the muckpile is already on a natural slope. And also the drift or road on which the muckpile lies is not completely flat either. Because the images are taken at an angle that is not optimal the results are therefore not optimal either (See Section 7.3.3 Image Requirements).

• Because images are often not taken orthogonal to its surface of interest fragments are being photographed with more than one side. Ideally this should be avoided, as only one side is required. Having multiple sides creates a bias as the same fragment is taken into account multiple times. (See Section 7.4.3 Errors related to the imaging process)

• The combination of time and confined spaces is a real issue in an operational mine. Production always continues; meaning it was only possible to do this research without intervening with production crews. This means the best opportunities of getting the desired data were within the shift-changing window. The set-up time of the entire equipment is about 30 minutes and so is the break down time, which leaves a maximum of 30-45 minutes for data gathering. It is possible, but every image must be right. Because there is literally no going back after the production operations start (See Section 8.8 Software and Project limits)

• Fines are another issue, they are natural but in quarries and open pit mines the natural airflow would blow them away. This issue can be resolved by washing the muckpile (a requirement anyway before the mucking operations start) however a washed muckpile is very shiny and therefore reflective, it results in a better picture than a face full of fines, but is still not picked up adequately by the software. (See Section 7.3.3 Image Requirements)

• Additional lighting it is an absolute necessity for photography underground. The constructed LED bars (see Figure 2) were decent tools but the bars weren’t perfect. The light source was still quite concentrated. This resulted in darker areas near the corners of the image. These areas were often too dark to process in WipFrag (See Section 8.8 Software and Project limits).

11.2. Discussion
It is too easy to say that fragmentation analysis does not work in underground mines, but it did not work fully with this approach. It could work when the conditions are more optimized. As discussed in section ‘7.6 Comparison’ there are more locations and systems available to take images, some of these are automated. These automated systems can be calibrated and use infrared light, which is less affected by dust and does not cause any nuisance for operators. Cameras are placed above tipping points and have a perfect (orthogonal) view on its area of interest. But there is no guarantee that these expensive systems will work at Lisheen without testing. Because the system is automated there would be no manual editing. All the algorithms will have to work without manual intervention.

Section 8.6 Demo images, shows that images can be processed with WipFrag with only minor manual editing. If it is possible to simulate similar conditions in the mine it will increase the chances for less manual editing.
Both WipFrag and Split Desktop have been used, although for the majority of this research WipFrag was used for the underground pictures and Split Desktop was used for the pictures taken on surface. The ideology behind the two programs is exactly the same; both software packages delineate rock fragments by applying statistical algorithms to accurately assess 3D volumes and fines from 2D images. These volumes are then unfolded so that they can be digitally sieved based on their diameter or equivalent spherical diameter. Based on the experience gained from this research, WipFrag seems to be a user-friendlier program (because the manual editing is made easier) and its output looks better for presentation (Personal Observation, 2012). On all analyzed images of the dataset Split Desktop seems to do a better delineation than WipFrag, and that is its main function, an example of this can be seen in Appendix J – Comparing WipFrag and Split Desktop.

Another difference between the two programs is that Split Desktop allows more functions to be displayed in the same figure. WipFrag only allows 4 functions in version (2.7.17) whereas Split Desktop can have up to 18 different graphs that are all displayed in another color.

Although the theoretical side of taking pictures near the tipping area appeared promising in the beginning, the practical side is much different. The amount of dust in the air and the other lights which are already present at the tipping bay make it nearly impossible to get a suitable photograph. Also the fact that the LED-arrays are blocking the truck drivers view does not help. This issue could be solved by using a more expensive infrared system (both lights and camera). Infrared LED arrays have a low power factor and are considered no more harmful to personnel than a couple of 100 watt light bulbs (Maerz & Palangio, 2004). Infrared type lighting has the ability to cut through dust particles suspended in the air. This results in highlighting the matter instead of illuminating the dust particle that it cuts through.

Metso’s simulation required the s.g. and the UCS of the rock in order to come up with an optimal process simulation. The s.g. and UCS can vary a lot per mining area. Each and every single variation (or combination) would result in a different optimal scenario for the size reduction in the crusher. It is therefore rather pointless to come up with only one desired fragmentation range. Because in reality, trucks throughout the entire mine tip their ore into the bin, it results in a mixed load.

Also the underground material handling energy costs were analyzed. The overview of the underground energy costs showed that these costs (max. 1.42%) were of minor influence compared to the total underground energy costs on an annual basis. But if they were of significant impact, it would still have been very hard to relate these costs to size reduction because the amount of undersize material is not known, so the costs only tell us something about the entire underground material throughput.

Due to production constraints, some data could not be gathered by only one person, as production continued around the clock. Any future projects should therefore consider using at least two researchers. This results in investigating the differences between both shifts.

When the fragmentation measurements are not automatically carried out one would ideally perform these muckpile analyses on surface, where the ore is being brought up by a truck. This truck would then slowly drive forward while tipping. The result is a well mixed relatively flat surface with ore. One would then need to access a teleporter’s basket so that pictures can be taken while being positioned above the muckpile. If this can be done for every first and last truckload and a truckload
in between the shifts one can gather a substantial amount of data. In practice, this would be unrealistic as the ore would need to be scooped up and driven down to the crusher afterwards, a time and manpower consuming operation. It also very unlikely that trucks are driving upwards on the decline while transporting material upwards, therefore this would only work in theory.

Based on the accuracy analysis that is performed in WipFrag, it is fair to call WipFrag accurate. In 7/8 datasets, there is a certainty of 95% (based on the normal distribution) that the calculated WipFrag diameter lies within -5% or +5% from its true diameter. It has shown that on average the net effect of over and underestimation cancels each other out (as low as -0.66% over 1000 fragments). In most cases, the editing of the images has lead to an underestimation of the true diameter. This should be taken into account when interpreting the results. Outliers can be as high as 8.43% and in 0.01% of all samples the data was found to be exactly equal to the ‘true diameter’.

It must be taken into account that this accuracy analysis was carried out by simulating conditions that are close to ideal conditions. In most cases, when image analysis programs are used, the conditions are not ideal. This makes it likely to assume that the program, will have larger errors when operating in non-idealized situations. The choice was made for this approach to minimize the amount of errors (6 possible errors have been eliminated, see chapter 10. Accuracy Analysis) that can be made, by doing so the program is allowed to perform in optimum conditions and can achieve the highest standards (less errors and more accurate).

Mines and quarries would prefer to use the best techniques and locations to set up the image analysis equipment. It would be harder and more expensive to set-up the best possible setting, but not impossible. Therefore it seems preferable to know what the best-case scenario is instead of the worst case scenario. As it is more likely that companies would use the best possible set-up instead of an average or worse set-up for image analysis.
12. Conclusions
Performing an optical fragmentation analysis in an underground mine was a hard and difficult challenge. The aim of this research was to apply an optical fragmentation analysis method at Lisheen in such a way that the fragmentation can be measured and optimized.

- Illumination was essential and is a critical parameter for underground optical fragmentation analysis.
- Processing time was a key constraint during this research.
- The tipping process of a truck cannot be photographed with the current equipment.
- Images could not be taken from a consistent orthogonal angle.
- Fines were natural but did block the surface of the area of interest.
- Data gathering was difficult due to operating hours.
- The human eye still did a better job in delineating particles than WipFrag and Split Desktop’s edge detection algorithms.
- An expensive automated system would not necessarily work either without testing.
- A simulation by the crusher’s manufacturer was too theoretical to compare it with the actual fragmentation.
- The underground material handling (crusher) energy costs cannot yet be related to fragmentation.
- In general, WipFrag gives a higher of the calculated equivalent spherical diameter than Split Desktop for particle size distributions.
- Based on the accuracy analysis WipFrag is accurate, but is most likely to underestimate. Over the entire analysis the net effect of over- and underestimation nearly (~ 0.66%) cancel each other out.
- Fragmentation in a mine cannot be fully monitored by only one person.

Fragmentation can be measured with an optical analysis method, but for optimizing fragmentation to the needs of the crusher it is required that more parameters are investigated in future studies, as there are too many variables that have an influence on the feed of the crusher.
13. **Recommendations**

The following recommendations can be made with respect to any possible further research relating to this thesis and its methodology.

**Technical Recommendations:**

- Perform a study which gives more insight in the amount of material (undersize) which bypasses the crusher.

- A direct comparison of both accuracy analysis's would give a clear result about both image analysis programs. It is therefore recommended that a license of Split Desktop is purchased, this would make it possible to perform the accuracy analysis on the same images as used in WipFrag.

**Operational Recommendations:**

- In order to increase the chances of success when monitoring fragmentation it should be done during both day and night shifts. This allows to monitor a full mining cycle and the influence of specific crews over time can be taken into account.

- The previous recommendation indicates that more than one person should be allocated to this research.

- Infrared equipment (camera + lights) should be used instead of the LED-arrays if one wants to successfully take photos of the tipping process.

**Scientific Recommendations:**

- Do not invest in a consultant or another future study about fragmentation as long as the first technical recommendation has not been carried out.

- For comparing WipFrag and Split Desktop with each other more images should be analyzed on both programs. This would make the research more statistically significant.

- This research has focussed around the application of an optical fragmentation analysis. All data is gathered post-blast. More research should be carried out on the pre-blast parameters (e.g. geological influences).
14. Literature Index

14.1 Personal Communication

Verbal:

*Personal Observations*
- Personal Observations at the Lisheen Mine, Ireland over 3 months: January – March 2012. Observations were made underground while being part of the production crews.

*Conversations*
- Morris, B. (2012, February 12). Lisheen Mine. First meeting considering this research project defining the areas of interest.

*E-mail:*

*LED Autolamps Europe LLP*

*Split Desktop*

*CallFrag, subsidiary of WipWare*
- Watson, H. (2012a, March 5). Email Conversation with CallFrag Director. United Kingdom.
- Watson, H. (2012b, June 26). Email conversation with CallFrag Director. United Kingdom.

14.2 Unpublished data & information accessed via Lisheen Mine

*Internal Presentations*

*Operating manual*
14.3 Literature References


**Websites:**


Appendix A – Lux- test results

### Table 28 Lux-test results

<table>
<thead>
<tr>
<th>Test #</th>
<th>m</th>
<th>4 LEDs</th>
<th>LED-test</th>
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<th>24V</th>
<th>1 LED</th>
<th>12V</th>
<th>24V</th>
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### Table 29 4-LED’s LUX test results

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<tr>
<th>m</th>
<th>4 LEDs</th>
<th>Avg. lux at 12 V</th>
<th>Avg. lux at 24 V</th>
<th>Average</th>
<th>Difference (Lux)</th>
<th>% at 12V</th>
<th>% at 24V</th>
<th>Avg. % of all.</th>
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<td>1</td>
<td>6836.7</td>
<td>7386.7</td>
<td>7111.7</td>
<td>550.0</td>
<td>8</td>
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<td>2</td>
<td>2860.0</td>
<td>2726.7</td>
<td>2793.3</td>
<td>133.3</td>
<td>4.7</td>
<td>4.9</td>
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<tr>
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<td>1336.7</td>
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<td>680.0</td>
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<td>688.3</td>
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### Table 30 1-LED LUX test results

<table>
<thead>
<tr>
<th>m</th>
<th>1 LED</th>
<th>Avg. lux at 12 V</th>
<th>Avg. lux at 24 V</th>
<th>Average</th>
<th>Difference (Lux)</th>
<th>% at 12V</th>
<th>% at 24V</th>
<th>Avg. % of all.</th>
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<td>4226.7</td>
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<td>1036.7</td>
<td>1093.0</td>
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</tbody>
</table>
Figure 52 1 LED-LUX Chart

Figure 53 4 LED-LUX Chart
Appendix B - Detailed company profile of Lisheen

This appendix gives a detailed company profile of the Lisheen Mine in Ireland

From the past to the present

The discovery of Lisheen goes back to April 1990 when Ivernia West and Chevron Mineral Corporation of Ireland (CMCI) discovered the Lisheen deposit. Four years later in November Minorco SA acquired CMCI’s share in Lisheen and together with Ivernia West they set up a joint venture. In December 1995 Minorco completed the feasibility study for the Lisheen deposit. Permission was granted by the Irish state in June 1997 and three months later construction was started. Anglo American Corporation merged with Minorco to form Anglo American plc in May 1999. Four months later the first ore from the Lisheen mine is brought to surface. It took until the end of the year before the first shipment with zinc concentrate left the Port of Cork. In 2003 Anglo American gained full control over Lisheen by acquiring Ivernia West’s share in Lisheen. The Lisheen mine is now fully owned by Vedanta Resources plc, this took place in February 2011. Vedanta Resources is the largest mining and non-ferrous metals company in India. Besides India it also has operations in Australia (Copper mines of Tasmania), Liberia (Liberia Ore), Namibia (Skorpion mine), South Africa (Black Mountain Mining) and Zambia (Konkola Copper Mines).

5 year production history

The table and figure below shows Lisheen’s production figures over the last 5 years. All numbers in the table and figure below have been collected from Lisheen’s End Of Month (EOM) reports. For the year 2011, two different reports have been used and combined as Lisheen’s financial year changed from the 1st of April to the 31st of March after Vedanta Resources took over Lisheen. The total tonnes mined does not account for the purchased ore of Galmoy. Total tonnes mined only accounts for all the material (ore, waste and paste) that Lisheen has mined in the Lisheen mine. The table and figure below show the most recent numbers which have been published.

<table>
<thead>
<tr>
<th>Year (Jan-Dec)</th>
<th>Tonnes Ore (incl. dilution)</th>
<th>Tonnes Galmoy Ore</th>
<th>Tonnes Waste + Paste</th>
<th>Zn%</th>
<th>Pb%</th>
<th>Total Tonnes Mined</th>
<th>Total Production Mill Conveyor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1,584,732</td>
<td>-</td>
<td>249,885</td>
<td>12.01</td>
<td>1.91</td>
<td>1,834,617</td>
<td>1,513,608</td>
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<tr>
<td>2008</td>
<td>1,561,919</td>
<td>-</td>
<td>123,261</td>
<td>12.10</td>
<td>1.63</td>
<td>1,685,180</td>
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<td>2009</td>
<td>1,534,482</td>
<td>18,676</td>
<td>175,745</td>
<td>12.35</td>
<td>1.68</td>
<td>1,710,227</td>
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<td>2010</td>
<td>1,531,718</td>
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<td>11.72</td>
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<td>193,045</td>
<td>296,620</td>
<td>11.70</td>
<td>2.16</td>
<td>1,656,524</td>
<td>1,330,528</td>
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</table>
One can see in the table and figure above that the tonnes Lisheen ore + tonnes Galmoy ore do not equal the total tonnes production of the mill conveyor. This is because there are differences measured at three different locations; survey volumes, mine conveyor belt and the mill conveyor belt. Survey volumes are measured after areas have been blasted. A volume is based on a 3-D scan of the blasted area. Material leaving the underground crusher is measured on the conveyor belt which leaves the mine. The mill conveyor measures the processed material after it is being processed.

Differences occur because of ore is blasted but does not get mucked or because ore falls of the conveyor belt or is accidentally dropped on its way to the crusher. Negative differences between the survey volumes and mill belt volumes can occur for instance when Galmoy ore is added together with Lisheen ore, if the amount of added Galmoy ore is not carefully measured. If a value in the table above is positive it means that the first mentioned measuring location has a higher value than the second location. The values in each of the ‘Range’ columns show the maximum variations between all months in a calendar year. It is believed that the mine conveyor belt is the least accurate of all of the measurements.

**Employment**

Lisheen employs approximately 379 people and 28 permanent contractors and around 50 persons in businesses through induced employment. About 85% of the work force resides in the local...
communities surrounding the mine. The remaining 15% lives with a 40km radius. Forty employees (11%) are from the Moyne and Templeuohy parish. A total of 305 Irish nationals are working at Lisheen together with 38 EU nationals and 36 non EU nationals (Lisheen, 2011a)

**HSE accreditations and awards**
Lisheen has been accredited the ISO 14 001 (environmental sytems) and OHSAS 18 001 (occupational health and safety systems) by the National Standards Authority of Ireland (NSAI) since respectively 2002 and 2005. Lisheen’s Safety Management System is based on Det Norske Verita’s International Safety Rating System since 2002 and is accredited with level 8. In Ireland there are only two operations who have achieved this level. Foras Áiseanna Saothair (FAS, Training & Employment Authority) has also accredited Lisheen with Excellence Through People, currently the accreditation for this national human resource management scheme goes via the NSAI. Last year (2011), Lisheen was audited against the new Gold Standard and were awarded accreditation, there are only 20 businesses in Ireland who have achieved this accreditation. An Integrated Pollution Control License was received from the Irish Environmental Protection Agency (EPA), Lisheen was the first mine in Ireland to receive this license. This license is now converted to the new Integrated Pollution and Prevention and Control License (Lisheen, 2011a)

**Community interaction**
Lisheen holds an annual safety expo each year; all local communities and employees are invited for this event. Also the company takes care of the livestock of local farmers by protecting the livestock with electric fencing from the Drish and Rossestown rivers. Therefore it provides alternate water sources for the livestock, pumps and electrics. A community engagement programme was formalised in 2007. Lisheen also encourages its workers to participate in charity events such as the 3 or 4 peaks Challenge in Ireland, in which the participants will climb the highest peak per Irish province in two days. Over the past years Lisheen has supported many local community events and projects for approximately 325 000€ per year (Lisheen, 2011a)

**Local Area**
Tipperary is characterized by a cool, wet climate. The average temperature in this county varies from 4.4°C in January to 15°C in July, with an average humidity of 83% the annual rainfall varies between 700 and 1000mm. The surrounding area can be categorized as an area which is mainly used for dairy farming, cattle and sheep rearing, forestry and peat mining (Lisheen Mine, 2008)
Appendix C – Material handling systems

This appendix describes the underground crushing station, mineral processing, tailings management and water treatment and backfill operations that are present at Lisheen.

Underground materials handling

At Lisheen, the material handling system receives its material from 40 and 50 tonne Toro trucks. Ideally the trucks dump their load onto a steel grizly grid in the 300 ton bin. The oversized rock will stay on the grizzly and then needs to be broken by the hydraulic rockbreaker. The system is designed to stockpile an average of 420 tonnes/hour of lead-zinc ore with a density of 2-2.6 t/m³.

If the 300 ton bin is full, ore is tipped into the 1000 tonne bin. It then needs to be remucked by a scoop to the 300 ton bin. After the material falls through the steel grizzly grid, a hydraulically driven plate feeder controls the bin output onto a vibrating scalping grizzly. From here, the undersized material is transported to a 1500mm wide ‘accelerator’ conveyor via a ‘rock box’ chute.

Product size is set to 150mm and maximised to 200mm. Lisheen uses a Nordberg Primary Jaw Crusher C140 B5. The digits behind the type indicate the width of the feed opening of the crusher in centimetres. In general the depth of the feed opening is about 0.65 to 0.8 times the width of the feed opening for Nordberg type C crushers. At Lisheen it is 0.76 meaning, the depth of the feed opening is 107cm.

A systematic sketch is shown below this helps to understand the crusher terminology.

![Figure 55 Modified sketch after Nordberg manual. Sketch is not to scale.](image)

The opening where the feed enters the crusher is called the feed opening (FO). This is measured from the tooth groove bottom of the moving jaw (J) to the tooth crown of the fixed jaw (F) in a straight line perpendicular to the centre line (C) of the crushing cavity (G). To measure the feed opening one must use the maximum setting with half-worn jaw dies and when the pitman (P) is in rear position. The maximum feed size should be about 80% of the feed opening depending on the crusher type and material to be crushed. The crushing cavity is the internal contour formed by the two crushing jaws and cheek plates. The closed side setting (A, c.s.s) is measured between the bottom of the fixed and moving jaws. This is also called the discharge setting. It must be measured in a straight angle at the centre line of the crushing cavity. During one revolution of the eccentric shaft (E) one can measure the difference between the maximum and minimum distance between the both jaws, this distance is called the stroke (D). This should be measured in a straight angle at
the centre line of the crushing cavity. Between the fixed and moving jaws one can measure the angle, this angle is called the nip angle and is not displayed on the figure above (Nordberg, 1999).

The electric motor (M) drives the eccentric shaft via V-belts (B) and flywheel (W). The pitman’s stroke is generated by the eccentricity of the eccentric shaft. And finally involving the tension springs (S) pull the lower end of the pitman (P) against the toggle plate (T). This makes sure that in case of overloading; the toggle plate reacts as a safety measure and collapses through elastic buckling. It prevents more valuable parts of getting damaged (Nordberg, 1999).

![Figure 56 Various types of jaws are available for different applications, after Metso C-series brochure.](image)

Various types of jaws can be installed on the crusher; Lisheen uses the corrugated jaws which are displayed on the far right of the picture above.
Mineral processing

Ore from Galmoy, is blended with the Lisheen ore to fill the production gap between the mine and the mill. In the processing plant, mineral processing consists of the following stages: comminution, flotation of the galena and sphalerite, dewatering. The concentrates leave the premises via truck to the Port of Cork for shipping to smelters in Europe and North America. The tailings are stored in a 78 hectare tailings management facility (TMF). The full processing chart is shown below.

Comminution

Comminution is the first step of the lead and zinc processing. The ore is reduced from 250mm to 75μm, these are P₈₀ values. This is accomplished by conveying the ore from the teepee via vibrating feeders to a semi-autogenous grinding mill (SAG). The SAG mill is a rotating cylindrical vessel which has 8-12% 125mm diameter steel balls in it that reduce the particle size of the ore. Oversized discharge is conveyed back to the SAG mill for further size reduction. The slurry (consisting of ground material and water) goes out of the mill and is transported to the mill pumping box. A cluster of hydrocyclones are fed from the slurry pumping box. The finer overflow (<75 μm P₈₀) is sent to the flotation section whereas the discharge (course overflow material) of the hydrocyclones is fed back to the ball mill which contains 30% steel balls of approximately 50mm in diameter.

Lead-Zinc flotation and leaching

Flotation is a process which is used to separate valuable minerals from non-valuable minerals, in this case to separate the lead and zinc minerals, from the host rock once at 75μm (P₈₀). The slurry is agitated, reagents are added and air is fed into the slurry. This results in mineralized bubbles which rise to the surface of the slurry forming a froth. The upgraded froth is concentrate and the material which does not float is tailings. The flotation processes is broken down into a lead circuit and a zinc circuit both have roughers, cleaners, and cleaner scavengers. An additional leaching stage is added to the zinc circuits to further improve the concentrate grade.

Figure 57 Mineral processing flow sheet of Lisheen.
The flotation feed coming in to the processing plant averages 1.8% lead but can vary from 1% to 3%. Lead flotation is conducted at natural pH which can range from 7-8. Two different collectors are used the stronger dithiophosphate and the weaker xanthate (SIPX, sodium isopropyl xanthate) they are used to maximize the flotation selectivity. This finally leads to a recovery of 71% lead with a concentrate grade of 62%.

The rejected sphalerite of the lead flotation tails is then floated in a second flotation step. The feed grade contains about 12.5 % Zn on average. The pH is raised in two different stages first in the roughers to a pH of 10 and then further increased to 11.5 in the cleaners, this is done to improve the rejection of iron sulphide minerals to the flotation tails. Zinc is then activated with coppersulphate (CUSO₄). The copper atoms adhere with the zinc atoms, this creates a pseudocopper mineral. Lisheen uses Potassium Amyl Xanthate (PAX) as a collector. Extra liberation is achieved with the regrind mill and improves the size for recovery in the columns. Sulphuric acid (H₂SO₄) is used in the final zinc processing circuit to recover the dolomite due to entrainment, which initially caused poor liberation. The concentrator recovers 91% of the zinc and in the end the concentrate grades are in the order of 53.5%.

Dewatering
The water content is too high at this stage for shipping and storage purposes. The concentrate is thickened by feeding the slurry into a thickener and additional chemicals enhance the settling process by amassing individual particles into larger clumps. The larger solid particles will settle on the bottom of the tank reducing the water content. The underflow of the thickened concentrate flows to the filtration stage, where two horizontal pressure filters are used for the zinc concentrate, to reduce the moisture content to 8%, only one horizontal pressure filter is used for the lead concentrate to produce a moisture content of 6%. These final products are now ready for shipment to the port of Cork.
Tailings Management Facility and water treatment

Tailings from the mineral processing plant are either sent to the tailings management facility (TMF) or they are thickened and used for backfill purposes in the mine. Backfill tailings are first dewatered using a deep cone thickener (DCT). In the underflow a high density paste is formed. Whereas the overflow water is pumped directly in the TMF. The overflow water is one of the 3 liquids that are directly pumped into the TMF. The other two are the tailings and the sludge underflow from the water treatment plants.

Under water the concentrator tailings are directly pumped into the TMF, this prevents oxidation and resultant acid formation. The system that pumps the tailings into the TMF is a continuously moving system with a floatable distribution head and flexible pipelines. The TMF is lined with low-density polyethylene liner and is designed as a water retaining structure.

In the concentrator the reclaimed water from the TMF is used as process water after it has been treated in the mine water treatment plant (MWTP) and reclaim water treatment plant (RWTP) (Lisheen, 2011c).

![Figure 58 The Tailings Management Facility in 2007, after Lisheen Mine Closure, Restoration & Aftercare Management Plan (CRAMP) Presentation, August 2011.](image-url)
Backfill plant

Backfill is required to allow extraction of secondary stopes and improve extraction of the higher grade thicker ores. It provides a structural support both laterally and vertically. It also increases the capacity for the TMF, because otherwise the tailings which were used for backfill ended up in the TMF if they were not used for backfill purposes. This all helps to improve the economic return of the mine.

The DCT as discussed in the previous page, has a feed rate of approximately 150 tonnes per hour at 22% solids w/w. These tailings are diluted by e-ducts to 5-10% w/w. This is required to induce adequate flocculation. The solids have an average specific gravity of 3.5 and slurry density of 2.1-2.2 kg/m³ and a residence time of 16-20 hours.

To bind the tailings ground granulated blast furnace slag (GGBS) and ordinary Portland cement (OPC) are used. The required concentrations vary with the desired strength underground in general is varies from 60-100 kg/m³, the binder dose rate is set to 80kg/m³. Another important operating parameter is the ratio of GGBS:OPC it is usually set to 90:10, 80:20 or 0:100 again depending on the required underground strength and type of stope which needs to be filled. The reagent consumption is 9 kg/t for OPC and 16kg/t for GGBS and for the flocculent 25g/t. Both OPC and GGBS silos have a capacity of approximately 300 ton. The target set for the paste strength is 500kPa after 28 days, 200kPa would already be sufficient for preventing liquefaction (Lisheen, 2011c).

<table>
<thead>
<tr>
<th>Year</th>
<th>%</th>
<th>Type of mining</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>50</td>
<td>Secondary mining</td>
</tr>
<tr>
<td>2006</td>
<td>75</td>
<td>Secondary mining</td>
</tr>
<tr>
<td>2007</td>
<td>&gt;75</td>
<td>Secondary mining</td>
</tr>
<tr>
<td>2008</td>
<td>&gt;75</td>
<td>Secondary mining + Tertiary mining</td>
</tr>
<tr>
<td>2009</td>
<td>80</td>
<td>Secondary mining + Tertiary mining</td>
</tr>
<tr>
<td>2010</td>
<td>90</td>
<td>Secondary mining + Tertiary mining</td>
</tr>
</tbody>
</table>

The table above showed that backfilling is absolutely necessary at Lisheen, otherwise the secondary and tertiary mining areas could not have been mined. Before 2004 there was no secondary mining because the backfill plant was not in use (Lisheen, 2011c). An example of paste back fill is shown in the image below.

Figure 59 Paste back fill at discharge, with its processing chart to the right (Lisheen, 2011c).
Appendix D – Ventilation at Lisheen

This appendix gives more detailed information about the ventilation at Lisheen.

Ventilation
Ventilation requires a sufficient airflow, so that all personnel can work in acceptable environmental conditions. The required airflow removes and dilutes harmful gasses produced in the mine, by either natural phenomena or diesel consuming machinery.

Lisheen follows the Code of Practice for the Safety Health and Welfare at Work Regulations (2001). This code specifies the specific limits for noxious gas, dust, radiation and noise. The Code of Practice (2011) describes an occupational exposure limit (OEL) for a chemical in a workplace within either an 8-hour or 15-minute reference period. The occupational exposure limit values are the limit of the time-weighted average (TWA) concentration of a chemical agent in the air within the breathing zone of a worker in relation to a specific reference period.

Occupational Exposure Limits for some of the common gasses present at Lisheen are shown in the table below (Health and Safety Authority, 2011).

<p>| Table 34 Occupational Exposure Limits after the 2011 Code of Practice |
|-----------------------------|-------------------------------|-----------------------------|-------------------------------|-----------------------------|</p>
<table>
<thead>
<tr>
<th>Gas</th>
<th>( CH_3 ) (ppm)</th>
<th>( NH_3 ) (ppm)</th>
<th>( H_2S ) (ppm)</th>
<th>( CO ) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 hour</td>
<td>1000</td>
<td>20</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>15 minute</td>
<td>--</td>
<td>35</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 35 OEL 2011 limits for other hazardous contaminants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
</tr>
<tr>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Irrespirable dust</td>
</tr>
<tr>
<td>Respirable dust</td>
</tr>
<tr>
<td>Diesel Particulate Matter (DPM)</td>
</tr>
<tr>
<td>Radiation</td>
</tr>
</tbody>
</table>

At Lisheen the shift boss takes measurements of noxious gases regularly throughout every shift responsible for each zone. These measurements are taken by using a Dräger Xam 5000; this gas detector can be seen in the image on the left. Dust sampling is done every 3 months from all of the exhaust raises on surface. Radiation comes mostly from radon gas; it is controlled by ventilating the high output areas, in such a way that the concentration of radon decreases. Radiation levels are measured every six months. This is done at fixed locations around the mine with a radiation dosimeter. In order to control the noxious gases, there must be an adequate airflow in every area where the machinery is working. An adequate airflow will dilute the noxious gases in such a way that they are below acceptable occupational exposure limits. All machines are subjected to DPM – and emission analysis every six months.

Figure 60 Gas detector
Dust is an issue in underground mines; the only way to improve dust control is to use water suppression techniques. Near the crusher, a water spraying installation has been installed. After the truck has tipped its load, the sprinkling system sprays water in such a way that it tries to bind the dust particles and reduces the amount of dust.

There is no official legislation about the minimum amount of airflow that is required for underground working operations in Ireland. The current limits used at Lisheen have been derived from Australian limits and are set to 0.04m³/s per kW of rated engine power output. This results in the following recommended airflow at Lisheen.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Type</th>
<th>Engine Power (kW)</th>
<th>Recommended Airflow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toro 50D</td>
<td>Truck</td>
<td>450</td>
<td>18</td>
</tr>
<tr>
<td>Toro 40D</td>
<td>Truck</td>
<td>352</td>
<td>14</td>
</tr>
<tr>
<td>Sandvik 0010</td>
<td>Scoop</td>
<td>352</td>
<td>14</td>
</tr>
<tr>
<td>Sandvik 650</td>
<td>Scoop</td>
<td>243</td>
<td>10</td>
</tr>
<tr>
<td>Jama Scaler</td>
<td>Mechanical Scaler</td>
<td>190</td>
<td>8</td>
</tr>
</tbody>
</table>

Lisheen has 5 main fan installations underground.

- 1 at 250 kW at Vent Raise (VR) 1, estimated to run at 100% rates per minute (RPM).
- 1 at 250 kW at VR 2, running at 95% RPM.
- 2 at 75 kW in parallel at VR 3, one of them running at 95% RPM.
- 1 at 160 kW at VR 4 running at 70% RPM.
- 1 at 250 kW at VR7 running at 95% RPM.

The image above shows Lisheen’s mine ventilation model, which is build in Vnet PC. Vnet PC is made by Mine Ventilation Services and is a mine ventilation network simulator. The ventilation engineer uses it to plan ahead and investigate all possibilities before making changes to the actual fans.
There are 4 fresh air intake shafts, but VR6 is out of service, this leaves 3 intake shafts (VR8, VR9 and I31) and the portal to use for emergency egress. An alimak has been installed in the fresh airshafts for emergency procedures. Because these fresh air intake shafts are used as emergency escape routes no fan can be installed in the same shaft. Otherwise in the event of a fire, people could have trouble finding their way to shafts. All fans are located underground at the exhaust raises and use negative pressure to provide the required air movement. Currently Lisheen exhausts approximately 450-500 m$^3$/s. Only positive pressure forcing systems are used in Lisheen for the secondary ventilation network that uses auxiliary fans at either 900mm ø or 1400mm ø to ventilate dead end headings. There is a preference for the 1400mm ø for the larger headings because it has lower pressure loss characteristics and the smaller headings preferably use 900mm ø. The air is forced through lay flat collapsible ventilation ducts to deliver air to the face.
Appendix E – Metso Simulations

The real values will differ as Lisheen’s underground material handling system is not fully continuous and trouble free and the feed variability is also not constant. This can therefore only be seen as an indication.
## Appendix F – Underground Energy Consumption

Table 37 Underground Energy Consumption

<table>
<thead>
<tr>
<th>Financial Year</th>
<th>Fixed Pumping Actual (Kwh)</th>
<th>Other Power Actual (Kwh)</th>
<th>m³ Pumped Actual</th>
<th>kWh/m³</th>
<th>MCC10 (Kwh)</th>
<th>Total Actual (Kwh)</th>
<th>% MCC10 of Total Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr-11</td>
<td>2,404,611</td>
<td>2,704,889</td>
<td>2,044,422</td>
<td>1.18</td>
<td>71,830</td>
<td>5,109,500</td>
<td>1.41</td>
</tr>
<tr>
<td>May-11</td>
<td>2,366,392</td>
<td>2,845,608</td>
<td>1,991,892</td>
<td>1.19</td>
<td>74,880</td>
<td>5,212,000</td>
<td>1.44</td>
</tr>
<tr>
<td>Jun-11</td>
<td>2,068,100</td>
<td>2,883,500</td>
<td>1,817,080</td>
<td>1.14</td>
<td>70,950</td>
<td>4,951,600</td>
<td>1.43</td>
</tr>
<tr>
<td>Jul-11</td>
<td>2,251,330</td>
<td>2,692,670</td>
<td>1,957,365</td>
<td>1.15</td>
<td>74,690</td>
<td>4,944,000</td>
<td>1.51</td>
</tr>
<tr>
<td>Aug-11</td>
<td>2,314,450</td>
<td>2,533,450</td>
<td>1,951,586</td>
<td>1.19</td>
<td>74,180</td>
<td>4,847,900</td>
<td>1.53</td>
</tr>
<tr>
<td>Sep-11</td>
<td>1,993,430</td>
<td>2,579,750</td>
<td>1,590,475</td>
<td>1.25</td>
<td>73,450</td>
<td>4,573,180</td>
<td>1.61</td>
</tr>
<tr>
<td>Oct-11</td>
<td>1,986,300</td>
<td>2,513,600</td>
<td>1,597,667</td>
<td>1.24</td>
<td>67,000</td>
<td>4,499,900</td>
<td>1.49</td>
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<tr>
<td>Nov-11</td>
<td>2,109,240</td>
<td>2,822,060</td>
<td>1,715,836</td>
<td>1.23</td>
<td>73,980</td>
<td>4,931,300</td>
<td>1.5</td>
</tr>
<tr>
<td>Dec-11</td>
<td>2,582,610</td>
<td>2,604,090</td>
<td>2,193,838</td>
<td>1.18</td>
<td>63,070</td>
<td>5,186,700</td>
<td>1.22</td>
</tr>
<tr>
<td>Jan-12</td>
<td>2,431,970</td>
<td>3,228,254</td>
<td>1,957,713</td>
<td>1.24</td>
<td>71,780</td>
<td>5,660,224</td>
<td>1.27</td>
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<tr>
<td>Feb-12</td>
<td>2,288,930</td>
<td>2,825,574</td>
<td>1,928,982</td>
<td>1.19</td>
<td>68,110</td>
<td>5,114,504</td>
<td>1.33</td>
</tr>
<tr>
<td>Mar-12</td>
<td>2,338,510</td>
<td>3,031,179</td>
<td>1,941,182</td>
<td>1.20</td>
<td>72,270</td>
<td>5,369,689</td>
<td>1.35</td>
</tr>
<tr>
<td>Total</td>
<td>27,135,873</td>
<td>33,264,624</td>
<td>22,688,036</td>
<td>1.22</td>
<td>856,190</td>
<td>60,400,497</td>
<td>1.42</td>
</tr>
</tbody>
</table>

The column MCC10 shows the underground materials handling system.
Appendix G – Demo Charts

WipFrag Analysis
WipFrag 2010 Build 16  Thomas Waterman - Delft University - Demo
Clear Crushed Gravel  June 05, 2012, 10:35:08 AM GMT Standard Time

Size (mm)    % Passing
1000.00      100.00%
500.00       100.00%
300.00       100.00%
150.00       100.00%
126.00       100.00%
100.00       100.00%
75.00        100.00%
60.00        100.00%
40.00        100.00%
37.50        100.00%
35.50        100.00%
31.50        100.00%
25.00        100.00%
16.00        100.00%
12.50        96.50%
10.00        82.59%
8.00         53.05%
6.70         37.71%
5.60         23.08%
4.15         14.85%
4.00         9.89%
3.35         6.00%
2.00         1.70%
1.40         0.94%
1.00         0.47%
0.85         0.32%
0.60         0.15%

Figure 63 Results of Clear Crushed Gravel - Chart processed in WipFrag.

Size Distribution

clearcrushedgravel

Figure 64 Results of Clear Crushed Gravel - Chart processed in Split Desktop.
WipFrag Analysis

WipFrag 2010 Build 16  Thomas Waterman - Delft University - Demo
Natural Pea Gravel  June 05, 2012, 10:36:19 AM GMT Standard Time

![Graph showing size distribution of Natural Pea Gravel processed in WipFrag.](image1)

**Figure 65 Results of Natural Pea Gravel - Chart processed in WipFrag.**

![Graph showing size distribution of Natural Pea Gravel processed in Split Desktop.](image2)

**Figure 66 Results of Natural Pea Gravel - Chart processed in Split Desktop.**
Figure 67 Results of Prills - Demo processed in WipFrag.

Figure 68 Results of Prills - Demo processed in Split Desktop.
Appendix H – Lights Comparison

Jeep Lights:

![Figure 69 Jeep Lights](image1)

Camera Flash:

![Figure 70 Camera Flash](image2)
LED Lights:

![Image of a cave with LED lights on]

*Figure 71 With LEDs*

Without LED:

![Image of a cave without LED lights]

*Figure 72 Without LEDs*
With LED:

![Image of a cave with LED lighting]

**Figure 73 LED Extra visibility**

Extra visibility is up to 20-30 meter.
Appendix I – Data collection including processed images
The following images are the result of processing the data in WipFrag. The first data set consists of 5 images and the second data set consists of 3 images per set.

Each image is shown in 3 different ways:

- as software input
- as processed
- as the actual result

Figure 74 Pre-Processed MS08S18 image #1

Figure 75 Processed MS08S18 image #1
Figure 76 Result of MS08S18 image #1

Figure 77 Pre-Processed MS08S18 image #2
Figure 78 Processed MS08S18 image #2

Figure 79 Results MS08S18 image #2
Figure 80 Pre-Processed MS08S18 image #3

Figure 81 Processed MS08S18 image #3
**Figure 82** Results of MS08S18 image #3

**Figure 83** Pre-Processed MS08S18 image #4
Figure 84 Processed MS08S18 image #4

WipFrag 2010 Build 16 Thomas Waterman - Delft University - 01B8
04 May 21, 2012 09:33:29 AM GMT Standard Time

<table>
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<th>Size (mm)</th>
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</tr>
</thead>
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<td>100.00%</td>
</tr>
<tr>
<td>300.00</td>
<td>85.00%</td>
</tr>
<tr>
<td>150.00</td>
<td>40.00%</td>
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<td>1.40</td>
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<td>1.00</td>
<td>0.00%</td>
</tr>
<tr>
<td>0.85</td>
<td>0.00%</td>
</tr>
<tr>
<td>0.60</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Figure 85 Results MS08S18 image #4

679 Particles:
- min = 2.428 mm
- max = 438.474 mm
- mean = 58.713 mm
- stddev = 65.351 mm
- mode = 150.000 mm
- D10 = 70.534 mm
- D25 = 117.555 mm
- D50 = 181.720 mm
- D75 = 263.354 mm
- D90 = 387.595 mm
- sph = 0.642

Non-Calibrated:
- Xmax = 438.474 mm
- Xc = 225.139 mm
- b = 2.969
- n = 2.149
Figure 86 Pre-Processed MS08S18 image #5

Figure 87 Processed MS08S18 image #5
Figure 88 Results of MS08S18 image #5

The first image above is the result of merging all of the 5 files together. A new data set starts at the next page.
Figure 90 Image of processed MS08S18 called 'left'.

Figure 91 Processed Image of MS08S18 called 'left'.
Figure 92 Results of MS08S18 image called 'left'.

Figure 93 Image of processed MS08S18 called 'middle'.
Figure 94  Processed image MS08S18 called 'middle'.

Figure 95 Results of MS08S15 image called 'middle'
Figure 96 Image of processed MS08S15 called 'right'.

Figure 97 Processed image of MS08S15 called 'right'.
Figure 98 Results of MS08S15 image called 'right'.

Figure 99 Results of MS08S15 merged analysis 3 images containing left, middle and right.
Galmoy Stockpile images

Figure 100 Image 'IMGP0358' - Raw data.

Figure 101 'IMGP0358' after processing in Split Desktop.

* Red areas are classified as fines, light blue areas are classified as ignored areas. This applies to all Split Desktop images.
Figure 102 Image 'IMG0361' - Raw data.

Figure 103 Image 0361 after processing in Split Desktop.
Figure 104 Image 'IMG0362' - Raw data.

Figure 105 Image 0362 after processing in Split Desktop.
Figure 106 Image 'IMG0371' - Raw data.

Figure 107 Image 0371 after processing in Split Desktop.
Figure 108 Image 'IMG0387' - Raw data.

Figure 109 Image 0387 after processing in Split Desktop.

*Image has been rotated to fit on page.*
Figure 110 Image 'IMGP0390' - Raw data.

Figure 111 Image 0390 after processing in Split Desktop.
Figure 112 Figure 104 Image 'IMGP0391' - Raw data.

Figure 113 Image 0391 after processing in Split Desktop.
Figure 114 Image 'IMG0392' - Raw data.

Image has been rotated to fit on page.

Figure 115 Image 0392 after processing in Split Desktop.
Figure 116 Image 'IMG0394' - Raw data.

Figure 117 Image 0394 after processing in Split Desktop.

*Image has been rotated to fit on page.*
Figure 118 Figure 110 Image 'IMGP0404' - Raw data.

Image has been rotated to fit on page.

Figure 119 Image 0404 after processing in Split Desktop.
Appendix J – Comparing WipFrag and Split Desktop

Figure 120 Image 0390 processed in Split Desktop.

Figure 121 Image 0390 processed in WipFrag.

The results are shown on the next page.
Figure 122 Results of image 0390 processed in Split Desktop.

Figure 123 Results of image 0390 processed in WipFrag.
The results are shown on the next page.
Figure 126 Results of image 0371 processed in Split Desktop.

Figure 127 Results of image 0371 processed in WipFrag.
The image above is from Split Desktop, and the image below is from WipFrag.

Values out of Split Desktop derived from image 05 taken in MS08S15 on 15-05-2012. Both pictures are after manual editing the images on the previous page are before manual editing in both programs. Data from Split Desktop can be found on the next page.
Table 38 Comparison of image #5 of MS08S15 in both programs.

<table>
<thead>
<tr>
<th>Split Desktop</th>
<th>Image 05</th>
<th>WipFrag</th>
<th>Image 05</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>Size[mm]</td>
<td>% Passing</td>
<td>Size[mm]</td>
</tr>
<tr>
<td>F10</td>
<td>44.33</td>
<td>F10</td>
<td>57.58</td>
</tr>
<tr>
<td>F20</td>
<td>75.72</td>
<td>F20</td>
<td>92.74</td>
</tr>
<tr>
<td>F30</td>
<td>103.72</td>
<td>F30</td>
<td>120.60</td>
</tr>
<tr>
<td>F50</td>
<td>153.73</td>
<td>F50</td>
<td>182.00</td>
</tr>
<tr>
<td>F70</td>
<td>206.03</td>
<td>F70</td>
<td>263.80</td>
</tr>
<tr>
<td>F80</td>
<td>240</td>
<td>F80</td>
<td>310.80</td>
</tr>
<tr>
<td>F90</td>
<td>291.91</td>
<td>F90</td>
<td>405.40</td>
</tr>
<tr>
<td>Topsize</td>
<td>457.14</td>
<td>Topsize (99.95%)</td>
<td>490.50</td>
</tr>
</tbody>
</table>

Table 39 Split Desktop results of image 05 taken in MS08S15.

<table>
<thead>
<tr>
<th>Split Desktop</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
</tr>
<tr>
<td>Size[mm]</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>300</td>
</tr>
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<td>150</td>
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<tr>
<td>125</td>
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<td>100</td>
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<tr>
<td>75</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>37.5</td>
</tr>
<tr>
<td>35.5</td>
</tr>
<tr>
<td>31.5</td>
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<tr>
<td>25</td>
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<td>16</td>
</tr>
<tr>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>6.7</td>
</tr>
<tr>
<td>5.6</td>
</tr>
<tr>
<td>4.75</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3.35</td>
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<tr>
<td>2</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0.85</td>
</tr>
<tr>
<td>0.6</td>
</tr>
</tbody>
</table>
Appendix K – WipFrag definitions

\( C_u = \text{Coefficient of Uniformity} = \frac{D_{60}}{D_{10}}, \) a measure of the slope of the cumulative weight \% curve between the 60- and 10-percentiles.

\( D_n = \text{Nominal diameter, or equivalent spherical diameter, i.e. the diameter of a sphere with the same volume as that computed for the fragment.} \)

\( D_{10}, D_{25}, \text{etc.} = \text{Percentile sizes. For example } D_{10} \text{ is the ten-percentile, the value of } D \text{ for which } 10\% \text{ by weight of the sample is finer and } 90\% \text{ coarser. In terms of sieving, } D_{10} \text{ is the size of sieve opening through which } 10\% \text{ by weight of the sample would pass.} \)

\( D_{50} = \text{The Median or 50-percentile, the value of } D_n \text{ for which half the sample weight is finer and half coarser.} \)

\( \text{blocks} = \text{Number of net elements detected in the NET image} \)

\( \text{max} = \text{Maximum size of fragment in the image } [D_n (m)] \)

\( \text{mean} = \text{Arithmetic mean (average) fragment size, equal to the sum of all equivalent spherical diameters divided by the total number of particles } [D_{av} (m)] \)

\( \text{min} = \text{Minimum size of fragment in the image } [D_n (m)] \)

\( \text{mode} = \text{Most common sized particle, the geometric mean } D_h \text{ size class interval for the class containing the greatest number of net elements (fragments) } [D_h (m)] \)

\( n = \text{Rosin-Rammler (and Gaudin-Schuhman) Uniformity Coefficient, equal to the slope of the Rosin-Rammler straight line fitted to the data in log-log co-ordinates.} \)

\( \text{Sphericity} = \frac{D_n}{D_s}, \) the ratio of equivalent spherical diameter to the diameter of a circumscribing sphere (long axis of the fragment)

\( \text{stdev} = \text{Standard deviation of fragment size } D_{av} \)

\( X_c = \text{Characteristic Size, the intercept of the Rosin-Rammler straight line fitted to the WipFrag } D_n \text{ data in log-log co-ordinates. This is equivalent to the } D_{63.2}. \)

\( X_{\text{max}} = \text{Gaudin-Schuhman characteristic size, the intercept of the } 100\% \text{ passing and the slope of the Gaudin-Schuman straight line.} \)

Definitions of WipFrag Statistics

\( X_{\text{max}}^2 = \text{Is the calibrated Gaudin-Schuhman characteristic size, the intercept of the } 100\% \text{ passing and the slope of the Gaudin-Schuman straight line} \)

\( X_c^2 = \text{Is the calibrated Characteristic Size, the intercept of the Rosin-Rammler straight line fitted to the WipFrag } D_n \text{ data in log-log co-ordinates. This is equivalent to the } 63.2. \)

\( N_{\text{res}}^2 = \text{Is the calibrated Rosin-Rammler (and Gaudin-Schuhman) Uniformity Coefficient, equal to the slope of the Rosin-Rammler straight line fitted to the data in log-log co-ordinates.} \)
Appendix M – Mining Methods

Longhole Open Stoping

Longhole open stoping is the preferred mining methods for areas with very thick ore layers, the width of a stope can vary from 10 meters up to 15 meters and the height varies from 10 to 30 meters. Uphole retreat from a single footwall drive has been predominantly used during the last couple of years. Also several stopes with a hanging –and footwall access have been mined successfully. Two different access levels (upper and lower) are required when the thickness of the orebody is too large to be drilled from one drift. An upper and lower access level is also required when the hanging wall of the orebody is expected to be in bad ground conditions.

Room and Pillar

For thin areas, the room and pillar mining method is the most preferred method because this method is very flexible to changes in the mining layout based on changes in geological and geotechnical parameters. The image below shows a typical room and pillar lay-out.

Figure 130 Different stages of longhole open stoping mining method.

Figure 131 Room and Pillar mining method.
Drift and Fill

Drift and fill mining is mainly used in areas which aren’t thick enough for longhole open stoping and areas which are geologically seen not very complex. Its most important issue is to ensure safe working conditions for all men and material. Safety is the most important aspect of this operation; geo-technicians assess the headings and faces and recommend the necessary support. An overview of the different phases for drift and fill mining is shown in the image below.

Figure 132 Different stages of drift and fill mining method.
Appendix N – Development drilling

In general the most important distinction between the different drill and blast patterns is the difference between development and production drilling. The width of a development drift is normally 6.0 meters wide and 4.5 meters high. Two Atlas Copco M2D and two L2C drill rigs are used for developing faces. The picture below shows a standard drilling pattern consisting of 60 shot holes and four reamer holes. Reamer holes are 105mm wide (60 mm wider than the normal shot holes). The cut holes indicated in the image below in the yellow square are the first part of the face which is fired. It generates the free face for the remaining part of the face. Holes are drilled to a depth of 3.9 meters and they have an average pull of 3.5 meters per round.

![Drilling Pattern](image)

This pattern is only seen as guidance to the driller as they are allowed to modify the pattern according to local conditions. Development rigs can drill this pattern at dips varying from -15% to +15% depending on geological and mining requirements. Often patterns change because of local drilling difficulties such as water problems, lost drill steels or rock support (cable bolts) can cause drill holes to be re-drilled. This has influence on the fragmentation. Energy can dissipate much easier therefore the rock is harder to break as the energy disappears into the free face. This problem occurs for both development and production drilling. For floor, roof, start and side slashes other drilling patterns are used, but similar problems can occur.

The perimeter ‘contour’ holes are charged with 2.5kg per hole (C1) and the other contour charge (C2) is used for the perimeter ‘easer’ holes and is set to a charge of 3.5kg per hole. The roof will have a better profile and a better ground condition because of the lower powder factor. All other holes are charged up to 5.3kg per hole. An uncharged collar of 0.5 meter is used for all holes except the cut holes. Every shot hole uses one LP detonator and is connected to a bunch connector together with several other detonators. The bunch connectors are connected to the Dynoline and the same 200 meter safety distance is used for development blasts by the shot firer to fire the blast. The duration of a single blast for development is up to 6000ms; the maximum delay for Nonel MS.
Appendix O – Geotechnical support

Lisheen uses a site specific ground classification system which is used to produce a simplified computer layer showing the ground conditions for a 2m thick beam in the hanging wall by using the known and predicted structures of the area. This classification system is based on the following parameters: Rock Quality Designation, Joint Set Number, Fracture Frequency and Joint Alteration. It has resulted in 4 different ground condition classes.

<table>
<thead>
<tr>
<th>Ground Condition</th>
<th>Rock Mass Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>61-100</td>
</tr>
<tr>
<td>Class 2</td>
<td>41-60</td>
</tr>
<tr>
<td>Class 3</td>
<td>21-40</td>
</tr>
<tr>
<td>Class 4</td>
<td>0-20</td>
</tr>
</tbody>
</table>

The geotechnical database consists of over 2000 diamond drill holes from surface on a 30*30m spacing. Over 110 diamond drill holes are drilled in the hangingwall from underground. The generated prediction layer is used to assist with the mining design and scheduling of development rates and extraction sequences.

The following structures are present at Lisheen Mine.

<table>
<thead>
<tr>
<th>Type of structure</th>
<th>Direction</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp faults</td>
<td>ENE trending dipping 50-70 degrees</td>
<td>Shallow dips, domes, shear contacts, laminated weak footwall</td>
</tr>
<tr>
<td>Fissure (F type)</td>
<td>NW trending, sub vertical, approx. 3m wide,</td>
<td>Water, local intense jointing with rubble infill</td>
</tr>
<tr>
<td>Wrench</td>
<td>NNW trending, sub vertical.</td>
<td>Intensely weathered, wide scale horizontal weathering with clay infill and cavities</td>
</tr>
<tr>
<td>Jointing</td>
<td>NW trending, sub vertical</td>
<td>Prominent in Main South intense in HW and can be highly weathered</td>
</tr>
</tbody>
</table>

Identification of geotechnical risks

In order to provide the right geotechnical support, Lisheen has developed a Fall Off Ground Management (FOGM) system. It consists of the following 5 steps:

1. *Prevention*; do not damage the rock.
2. *Protection*; support the rock.
3. *Monitor*; monitor the rock.
4. *Design sequence and communicate*; how can it be improved.
5. *Problem solving*; research and development, technology and innovation.

It all starts with creating the best possible ground conditions. From there on the appropriate support systems are designed according to the support standards and procedures. The next important step is
to communicate and implement support strategies. This is done by giving the appropriate training and coaching to the support crews and by making employees aware of ground conditions. Communication needs to be accurate on a daily basis; this is done by updating the face sheets daily. Also noddy plans (basic written instructions, including a map of the local area) are given out and instructions are also placed on panel boards. Every month a 3 month roller forecast (3MRF) is carried out to discuss the plans for the coming 3 months and update the previous 3MRF. After implementing the support design it needs to be monitored to make sure it is in compliance with the current safety standards and to assure quality of the support design. By checking up on the support plans it will also become clear how the rockmass responds to the designed support. This information will help to spot risks and trends and is also useful for similar support designs. The last step is to improve the working conditions through an increase in knowledge. In such a way that information from research, testing new products, audits or incident investigations is used to solve problems which had not been solved before.

At Lisheen the following geotechnical risks are present:

<table>
<thead>
<tr>
<th>Table 42 General geotechnical risks at Lisheen mine.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General geotechnical risks</strong></td>
</tr>
<tr>
<td>Alteration between clay and sand</td>
</tr>
<tr>
<td>Steep ABL contacts</td>
</tr>
</tbody>
</table>

During 2010 Lisheen has used approximately 380 000m³ of paste backfill. When looking at paste it is also important to know the risks associated with paste such as:

<table>
<thead>
<tr>
<th>Table 43 Backfill geotechnical risks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Backfill geotechnical risks</strong></td>
</tr>
<tr>
<td>Paste has the structure of a weak rock</td>
</tr>
<tr>
<td>Flat dipping wedges in roof</td>
</tr>
</tbody>
</table>

The following risks are present when looking into room and pillar and longhole open stoping.

<table>
<thead>
<tr>
<th>Table 44 Room and pillar geotechnical risks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Room and pillar geotechnical risks</strong></td>
</tr>
<tr>
<td>Large unsupported spans 150-600m, regional pillars and paste fill</td>
</tr>
<tr>
<td>Geological features bracket pillars, extraction sequencing, incremental paste filling</td>
</tr>
<tr>
<td>Pillar failure stable pillar design, extraction sequencing, incremental paste filling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 45 Longhole open stoping geotechnical risks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longhole open stoping geotechnical risks</strong></td>
</tr>
<tr>
<td>Airblast Laminated roof Uncontrolled hanging wall failure Weathered roof</td>
</tr>
<tr>
<td>Sinkholes Mining alongside past Mining hanging wall Steep tectonic shears</td>
</tr>
</tbody>
</table>
Currently Lisheen has 3 Atlas Copco Boltecs in operation providing the standard support with 2.4m long Y25 rebar in a 33mm hole tensioned using two speed resin to 5 tonne. A modified Atlas Copco LC2 together with a Sandvik Automated Cable Bolt rig is used to install the cable bolts. The standard cable bolt is a 15.2mm birdcage with a nominal cage size of 38mm and bearing capacity of 250kN, cablebolt lengths are variable but the standard is 6m. This type of cable bolt is used because it suits soft ground conditions very well and allows a weaker water cement ratio to be used. This results in a better bond strength, fill cavities and cable cages.

For shotcreting purposes two Normet Spraymecs 1050 WPC are available. Shotcrete is used for support and for backfill barricades. Poor ground conditions require a minimum thickness of 50mm to seal the rock with an unreinforced shotcrete. The thickness rises up to 75mm of synthetic fiber shotcrete in areas with very poor ground conditions. This is applied at a rate of 5kg/m³ to achieve a strength of 50MPa at 28 days with an energy absorption of 4000 joules at 40mm deflection (Burk, 2008).

There are different support plans for the different types of mining operations; development, stopes, room and pillar. The support plans for development and room and pillar areas can be found in
Appendix O – Geotechnical support

Stopes
Remote mucking takes places in stopes without additional support. These stable areas can have spans up to 15m spans. Paste backfill is used to fill the cavities and to confine the sidewalls and roof as soon as possible. In some conditions additional support is required to safely maximize extraction.

A development drive is driven and supported when the hangingwall is accessible. Additional support is installed to allow the optimum width of the stope to be maintained.

If the hangingwall is not accessible, or the ground is extremely poor then the hangingwall must be supported via the footwall. Developing the footwall drive and longhole drilling of the stope with 64mm holes does this. Following a design pattern some production holes are extended into the poor ground using a 51mm diameter hole. A 6m long 22m solid fibreclass cable is then remotely installed into the end of the hole. A delayed seal is obtained by using expanding resin foam in an elastic stocking secured to the cable and grouting tubes in such a way that this allows the support unit to be grouted and leaving the production hole ready for charging.

In the areas where drift and fill is used as a mining method additional support in the form of cables are used to cover for the enlarged spans. Drifts can be paste filled later to provide the required panel support.

Development
One of the development support methods that are used is based on the New Austrian Tunneling Method (NATM). Using this NATM the ground around an excavation is deliberately mobilized to the maximum extent possible by allowing controlled deformation. It is used when the ground needs to develop into a self-supporting arch. A thin layer of shotcrete is then applied to seal the ground followed by a pattern of bolts to provide rigid support and deep anchorage. A thicker layer of synthetic reinforced shotcrete is then applied as permanent support; sometimes mesh and straps or a combination is used as well.

A ground improvement approach is adopted for areas that are not suitable to develop ground arches. Normally this is done by spiling with a fan of birdcage cables, and dewatering if necessary and sequentially excavating the ground by taking shorter rounds and resuing from the bottom up. For permanent support mesh or lattice brattices are installed together with a thick layer of shotcrete.

A truss sling method is used to secure open fissures because there is a risk of loose material falling from a height. Once the fissure is intersected, the brows on both sides of the fissure are scaled and shotcreted. On both sides of the fissure holes are drilled angled vertically to install a modified birdcage cable with only two bulbs which is then grouted. Weld mesh sheets are threaded through the parallel cables and worked under the fissure. In order to fill the open cavity as much as possible polystyrene blocks are cut to size and placed on top of the mesh and maneuvered into position under the fissure. Finally the truss slings are tensioned and the sealed cavity is shotcreted to minimize the risk of fine material falling through.

Pillars
Pillars are kept at a standard safe dimension to allow easier extraction on retreat; limiting the span
of rooms does this. The unsupported span is kept to 50m. Voids are packed with waste rock pushed tight to the roof with a ‘rammer jammer’ fitted to an LHD bucket or paste backfilled. This is done to limit the extent of roof failures. By filling the voids with either paste or waste areas up to 150m² have been successfully extracted with an average ore recovery of 97% (Burk, 2008).
Appendix P - Accuracy Analysis Images

Figure 134  Original IMG_0648, Accuracy Analysis Photo 1.

Figure 135  IMG_0648, Accuracy Analysis, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size

WipFrag 2010 Build 16   Thomas Waterman - TU Delft - 01B8
IMG_0648   January 13, 2014, 06:21:29 PM W. Europe Standard Time

149 Particles:
min = 0.139 mm
max = 25.805 mm
mean = 8.076 mm
stdev = 10.017 mm
mode = 22.000 mm
D10 = 16.914 mm
D25 = 19.354 mm
D50 = 21.433 mm
D75 = 22.505 mm
D90 = 24.265 mm
sph = 0.907

Non-Calibrated:
Xmax = 25.805 mm
X50 = 21.433 mm
Xc = 22.142 mm
b = 2.910
n = 18.502

Size (mm) % Passing
27.50 100.00%
26.25 100.00%
25.00 94.63%
23.50 85.18%
22.75 82.95%
22.00 56.58%
20.75 39.67%
19.50 26.88%
18.25 10.74%
17.00 10.74%
15.75 0.01%
15.00 0.01%

Figure 136  IMG_0648, Accuracy Analysis Photo 1 WipFrag Results
Figure 137 Original IMG_0650, Accuracy Analysis Photo 2

Figure 138 IMG_0659, Accuracy Analysis, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size
WipFrag 2010 Build 16 Thomas Waterman - TU Delft - 01B8

Size (mm) % Passing
27.50 100.00%
26.25 100.00%
25.00 94.19%
23.50 79.88%
22.75 71.55%
22.00 59.37%
20.75 39.16%
19.50 25.29%
18.25 9.35%
17.00 7.87%
15.75 1.64%
15.00 0.02%

Figure 139 IMG_0650, Accuracy Analysis Photo 2 WipFrag Results
Figure 140 Original IMG_0655, Accuracy Analysis Photo 3

Figure 141 IMG_0655, Accuracy Analysis Photo 3 WipFrag Processed

Figure 142 IMG_0655, Accuracy Analysis Photo 3 WipFrag Results
Figure 143 Original IMG_0661, Accuracy Analysis Photo 4

Figure 144 IMG_0661, Accuracy Analysis Photo 4, WipFrag Processed

Figure 145 IMG_0661, Accuracy Analysis Photo 4, WipFrag Results
Figure 146 Original IMG_0664, Accuracy Analysis Photo 5

Figure 147 IMG_0664, Accuracy Analysis Photo 5, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size
WipFrag 2010 Build 16  Thomas Waterman - TU Delft - 01B8
IMG_0664  February 05, 2014, 12:47:53 PM GMT Standard Time

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.50</td>
<td>100.00%</td>
</tr>
<tr>
<td>26.25</td>
<td>95.40%</td>
</tr>
<tr>
<td>25.00</td>
<td>86.73%</td>
</tr>
<tr>
<td>23.50</td>
<td>54.11%</td>
</tr>
<tr>
<td>22.75</td>
<td>40.16%</td>
</tr>
<tr>
<td>22.00</td>
<td>30.60%</td>
</tr>
<tr>
<td>20.75</td>
<td>15.56%</td>
</tr>
<tr>
<td>19.50</td>
<td>8.89%</td>
</tr>
<tr>
<td>18.25</td>
<td>3.44%</td>
</tr>
<tr>
<td>17.00</td>
<td>3.44%</td>
</tr>
<tr>
<td>15.75</td>
<td>0.53%</td>
</tr>
<tr>
<td>15.00</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

221 Particles:
min = 0.197 mm
max = 26.631 mm
mean = 9.407 mm
stdev = 10.977 mm
mode = 23.500 mm
D10 = 19.708 mm
D25 = 21.534 mm
D50 = 23.279 mm
D75 = 24.459 mm
D90 = 25.466 mm
sph = 0.907

Non-Calibrated:
Xmax = 26.631 mm
X50 = 23.279 mm
b = 2.660
n = 13.289

Figure 148 IMG_0664, Accuracy Analysis Photo 5, WipFrag Results
Figure 149 Original IMG_0666, Accuracy Analysis Photo 6

Figure 150 IMG_0666, Accuracy Analysis Photo 6, WipFrag Processed

Figure 151 IMG_0666, Accuracy Analysis Photo 6, WipFrag Results

Coins Accuracy Analysis
Custom Bin Size

WipFrag 2010 Build 16 Thomas Waterman - TU Delft - 01B8
IMG_0666 February 06, 2014, 03:09:51 PM GMT Standard Time

235 Particles:
min = 0.203 mm
max = 26.987 mm
mean = 9.157 mm
stdev = 10.790 mm
mode = 23.500 mm
D10 = 18.463 mm
D25 = 20.463 mm
D50 = 23.101 mm
D75 = 24.710 mm
D90 = 26.151 mm
sph = 0.906

Non-Calibrated:
Xmax = 26.987 mm
X50 = 23.101 mm
Xc = 24.002 mm
b = 2.230
n = 10.587

Size (mm) % Passing

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.00%</td>
</tr>
<tr>
<td>1.0</td>
<td>5.00%</td>
</tr>
<tr>
<td>10.0</td>
<td>27.50%</td>
</tr>
<tr>
<td>20.0</td>
<td>45.75%</td>
</tr>
<tr>
<td>30.0</td>
<td>54.82%</td>
</tr>
<tr>
<td>40.0</td>
<td>79.84%</td>
</tr>
<tr>
<td>50.0</td>
<td>90.87%</td>
</tr>
<tr>
<td>60.0</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Diameter of an Equivalent Sphere

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.50</td>
<td>100.00%</td>
</tr>
<tr>
<td>26.25</td>
<td>90.87%</td>
</tr>
<tr>
<td>25.00</td>
<td>79.84%</td>
</tr>
<tr>
<td>23.50</td>
<td>54.82%</td>
</tr>
<tr>
<td>22.75</td>
<td>45.75%</td>
</tr>
<tr>
<td>22.00</td>
<td>37.32%</td>
</tr>
<tr>
<td>20.75</td>
<td>27.59%</td>
</tr>
<tr>
<td>19.50</td>
<td>16.31%</td>
</tr>
<tr>
<td>18.25</td>
<td>9.00%</td>
</tr>
<tr>
<td>18.00</td>
<td>5.02%</td>
</tr>
<tr>
<td>17.00</td>
<td>0.54%</td>
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<tr>
<td>15.75</td>
<td>0.02%</td>
</tr>
<tr>
<td>15.00</td>
<td>0.02%</td>
</tr>
</tbody>
</table>
Figure 152 Original IMG_0667, Accuracy Analysis Photo 7

Figure 153 IMG_0667, Accuracy Analysis Photo 7, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size

WipFrag 2010 Build 16   Thomas Waterman - TU Delft - 01B8

302 Particles:
min = 0.188 mm
max = 26.583 mm
mean = 7.391 mm
stddev = 9.967 mm
mode = 23.550 mm
D10 = 17.352 mm
D25 = 19.396 mm
D50 = 21.929 mm
D75 = 24.460 mm
D90 = 25.767 mm
sph = 0.910

Non-Calibrated:
Xmax = 26.583 mm
X50 = 21.929 mm
Xc = 23.419 mm
b = 2.190
n = 8.253

Size (mm) % Passing
27.50 100.00%
26.25 95.47%
25.00 81.30%
23.50 63.82%
22.75 58.11%
22.00 50.56%
20.75 40.77%
19.50 26.33%
18.25 10.34%
17.00 9.63%
15.75 0.55%
15.00 0.03%

Figure 154 IMG_0667, Accuracy Analysis Photo 7, WipFrag Results
# Coins Accuracy Analysis

## Custom Bin Size

**WipFrag 2010 Build 16  Thomas Waterman - TU Delft - 01B8**  
**IMG_0820  March 05, 2014, 12:58:53 PM GMT Standard Time**

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
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<td>0.1</td>
<td>100.00%</td>
</tr>
<tr>
<td>1.0</td>
<td>100.00%</td>
</tr>
<tr>
<td>2.0</td>
<td>85.50%</td>
</tr>
<tr>
<td>3.0</td>
<td>65.60%</td>
</tr>
<tr>
<td>4.0</td>
<td>60.85%</td>
</tr>
<tr>
<td>5.0</td>
<td>50.65%</td>
</tr>
<tr>
<td>6.0</td>
<td>34.92%</td>
</tr>
<tr>
<td>7.0</td>
<td>25.96%</td>
</tr>
<tr>
<td>8.0</td>
<td>13.29%</td>
</tr>
<tr>
<td>9.0</td>
<td>7.46%</td>
</tr>
<tr>
<td>10.0</td>
<td>1.61%</td>
</tr>
<tr>
<td>15.0</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

**Non-Calibrated:**  
- $X_{max} = 26.099$ mm  
- $X_c = 23.121$ mm  
- $b = 2.140$  
- $n = 8.552$

---

Figure 155 Original IMG_0820, Accuracy Analysis Photo 8

Figure 156 IMG_0820, Accuracy Analysis Photo 8, WipFrag Processed

Figure 157 IMG_0820, Accuracy Analysis Photo 8, WipFrag Results
Figure 158 Original IMG_0821, Accuracy Analysis Photo 9

Figure 159 IMG_0821, Accuracy Analysis Photo 9, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size
WipFrag 2010 Build 16 Thomas Waterman - TU Delft - 01B8
IMG_0821 March 09, 2014, 10:43:57 PM GMT Standard Time

Size (mm) % Passing
27.50 100.00%
26.25 100.00%
25.00 71.98%
23.50 63.95%
22.75 35.93%
22.00 24.51%
20.75 15.22%
19.50 12.44%
18.25 4.27%
17.00 2.89%
15.75 1.11%
15.00 0.03%

Figure 160 IMG_0821, Accuracy Analysis Photo 9, WipFrag Results
Figure 161 Original IMG_0822, Accuracy Analysis Photo 10

Figure 162 IMG_0822, Accuracy Analysis Photo 10, WipFrag Processed

Figure 163 IMG_0822, Accuracy Analysis Photo 10, WipFrag Results
Figure 164 Original IMG_0823, Accuracy Analysis Photo 11

Figure 165 IMG_0823, Accuracy Analysis Photo 11, WipFrag Processed

Coins Accuracy Analysis
Custom Bin Size
WipFrag 2010 Build 16   Thomas Waterman - TU Delft - 01B8
IMG_0823   March 14, 2014, 08:41:40 PM GMT Standard Time

198 Particles:
min = 0.197 mm
max = 27.034 mm
mean = 9.014 mm
stddev = 10.944 mm
D10 = 19.061 mm
D25 = 20.886 mm
D50 = 23.203 mm
D75 = 25.516 mm
D90 = 26.501 mm
sph = 0.905

Non-Calibrated:
Xmax = 27.034 mm
X50 = 23.203 mm
Xc = 24.621 mm
b = 2.080
n = 9.789

Size (mm) % Passing
27.50 100.00%
26.25 87.49%
25.00 66.22%
23.50 54.26%
22.75 43.50%
22.00 31.03%
20.75 24.27%
19.50 11.91%
18.25 6.48%
17.00 3.33%
15.75 0.02%
15.00 0.02%

Figure 166 IMG_0823, Accuracy Analysis Photo 11, WipFrag Results
Normal Distribution + Cumulative Distribution Graphs.

**Figure 167 0.01 EUR Histogram**

- **Standard Deviation = 0.378 mm, μ = 16.077 mm**

**Figure 168 0.02 EUR Histogram**

- **Standard Deviation = 0.468 mm, μ = 18.656 mm**
Figure 169 0.05 EUR Histogram

Figure 170 0.1 EUR Histogram

Figure 171 0.2 EUR Histogram
Figure 172 0.5 EUR Histogram

Figure 173 1 EUR Histogram

Figure 174 2 EUR Histogram
Figure 175 0.01 Normal Distribution + Cumulative Distribution Graph

Figure 176 0.02 Normal Distribution + Cumulative Distribution Graph

Figure 177 0.05 Normal Distribution + Cumulative Distribution Graph
Figure 181 1 EUR Normal Distribution + Cumulative Distribution Graph

Figure 182 2 EUR Normal Distribution + Cumulative Distribution Graph