Borehole Dimension Impact on LHD Operation in Malmberget Mine

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Abstract

Sublevel caving is a highly mechanizable mass mining method normally utilized in large, steeply dipping orebodies. The fragmented ore flows freely, aided by gravity, down to the drawpoint while the surrounding waste rock caves in due to induced stresses and gravity. Fragmentation of the blasted ore is a vital component in any mining operation and directly affects productivity and efficiency of the following production steps (Nielsen et. al, 1996).

In an attempt to reduce mining induced seismicity in Malmberget, LKAB is initiating various trials. One of these trials involves a reduction in blasthole dimension and an increase in the number of blastholes utilized in each ring. A reduction in blasthole dimension is undertaken to achieve a less impactful mining operation in terms of disturbances to surface populated areas, particularly addressed to ground vibrations. Therefore, it is of utmost importance to analyse if fragmentation and production is affected as a consequence of this change.

This thesis sets out to evaluate how fragmentation and the LHD operation is affected by variations in blasthole dimension. The evaluation is carried out through analysis of logged production data, on-site filming of the loading sequence and interviews with the LHD operators. The discoveries will be presented chronologically to illustrate the complexities related to compiling a viable dataset to rely on for a credible analysis. The initial theory did not hold up properly and therefore the project was reshaped along the course of progression to provide further information and clarify uncertainties. Unfortunate, major production delays inhibited a quantitative comparison of two parallel drifts with different blasthole dimensions. Hence, no final answer can be provided in this thesis whether a change in blasthole dimension causes any differences in loadability and/or fragmentation or not. However, an analysis of how cycle times vary depending on causes such as operator induced differences, machine induced differences and road conditions will be provided. The field test also provides information on various loading scenarios and the difficulties connected to these.

The result obtained in this project mainly addresses the significant operator difference in terms of cycle times which can extend to, on average, 60% depending on experience, road conditions and, most likely, preferences amongst operators. Time differences amongst seemingly experienced operators can reach more than, on average, 30% in hauling time alone. Roughly 96% of the operators state that road conditions in the production area is the controlling factor for hauling speed. Many of the operators further states that the risk of injuries is directly related to road conditions and this is a likely cause to why cycle times vary in this magnitude. Fragmentation was found to affect loadability but not to the same extent as shape and looseness of the muck pile. Compaction of the muck pile and flow disturbances where normally found to be connected to one another. Hence, good loadability would indicate a low occurrence of flow disturbances and a continuous flow of material into the drawpoint.

This thesis is written as a part of the final stage of the civil engineering program at Luleå University of Technology (LTU) and represents 30 credits in the field of Soil and Rock Construction. The thesis is a part of a larger project, *Face to surface*, which sets out to analyse the impact of fragmentation on different stages in the production chain.
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1 Introduction

1.1 Background

The progressive ore extraction in LKABs underground mine in Malmberget has reshaped the city during the last decades. Large pits have appeared on the surface as a consequence of ore removal more than a thousand meters below the ground surface. The induced seismicity, caused by mining operations, affects the surrounding civilization in a negative manner (Umeå tingsrätt, 2015). The vibrations from underground blasting causes damage to buildings and infrastructure, forcing residents to move elsewhere, further away from the influenced area to escape the impact. Figure 1 shows Kaptensgropen which is located next to the residential area of Malmberget, illustrating the impact of mining operations on the city.

Figure 1: Kaptensgropen in Malmberget (svid.se, 2015)

In May 2015, the environmental court in Umeå established a series of future regulations regarding LKABs mining operation in Malmberget. One of these regulations concerns vibrations and noise levels from underground blasting which causes discomfort for the residents living in the affected area. Summarized, the overall goal with all regulations issued by the environmental court is to minimize the effect from underground ore extraction on the surroundings. (Umeå tingsrätt, 2015)

In order to manage these regulations, LKAB is implementing various trials. One of these trials involves an increase in the number of boreholes in each production ring but with a reduction
in borehole dimension. A decreased hole dimension is believed to result in a somewhat lower impact (noise, vibration etc.) on the surroundings. A better distribution of explosives within the rock mass could potentially also improve fragmentation, enhance gravity flow and hence production (Brunton et al, 2009).

However, the outcome of such a change is not entirely tested and evaluated before. Hence, it is of importance to understand how, and where in the process, a reduction in borehole dimension affects production. The knowledge obtained from investigating this further could potentially be used in order to optimize the mining process and enable a more effective ore extraction, both in terms of energy consumption and production rate.

1.2 Problem statement

This study will focus on how the LHD operation is affected when the borehole diameter is reduced from 4,5” (~114mm) to 4” (~102mm) while maintaining roughly the same specific charge by utilizing an additional borehole in the rings with 4” holes.

1.3 Purpose and scope

The intention of this project is to determine if a reduction in borehole dimension has an effect on productivity. This is important due to the increasingly competitive nature of the mining industry along with tougher regulations introduced by authorities. Research like this is important to achieve a productive yet sustainable mining operation. It is vital to enable further mining advances while minimizing the effects on the surroundings.

1.3 Problem description

1.3.1 General

This project consists of a pre-investigation and a field test. The field test was primarily carried out to gain a better understanding of the logged data preliminary used for the analysis. However, data obtained from the field test was also analysed separately other than validating the initial analysis to gain further knowledge on the muck pile characteristics along the course of extraction.
1.3.2 Pre-investigation

An initial analysis of historical and recent data from Fabian ore body was carried out to gain knowledge on what kind of information that can be extracted from logged data obtained from Giron (LKAB database). In order to solve the stated problem, the following questions have to be answered:

- Is it possible to use cycle times as an indirect measurement on muck pile loadability and/or fragmentation?
- Is volumetric bucket filling statistically affected by variations in blasthole dimension?
- Is there a visible trend indicating that the frequency of oversized boulders increases or decreases with a reduction in blasthole dimension?
- Is there a visible trend in terms of crushing energy requirements separating conventional rings from rings with a reduced blasthole dimension?

1.3.3 Field test

A field test was carried out in Fabian 905 to clarify uncertainties in the logged data obtained from Giron (LKAB database). A camera was mounted in the ceiling, alternating between drift 1450 and 1470 and roughly 700 loading cycles were captured on film. This material was used to gain an improved understanding of the logged data and to provide further information on the LHD operation.

Interviews with the LHD operators were conducted sporadically during the course of the project. A larger survey was also performed to obtain statistical information regarding variations in loading times, hauling times, bucket filling and overall information on how the operators view their impact on production.

1.4 Challenges

The challenges presented in this thesis are many and varies in nature and difficulty. The main obstacle is to verify that the chosen method for evaluating loadability is suitable and reliable enough to use for the analysis. Once having a solid dataset to rely on, the analysis poses no direct challenges but rather careful observation. The main practical challenge is to get access to reliable information through underground field tests while interfering minimally with production.
1.5 Limitations

This project is largely limited to observation of existing logged data and on-site collected data. A thorough analysis and categorization of LHD operators in terms of efficiency will not be performed due to integrity related matters. The variation in operator efficiency will be addressed in general terms to enlighten the reader of the occurring problems related to using time as an indirect measurement of muck pile loadability. No statistically validated and confirmed data will be presented regarding efficiency of different LHD units. The variations amongst LHD units in terms of time requirements is addressed briefly and solely to inform the reader that differences exists and that time is an evasive measurement, influenced by multiple and separately controllable and uncontrollable factors.

2 Theory

2.1 Sublevel caving

Sublevel caving relies on gravitational forces along with induced stresses acting on the blasted ore and the surrounding waste rock. The blasted ore flows gravitationally to the drawpoint while the waste rock caves in and fills the void of the extracted ring, to some extent acting as support. (Kvapil, 1998)

Modern sublevel caving practice, as utilized today, differs substantially from the originally intended practice (Hustrulid & Kvapil, 2008). Initially the ore was not drilled and blasted completely between two sublevels but rather fractured by caving unlike today. Many argues that the mining method should be renamed to sublevel retreat stoping or continuous underhand sublevel stoping since it does not longer rely on the ore being fragmented by natural induced caving (Kvapil, 1998). The foundation to the modern practice of sublevel caving was established in the 1950s when the Royal Institute of Technology (KTH) in Stockholm developed models for gravity flow of broken rock. Initially, problems regarding early dilution entry, low tonnage factors and low recovery inhibited an effective and financially viable utilization of sublevel caving as a primary excavation method. To a large extent, this development took place in Swedish iron mines although the original method was adopted from America where geological conditions are less suitable for this kind of operation. (Hustrulid & Kvapil 2008).

The method has gradually been scaled up in order to cut costs and increase productivity (Fjellborg et. al, 1996). Sublevel caving is today mainly used in hard, strong ore materials, such as iron ore, where the hanging wall rock will naturally cave (Dunstan & Power, 2011).
Sublevel heights have increased over the years. In the early days roughly 25% of the ore recovery came from drifting while this percentage dropped to about 6% today. Initially the sublevel intervals spanned around 9 meters compared to 30 meters which is commonly used today. (Bullock & Hustrulid 2001)

The advantages of sublevel caving are its highly mechanizable production chain, high degree of ore recovery and the safety achievable while maintaining a high production pace. The disadvantages are high ore dilution i.e. problem with waste rock involvement in the extracted ore, and high development cost. The high degree of mechanization allows for a substantial automation of the process which today and in the future could improve production and increase safety. Sublevel caving is considered one of the most advanced underground mining methods and has been used as a primary mining method in LKAB since 1962. (Quinteiro et. al, 2001)

In the last three decades, SLC has evolved into a highly mechanized and low cost mass mining method. Many mines in Australia have recently adopted SLC as a primary extraction method with good results (Bull and Page, 2000).

2.2 Underground development

Sublevel caving requires intelligent development in order to maximize ore recovery while keeping dilution low (Dunstan & Power 2011). Ore is extracted through a network of sublevels which allows the blasted ore to flow freely from production rings into the draw point. Each level consists of a number of parallel drifts enabling access to the entire ore body. The sublevels are positioned 20 to 30 meters apart, beginning at the top of the ore body, progressively working its way downwards (Wimmer, 2010), see Figure 2.

![Sublevel caving layout](image)

*Figure 2: Sublevel caving layout (Underground mining methods, 2003)*
Sublevel caving relies on a fixed unit operation executed simultaneously in different areas to enable for a continuous production flow. The first step, development, involves enabling access to the orebody from the existing infrastructure i.e. ramps and main levels. The drifts are normally supported with shotcrete, bolts and mesh to ensure a safe working environment for the drillers, chargers and LHD operators (LKAB, n.d. “Sub-level caving”). Development is continuously progressed and new levels, drifts and ore passes are constantly developed to allow for continuous production without any interruptions.

When drifting is completed, vertical to near vertical holes are drilled up into the orebody. These sets of near vertical boreholes are collectively termed as a production ring or fan. The distance between two rings is normally 3-3.5m. A fan commonly consists of eight bore holes with a diameter of 115mm (Dunstan & Power, 2011). However, the number of holes and the relative angle of these vary depending on geology and other factors (Brunton, 2009). All fans in a drift are commonly drilled before the first blast takes place.

Charging is initiated at the bottom of the blasthole and the charging hose is then retracted automatically with a constant speed. The specific charge is normally 11-12 kg/m (1.35 kg/m³). In case of wet boreholes, packaged explosives can be utilized to prevent normally occurring problems in these conditions. The first ring is then detonated, breaking the ore into fragments which enters the drawpoint. Explosive sleep time, i.e. the time the explosive sits in the hole before blasting, is commonly one month but periods up to one year has been recorded. Nitrate leakage and degradation of the explosives might then occur, possibly influencing fragmentation negatively. (Wimmer et al. 2012)

The explosives in a ring are supposed to uniformly fracture the intact rock into somewhat similarly sized fragments. However, this is not the case due to the chaotic nature of underground blasting. Blasting in SLC takes place in semi-confined conditions where the blasted material swells and the caved material compacts. The caved material fills the void created (to some extent) in the production drift (Dunstan & Power, 2011).

The blasted material flows freely down to the drawpoint, this is generally referred to as gravity flow (Kvapil, 1995). One of the main difficulties connected to sublevel caving is to keep the inflow of caved waste rock from previous sublevels and previous rings low. Fragmentation is believed to have a significant effect on this undesirable phenomenon. (Wimmer, 2010). Figure 3 shows the panel layout in sublevel caving.
Figure 3: Sublevel panel layout

The broken material is removed successively using LHD (Load-Haul-Dump) units and dumped into ore passes leading down to the main level below. It is then loaded onto trucks or trains, depending on mine, for transportation to the crushers where the material is further fragmented before being hoisted to the surface. Oversized boulders will be treated separately and blasted further before being dumped into the ore passes. If the oversized boulders are too large for the LHD units to haul from the production drift to the designated area they are blasted on-site causing a temporary production stop in that drift. (Personal communication, LHD operator LKAB, 2016-02-28)

Loading continues until the material grade has dropped to a predetermined level termed as shut-down grade. This level is carefully governed by economic incentives and may vary with time (Nilsson, 1982). At this point, loading is ceased and the next ring is blasted after which loading is commenced again. Extraction rate is a term used to control the actual extracted material with the theoretical extraction for each ring. The actual extracted tonnage rarely coheres with the theoretical tonnage expected from each ring. This is due to ore being left in the upper levels and/or previous rings which causes additional ore to enter the draw point in another ring at a different time. The tonnage extracted from two separate rings might differ substantially although the theoretical tonnage was the same. (Personal communication, LHD operator LKAB, 2016-04-26)

Draw control is a vital function in any sublevel caving operation. Premature cut-off entails poor or insufficient ore recovery while delayed cut-off results in high dilution. Theories for determining the optimal cut-off point is constantly under development.
Hang-ups might occur when the material forms an arch over the muck pile causing gravity flow disturbances. Blasting of a ring in an adjacent drift or other measures such as utilization of water-cannons might be required to resume the flow. Problems in the ore passes are also a reoccurring problem causing major production delays and additional costs. (Personal communication, Peter Holmgren LKAB, 2016-04-15)

2.3 Malmberget mine

2.3.1 Introduction

LKAB (Loussavaara Kirunavaara AB) is a Swedish mining company specializing in production and refinement of high quality iron ore products. The company was founded in 1890 and has been fully state owned since 1976. The iron ore reserve in northern Sweden has been recognized since the early 1600s but the lack of infrastructure in the desolated landscape of northern Sweden prevented any serious attempt to extract iron ore on a large scale. Industrial extraction began in the early 1900s after completion of the infamous railway *malmbanan* which stretches from Luleå in the south to Narvik (Norway) in the north. Harbours are established in both cities to allow for shipping of iron ore products to customers around the world. Today LKAB is operating in Kiruna, Malmberget and Svappavaara, supplying roughly 4% of the world’s iron ore demand (Ericsson et al. 2011). See *Figure 4*.

![Figure 4: LKAB operational areas (LKAB database)](image)

Malmberget is situated in northern Sweden, roughly 70km north of the arctic circle, and is home to the second largest underground iron ore mine in the world. Around 17 million tons of ore is produced each year distributed from the 12 ore bodies, see *Figure 5*, currently being in
production in Malmberget (International Mining, 2014). There are eight more orebodies that are not being mined at this time. The entire underground area is about 5 by 2.5km and the orebodies are situated at different depths with main levels established at 600, 815, 1000 and 1250m. The main levels are developed successively for each area as production reaches new depths.

To this day more than 350 Mt of ore has been extracted in Malmberget and measurements prove that the reserve is more than 303 Mt and another 35 Mt is indicated and interfered beyond that (LKAB annual report, 2014).

![Figure 5: Malmberget from above (LKAB database)](image)

Normally, iron ore can be found shallowly in the earth’s crust enabling access through open pit mining which allows for utilization of larger equipment and a greater production rate than that of an underground mine. The reason to why LKAB is successfully mining iron ore at more than 1000 meters below the surface is due to high efficiency and large scale, comparable to open pit mines (LKAB, n.d. “Mining the ore”). The exceptional Fe-content and the advanced technology utilized is obviously a key factor to LKABs success. The underground operation in Kiruna and Malmberget is amongst the most advanced of its kind.
2.3.2 Sublevel caving in Malmberget mine

The mining operation in Malmberget is similar to the operation in Kiruna in terms of utilized methods and techniques. One of the most significant differences is the utilization of trucks (Malmberget) instead of trains (Kiruna) to haul the ore from ore passes to the crushers (International Mining, 2014). The layout of Malmberget mine is too complex and inhomogeneous to allow for an effective utilization of trains hence requiring a more flexible solution. The trucks have payload capacities of 90 to 100 tons and the extensive number of trucks operating at any given time reduces the risk of production stops due to machine failure. There are crushers at each level and the crushed ore is transported on conveyor belts to the skip shaft from where it is hoisted to the surface for further processing (International Mining, 2014).

In 2013, the Malmberget mining department had about 525 full time employees. Another 100, consisting of LKAB workforce and contractors, are also working in the mine at any given day. Ore production is mainly conducted by LKAB personell, but development of new levels and pre-production development are often conducted by contractors where Veidekke and Bergteamet are the largest (International Mining, 2014).

2.3.3 Geology

The ore deposit in Malmberget includes 21 ore bodies of various size and shape. They are spread out over an area of 5 kilometers in the W-E direction and 2.5 kilometers in the N-S direction. The ore bodies in the western field inherit 90-95% magnetite and 5-10% hematite while the ore bodies in the eastern field is constituted of almost 100% magnetite (International Mining, 2014). See Figure 6.

The most frequently occurring polluting minerals are apatite, amphibolite, pyroxene and biotite and the ore bodies are commonly surrounded by breccia or skarn breccia types. The host rocks inherits a felsic to mafic composition and are usually called leptites in the Malmberget area. The Malmberget deposit is stronger metamorphosed and deformed than the Kiirunavaara deposit and has been exposed to ductile deformations (Martinsson, 2004). Granite veins often intrude the ore (Hedstrom et al., 2001). The dip of the ore bodies varies from 45° to 70° and the iron content varies from 54 to 63% (Hedstrom et al., 2001).
2.3.4 LHDs in Malmberget

In Malmberget, ore is hauled from the drawpoint to the orepass using LHD machines. LHD machines consist of two separate parts connected by an axis, allowing for a shorter turning radius which is required in narrow mine drifts (Dragt et al. 2005) See Figure 7.

The LHD machines used in LKAB Malmberget are Cat R2900G, Cat R2900Xtra, Cat R3000H, Toro 0011 and Toro LH621. The Cat machines utilized are roughly the same; the R3000H has a more powerful hydraulic system, a different beam and frame compared to the R2900G and R2900Xtra (Caterpillar, n.d. “Underjordslastare för gruvdrift”). Toro LH621 is an updated model of the Toro 0011 with a different engine and different brakes (Sandvik, n.d. “Underground LHDs”). The machines have a tramming capacity of 20-21t. The LHD’s operate at a speed of 10-20km/h and all LHD units in Malmberget mine runs on diesel. (Personal communication, LHD operator LKAB, 2015-12-04)
There are 13 LHDs operating at the eastern field of which 8.5 is available at any given time. Nine of these machines are Caterpillar and four are Sandvik Toro. Cat machines constitute 60% of the total fleet and Sandvik Toro 40% (International Mining, 2014). A 12 month trial of a semi-automated LHD (Cat R2900G) has taken place in Malmberget mine during 2007-2008. These tests has been conducted with promising results and production increase (10-20%) (Schunnesson, 2009) combined with reduced maintenance requirements (Caterpillar, 2008) giving a strong incentive to pursue this technology. However, no automated or semi-automated LHDs are currently in use in Malmberget.

A comparison between the different LHDs in use can be seen in table 1 below. Figure 8 and 9 shows a Caterpillar respectively a Toro machine.
### Table 1: LHD comparison

<table>
<thead>
<tr>
<th></th>
<th>Caterpillar R2900 XTRA</th>
<th>Caterpillar R2900G</th>
<th>Sandvik Toro LH621</th>
<th>Sandvik Toro 0011</th>
<th>Caterpillar R3000H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tramming capacity</strong></td>
<td>20 000kg</td>
<td>17 200kg</td>
<td>21 000kg</td>
<td>21 000kg</td>
<td>20 000kg</td>
</tr>
<tr>
<td><strong>Operating weight (unloaded)</strong></td>
<td>55 575kg</td>
<td>50 209kg</td>
<td>56 800kg</td>
<td>56 800kg</td>
<td>56 000kg</td>
</tr>
<tr>
<td><strong>Breakout force</strong></td>
<td>268 kN</td>
<td>268 kN</td>
<td>378 kN</td>
<td>378 kN</td>
<td>275 kN</td>
</tr>
<tr>
<td><strong>Tipping load</strong></td>
<td>47 800kg</td>
<td>40 000kg</td>
<td>47 700kg</td>
<td>47 700kg</td>
<td>47 300kg</td>
</tr>
<tr>
<td><strong>Raising time</strong></td>
<td>9,2 sec</td>
<td>9,2 sec</td>
<td>8,4 sec</td>
<td>8,4 sec</td>
<td>8,8 sec</td>
</tr>
<tr>
<td><strong>Lowering time</strong></td>
<td>3,1 sec</td>
<td>3,1 sec</td>
<td>4,5 sec</td>
<td>4,5 sec</td>
<td>3,5 sec</td>
</tr>
<tr>
<td><strong>Tipping time</strong></td>
<td>3,4 sec</td>
<td>3,4 sec</td>
<td>1,8 sec</td>
<td>1,8 sec</td>
<td>1,9 sec</td>
</tr>
<tr>
<td><strong>Engine output</strong></td>
<td>321 Kw (436 hp) 1900 rpm</td>
<td>305 Kw (409 hp) 1800 rpm</td>
<td>345 kW (469 hp) 1900 rpm</td>
<td>354 kW (475 hp) 2100 rpm</td>
<td>305 kW (409 hp) 1800 rpm</td>
</tr>
<tr>
<td><strong>Fuel tank capacity</strong></td>
<td>854 l</td>
<td>1425 l (dual)</td>
<td>620 l</td>
<td>620 l</td>
<td>1539 l</td>
</tr>
</tbody>
</table>

*Figure 8: Toro LH621, Courtesy of Sandvik  Figure 9: Cat R3000H, Courtesy of CAT*

Each machine is equipped with a tag locating and logging where the machine operates at different times. Cycle times, bucket weight, dumping point etc. are also logged internally and are transmitted to the surface using the *Wolis* system. Hydraulic systems are utilized to steer, brake and move the bucket. Built in systems monitoring the bucket weight at the end of each cycle is based on hydraulic pressure in the cylinder arms.
2.4 Fragmentation in SLC

Fragmentation is a measure of how well the rock has fractured post blasting. Block size, cracks and micro cracks are all dependent on how blasting affected the rock mechanical properties of the initially intact rock mass. The blasted rock should optimally be kept within a suitable size distribution span i.e. neither be too large or too small, and preferably have internal fractures (cracks, micro cracks etc.) in order to reduce crushing energy while maintaining an efficient handling during loading and transport. (Nielsen et. al, 1996)

It is verified that fragmentation affects both loadability, i.e. the initial handling of the blasted rock and energy consumption of the crusher (Ouchterlony et al. 2010). The frequency of stops due to occurrences of oversized boulders and prolonged cycle times due to sub-optimal digability, inhibits an effective and smooth operation.

Large boulders will not only be more difficult to handle for the LHD operator but will also affect the bucket filling in a negative manner (Doktan, 2001). Boulders also interfere with production and affect the quality of the crushing process (Johansson, 2008). If the loader can move the boulder, it is transported to a separate drift outside of the production area for further fragmentation by blasting. If the boulder cannot be moved by the loader it must be blasted at the drawpoint. Boulders might also cause hang-ups, inhibiting flow of material to the drawpoint. A stable production flow with less/smaller sized boulders could potentially decrease the number of problems occurring at the loading stage, hence increasing productivity. LHD operators frequently reports problems regarding boulders and earlier studies shows that these problems are not only frequent and costly but also increase the need for equipment maintenance and risks for accidents (Kumar, 1997).

Through small and large scale tests in LKAB sites, fragmentation of iron-ore and waste rock is proven to be similar if subjected to the same blasting conditions. The caving material however is thought to have a difference. The caved waste rock is generally coarser than the caved ore and the percentages of fines are higher for waste rock. Differences in Fe-content should therefore mainly affect fragmentation if the material is caved and not directly subjected to blasting. (Wimmer et al, 2008)

Recent and past fragmentation studies show that fragmentation varies substantially from bucket to bucket even though no waste rock inflow is present. A field test performed by Wimmer (2012) showed variations in fragmentation within a blasted ring. The rock conditions were judged to be competent and undisturbed and six consecutively buckets showed differences in $x_{50}$ from 14.3mm and 277.6mm whilst the bucket weights varied from 14.3t to 18.5t. Similar results regarding fragmentation were found earlier by Maripuu (1968).

Kumar (1995) recorded that the smallest Over Sized Boulders (OSBs) handled separately before dumping it in the ore pass was 100x90x80cm, when the definition of boulders at the time was 70x70x70cm. This indicates that many OSBs are fed to the ore pass, possibly causing problems further down the production chain. Wimmer et al. (2015) further concluded that the boulder handling increased by a factor of 3-4 when a reduction of grizzly gap from
1m to 0,7m was adopted in Kiruna. This indicates that the majority of boulders encountered are in the range of 0,7-1m.

Kumar (1995) also concluded that the number of OSBs was correlating well with the local geology and Rock Quality Designation (RQD) value. A high RQD value resulted in a higher frequency of OSBs. During the course of this particular study, no hang-ups occurred in the ore passes but it was recalled that the dumping of OSBs in the ore shaft increased the need for shaft maintenance and hence the maintenance costs.

Differences in geology can alter predicted fragmentation due to its inhomogeneous properties which are difficult to account for entirely (Dunstan & Power, 2011). Fragmentation in different rings with identical layout and use of explosives, may differ a lot due to this. The intact rock mass properties and local in-situ stress also determines the outcome of the blast (Dunstan & Power, 2011). Normally, in underground mining, the information on the rock mass is limited causing further uncertainties.

Hang-ups normally occurs when larger boulders together with smaller fragments creates an arch hindering blasted material above to flow freely into the drift. Reportedly, 50% of the rings in sublevel caving are subjected to hang-ups at various point of mucking (Dunstan & Power, 2011). Blasting of adjacent rings may resolve the problem but in extreme cases secondary blasting is utilized as a last resort. However, this is undesirable due to risks of damaging the brow (Dunstan & Power, 2011). Sub-optimal fragmentation is believed to increases the frequency of hang-ups in SLC (Wimmer et al. 2012).

Most of the problems occurring in the ore passes are addressed to boulders being present in the hauled material. The ore passes are blocked and the flow interrupted. Drilling and blasting is required to break the stoppage and resume the flow. When resolving these problems by drilling and blasting the ore passes are often damaged, increasing the risks for future blockages. (Kumar, 1995)

Ideally, no OSBs are transported to the ore pass but rather to a designated area to reduce their size before dumping them in the ore pass. However, operators are known to occasionally bypass this step (Kumar, 1995).

Large fragments require more energy to crush than smaller ones and the energy consumption of the crusher is directly linked to the fragment size and the micro-cracks within the fragments (Nielsen and Kristiansen, 1996). The amount of energy the intact rock mass is subjected to during blasting in non-confined conditions is negatively correlating to the amount of energy required in the crushing stage (Ouchterlony et al. 2010).
2.5 Loading

The efficiency of the loading process is heavily dependent on fragmentation; large boulders have to be treated separately by the LHD operator and can in some cases require further drilling and blasting before it is even possible to remove them from the drift. Temporary production stop in the drift will occur and production has to be relocated elsewhere. Larger fragments also interfere with a smooth digging cycle and might increase the need for reloading or separate boulder handling. (Personal communication, LHD operator LKAB, 2015-12-03)

The issues of confined blasting in terms of recovery are mentioned by Brunton (2009): “…The blasted material has little to no space to swell, therefore resulting in ‘tightness’ of the material or even ‘freezing’”. Cullum (1974) recalled that this will lead to a tight, semi-fractured material which will be difficult to draw.

Ouchterlony et al. (2010) evaluated the differences in loading time in relation to different blasting parameters in a quarry. A smooth loading with eventual reloading was separated from loading cycles including other activities such as material handling etc. The loading cycle started at initial penetration of the muck pile and ended when the bucket was in an upright position prepared for hauling. It was found that all loading cycles shorter than 32 sec did not include material handling or other activities. The blasting was performed with a “normal” specific charge (0.7kg/m³) and a “higher” specific charge (1 kg/m³) in order to visualize variations in fragmentation between the two test setups. It was found that if the loading cycle was smooth i.e. no reloading etc. the average loading time was roughly the same independent on the specific charge. However, the number of loading cycles involving reloading decreased with an increase in the specific charge. With the normal specific charge it was found that 80-85% of the cycles required reloading while with the higher specific charge that number dropped to 50-60%.

The total cycle times showed a reduction in standard deviation if a higher specific charge was utilized than if the specific charge was normal. The sieving test performed showed that using a higher specific charge lead to finer fragments. This would indicate that better fragmentation will result in, on average, shorter and less deviant cycle times. However, the increased complexity of blasting a ring underground, under semi-confined conditions, and limited clearance during loading should not be neglected. The compaction factor of the blasted material is a real obstacle in SLC while only a marginal effect is expected when loading in an open cast mine or quarry.

Greater drift widths improve the efficiency of the LHD operations as it has more clearance and allows for faster loading. See Figure 10 & 11. It is also an advantage that the LHD is able to load from side to side in the muck pile which ensures a more even flow of material into the production drift (Dunstan & Power, 2011). Width dimension also increases the width of draw and overall mobility of material (Quintero, 2001).
Disturbances interfering with the LHD operation are common and occur frequently in underground mining. Gustafson, 2013, found that seventy-five percent of the stops entailing interruptions in the productivity of the LHDs are due to operating environment. Better fragmentation and better roads are believed to reduce the frequency of these problems.

It is not certain that the degree of fragmentation is reflected in the digging rate. A finer fragmentation with an unfavorable distribution might cause a more problematic digging scenario since the muck pile characteristics might not be suitable (compacted). However, it is generally agreed upon that the median fragment size should be kept low and the uniformity high in order to optimize production for loading, hauling and crushing (Personal communication, operators LKAB 2015-12-03).

At an open pit mine site, shovel digging times were reduced by 35% addressed to finer fragmentation while the loading productivity increased by 23%. This increase in performance was credited to faster dig and swing times of the dipper and higher truck payload. A total saving of 9% was estimated for the loading and hauling costs. (Doktan, 2001)
Singh et al. (1991) reported that coarser fragmentation was normally observed to reduce digging time, after which the underlying finer fragmentation was encountered. Finer material tended to be compacted and more difficult to dig based on visual judgment. Oversized fragments results in temporary delays until being side casted or removed while a high percentage of fines resulted in a reduction in productivity.

Wimmer et al. (2012) recalled that many hang-ups are never recorded but are resolved by the operator as extraction progresses. Gravity flow in rings previous to rings subjected to hang-up situations were of the shallow draw character. Inflow of waste rock either came from above or from the previous extracted (empty) ring. In cases of flow disturbances (hang-up) a cavity could form and after the collapse both ore and waste rock from previous rings periodically entered the drawpoint. The unrecorded hang-ups might then be the cause for waste rock inflow during seemingly normal mucking.

Kanchibotla et al. (1998) concluded that diggability is, aside from fragmentation, dependent on the shape and looseness of the muckpile. Hence it is incorrect to assume that an optimized fragmentation alone will reduce dig time. They also concluded that the excavator productivity is heavily influenced by the operator’s efficiency.

Since the loading is relatively fast in comparison with the entire cycle time, a significant difference in loading time has to be achieved in order to increase productivity more than marginally. An increase in bucket filling, however, will result in an equal increase in productivity given that the loading time is maintained unchanged. (Brunton et al, 2003) Bucket filling is therefore of great importance in all mining operations.

2.6 Drilling

The ability to drill long straight holes is the main obstacle in scaling up any SLC operation (Dunstan & Power, 2011). The reason to this is mainly due to borehole deviations causing unpredictable and uneven fragmentation. This will in turn increase the frequency of hang-ups and other fragmentation related issues further down the production chain. The costs of borehole deviations and the causes for its occurrence are further discussed by Kangwa (2000). The fan layout, borehole diameter, burden and ring inclination all to some extent affects the fragmentation of the blasted ore (Dunstan & Power, 2011).

Bad fragmentation can in some instances be addressed to inaccurate drilling. If the longitudinal angle is larger than 2°, the ends of the longest rings will be positioned in the wrong ring. The sideway deviations can cause poor fragmentation due to dead pressing or low concentration of explosives in some areas and higher in others. (Dunstan & Power, 2011)

Normally the largest possible blasthole dimension is chosen in sublevel caving where drilling capacity and explosive charging are the limiting factors. The distance between drifts is mainly decided based on the ability to drill long, straight holes. To achieve satisfactory fragmentation
throughout the ring, the drill holes must be evenly spaced, straight and adequately charged with suitable explosives. (Dunstan & Power, 2011)

Marker trials have shown that a layout with shorter and flatter side holes does not work. The flow generally occurs within a slim and relatively vertical zone hence the silo-shaped layout used today (Wimmer, 2012).

Different geological conditions have a large impact on how well the bore holes are suited for blasting (Dunstan & Power, 2011). Cracks, cavities, obstructions, deformations etc. is thought to be common at some locations and likely cause problems when blasting. Ongoing research with MWD analysis could potentially give more information on the borehole status before charging, hence reducing the number of poorly blasted holes resulting in improved fragmentation.

### 2.7 Blasting

The intent of sublevel caving blasting is to initially compact the caved material in front of the blast to create a void area for the fired ring to access (Dunstan & Power, 2011). Following this, the ore is fragmented as much as possible to enable for efficient extraction using LHDs. However, the sections of the holes closest to the drift below have a larger potential to swell and move out into the drift while the upper sections of the holes have a limited possibility to swell. The lower sections will also have higher concentration of explosives than the upper section since the distance between the blast holes increases as the distance from the drift increases. Finer, more uniform fragmentation is expected in the lower sections while the opposite is true for the upper sections (Dunstan & Power, 2011).

In LKAB Kiruna, measurements of nitrate leakage and function control has revealed that 10-15% of the holes within a ring do not detonate as planned (Fjellborg, 2002; Hedström, 2000; Zhang, 2005). This will lead to an uneven breakage front which in turn most probable will entail irregular burden for the subsequent ring. An uneven breakage front will therefore likely cause an uneven fragmentation (Wimmer, 2012) which causes disturbances further down the production chain.

Blasting might have the most prominent effect on fragmentation and there is a lot of blasting related variables which influences the fragmentation of the blasted ore. These different factors can be divided into factors into two categories; chaotic- and non-chaotic variables.

#### Non-chaotic variables

The blasting sequence in combination with the specific charge will influence the outcome of the blast i.e. the fragment size distribution (Ouchterlony et al. 2010). A low specific charge will entail larger fragments while the opposite is true for a high specific charge. The number of holes in a SLC fan has proven to have an effect on fragmentation due to the improved
distribution of explosives in the rock mass. These factors can be accounted for when designing and developing the drift (Brunton et al. 2009).

**Chaotic variables**

The ability to charge is a debated subject since it often is difficult to obtain information on if a hole is charged as planned or not or if charging problems have been encountered. In the case of in-hole cavities there is a risk that the charging hose cannot successfully penetrate through the cavity. This will consequently mean that the hole will be charged up to the cavity but no further, leaving the upper part uncharged. If, however, the charging hose manage to penetrate the cavity there is a risk that the explosives, inheriting toothpaste consistent, loses its adhesion to the rock in the cavities entailing blasting of the lower part only. (Personal communication, chargers, 2015-12-19) Measurements have shown that there is a substantial explosive leakage as well, causing further uncertainties (Fjellborg, 2002; Hedström, 2000; Zhang, 2005).

Each blasted ring influences the surrounding rings due to phenomena such as back-break and hole deviations etc. The initially planned blast of a ring normally does not inherit the properties and geometry as the actual blast. The unpredicted factors influencing the blasting of a ring causes further uncertainties in the next ring and the number of parameters makes it difficult to verify any predictions (Dunstan & Power, 2011).

**2.8 Crushing**

A small scale study by Michaux & Djordjevic (2004) suggested a production increase by up to 20% by optimizing fragmentation and Nielsen & Kristiansen (1996) indicated that there was a clear correlation between crack generation within the fragments and further handling including reduction in crushing energies.

Ouchterlony (2010) showed that fragmentation is influenced by the specific charge through extensive sieving tests of the blasted material. The sieved material was crushed and analyzed based on energy consumption of the crusher for different blasts with varying specific charge. It was concluded that a higher specific charge lead to a 5% increase in flow through the crusher entailing an energy reduction by 16%. Coarser fragmented material was shown to reduce the flow by 7% and increasing the energy consumption by 19%.

Katsabanis et al (2003) concluded that grinding effect is only marginally affected as a consequence of differences in blasting. However, a softening effect i.e. a decrease of resistance of the rock was found in the crushing stage meaning that less energy is required in this stage.

Kumar (1995) showed that Over Sized Boulders (OSBs) was proven to cause delays of up to 1500 hours per year due to 3000 OSBs encountered in Kiruna mine. The mean time to failure (MTTF) was 26 hours without OSBs and 9.5 hours if stoppages due OSBs are considered. The requirements of maintenance increases and the availability reduce as a consequence of
bad fragmentation. It was further concluded that cost of OSBs was lowest at the loading point and highest at the ore pass gates.

Some studies indicate that grinding energy could be decreased substantially by optimized blasting (Workman et. al 2003) while others (Katsabanis et al, 2003) suggest only marginal improvements in this stage. Analyzes have shown that ore recovery is directly or inversely correlated to drilling and blasting parameters (Brunton et. at 2009).

Workman & Eloranta (2003) concluded in their study regarding crushing and grinding energy consumption that the greatest energy saving is available in the grinding stage due to the large change in particle size achieved. The improvements in grinding will mainly be addressed to the increase of micro fracturing due to optimized blasting. They also suggest that it is favorable from a financial point of view to increase the energy in the blasting phase rather than having to add energy in the following processes (crushing and grinding).

### 2.9 Measuring fragmentation

The issues and complexities related to measuring fragmentation from full-scale blasting are a recurrent obstacle when trying to evaluate blast outcomes. Multiple factors influence the yielded fragmentation and often fragmentation is altered before it is actually measured (water, loader influence etc.) which disturbs the reliability of the tests. (Cunningham 2005)

However, fragmentation might be the single most important aspect of any mining operation. There are strong economic incentives to understand and control the underlying causes for variations in fragmentation. Maerz et al. (1996) explains that “Fragmentation measurements can be used to evaluate different explosives, blasting patterns and delay timing […] the efficiency of the blasting, the accuracy of the blasting simulations [and] to optimize all blasting costs”. Furthermore: “to monitor and optimize the production of fines [and] to reduce oversize which results in excessive loading and hauling costs, expensive secondary blasting or crushing, and excessive wear on equipment” (p.1)

#### 2.9.1 Sieving

Sieving is the oldest and most reliable way to measure particle size distribution of fragmented material. The weight combined with the size distribution of the fragmented rock provides valuable information on the overall fragmentation of a sample. The material is passed through successively finer sieves and the weight is monitored for each sieve giving the percentage of material in each sieve (Wang & Stephansson, 1996). All fragments are represented since the entire bucket is analyzed unlike any image analysis were only the surface of the bucket is analyzed. The downsides connected to this method are the costs and time required to perform
these tests. It is not suitable for large scale testing and it is debated whether the very finest fragments are represented accurately since they are sensitive to environmental factors such as wind and water during transport and sieving which might alter the representation of these fragments during the actual test (Cunningham 2005).

2.9.2 Digital image analysis

Image analysis was first proposed by Carlson and Nyberg in 1983. Today, it is the most frequently used method of assessing size distribution and the first method allowing for extensive large scale tests (Latham et al. 2003).

Image analysis has the advantage of providing in-situ fragmentation estimations but the accuracy and reliability of this technique is yet to be proven. Resolution problems are one of the serious issues related to image analysis as a technique and the finer fractions are not adequately presented to make this a reliable method for evaluating fragmentation (Cunningham 2005).

Cunningham (1996) further expressed “The evaluation of images from a blast muck pile is particularly difficult owing to its size, depth and internal variation […] there is still a problem with only looking at the surface. If the major part of the tonnage is concealed below the surface, the uniformity index must be high for reasonably accurate estimation to be obtained (the problem of segregation). What cannot be seen has to be guessed”.

2.9.3 Compaphoto

Compaphoto is a method developed by Van Aswegen and Cunningham in 1986. As the name suggests, photos are compared in order to rapidly classify samples. Samples of a known size distribution are prepared and photographed making it easy to estimate the fragmentation of the unknown sample by comparing the known fragmentation with the unknown. However, it is perceived difficult and time consuming to obtain representative standard photos and the method has not proven to be a viable method for evaluating fragmentation under production conditions. Hence, when the digital image analysis gained popularity in the 90s this method was, to a large extent, neglected.
2.9.4 3D Laser scanning

Unlike image analysis based on a 2D view causing uncertainties due to overlaps, particle delineation errors, uncertainties in scale and perspective distortion, 3D laser scanning gives a more comprehensive view on fragmentation (Onederra, 2013). This method shows promising results but is still under development and the recurrent problems with fines still seems to inhibit the reliability of the tests due to resolution issues.

2.10 Gravity flow

The flow mechanism in sublevel caving has been investigated and debated since the mid-60s. Theories along with conceptual models has been developed and tested over the years to describe the complex nature of material flow in sublevel caving. Small and large-scale tests have been conducted to obtain the fundamental mechanisms influencing flow behaviour.

2.10.1 Waste rock peaks

Waste rock peaks often begin to appear after a certain extraction rate. These peaks can logically be explained with basic flow mechanics. The lower part of the ring inherits a finer fragmentation due to a higher local specific charge than the upper part of the ring combined with the ability to swell adequately as opposed the latter. When the finest fragments that are easily mobilized are hauled, a cavity between the solid rock, the blasted material in the upper part of the ring and the caved material from the previous ring appears. See Figure 12. The stresses will then cause the waste rock from the previous ring to start flowing in. Waste rock is loaded until the upper part of the ring is mobilized sufficient to enter the drift. High ore grade is then expected until the same scenario repeats itself again. (Gustafsson, 1998)

![Figure 12: Shallow draw and cavity formation (Wimmer, 2012)](image-url)
Waste rock might appear in the muck pile for several reasons. Marker trials shows that waste rock might be loaded from the previous ring when penetration depth is large enough (Wimmer 2012). Data analysed from a remote controlled LHD-machine showed that penetration depth could reach 3.6 m which could support that thesis (Andersson, 2004). Recent studies indicate that waste rock might also come from above the production ring (Nordqvist and Wimmer 2014).

2.10.2 Marker Trials

Marker trials are primarily used to provide information on gravity flow behaviour in a blasted ring. Markers are placed in boreholes at various depths in the sublevel panel and these are later recovered when appearing in the muck pile. Depending on where these markers appear in the muck pile, information on how the gravity flow of the blasted ore behaves can be processed. Gravity flow is believed to be directly linked to fragmentation and optimized fragmentation will most probable give a more stable and predictable gravity flow (Wimmer et al. 2015).

Wimmer et al. (2015) describes that flow disturbances are indirectly caused by occurrences of large boulders (≥ 2 m). Further, large outflows (>40m$^3$) follow as a consequence of temporary hang-ups. Large boulders may occur at a very low extraction rate (0-10%) and these are believed to originate from the uncharged part at the collar. Occurrences of boulders then increases at around 20% extraction and at 50% the number of boulders is more or less constant during the remaining extraction.

Brunton et. al (2009) concluded through marker trials that the ore blasted in one ring might appear in a ring further down the mine which makes it difficult to prove that the extracted ore/rock in a ring comes from the vicinity and not from a previous blast.

Nordqvist & Wimmer (2014) indicate that a chimney is created which allows the ore closest to the blast plane to become sufficiently broken to be mobilized. Hence, draw will predominantly occur closest to the blast front and progress upwards. The material further away from the blast plane will be confined and not mobile in the initial stage. The waste rock might then come from above and not from the front. The full height of the drift can be reached already after 10% extraction rate and successively cause early dilution entry.
3 Methodology

3.1 LHD cycle time analysis

In order to obtain data on loadability and to determine whether it is possible to use time as an indirect measurement of loadability, magnitude and standard deviations of cycle times were analysed. If loadability is good, cycle times should in general be low and vice versa. Further, loadability can be defined as good if the time requirements at the muck pile are low.

Cycle times were extracted from Giron (LKAB database). Each time the operator weighs the bucket, before, dumping, a time is logged together with bucket weight and additional information regarding location, LHD number and dumping point. Subtracting the logged time for one bucket with the previous logged time gives the cycle time for the current cycle. The median cycle time for a ring is derived to provide the overall LHD productivity of that specific ring.

3.2 Field test

A field test was performed in drift 1450 and 1470 on level 905 in the Fabian ore body, see Figure 13. The blastholes in drift 1450 were drilled with 115mm holes, while the blastholes in drift 1470 were drilled with 102mm holes.

Even though different blasthole dimensions were utilized, the specific charge has been maintained roughly the same. This has been obtained by drilling an additional hole in the ring with smaller diameter holes. The hypothesis for this test is that less distance between holes, and in particular at the end points of the hole, may improve fragmentation and thus the loadability. The assumption is that improved fragmentation will result in shorter cycle time for LHDs.

![Figure 13: Drift 1450 and 1470](image)
3.2.1 Draw point filming

A camera was mounted in the ceiling of drift 1450 and 1470 to obtain data regarding LHD digging time and fragmentation in the muck pile. See Figure 14. To allow for quick and easy access to the camera without utilizing a truck, the camera system was mounted in a box and hoisted to the ceiling using pre-fixed ropes and hooks. This hoisting system allows for one person alone to manage and control the field test. It also reduces the time requirements to remove the camera in case of OSB blasting in the muck pile, which in turn results in less production interference.

Figure 14: Map of Fabian 905 (LKAB database)

The camera utilized was a D-link DCS 7010L and the recorded material is stored in a NAS (network attached storage) device containing a SSD (solid state drive) of 1 terabyte. See Figure 15. The initial plan was to mount the camera inside the LHD cabin, but technical issues inhibited this during the field test. A SSD was utilized instead of the conventional option, HDD (hard disk drive), to allow for recording even though subjected to excessive vibrations and shocks likely occurring in the cabin of a LHD. A HDD would likely break down or provide poor video due to the built in shock-resistant feature which causes the drive to stop writing at times of large vibrations. The setup is able to record more than 15 days of continuous (24h) footage in 720p and 25 fps with no interference required. No extra light was installed in the drift for the initial filming instead, the LHD alone was judged to provide sufficient light for this test. However, an external LED light was utilized during the main test to capture material flows initiated by blasting in adjacent drifts.
Figure 15: Camera setup

The NAS utilized was a Synology Disk Station DS115j which has a built in feature to handle and manage recorded video. The internal SSD is a Samsung 850 EVO 1024GB 2.5” Sata-600 which requires an adapter to fit in the Synology NAS. See Figure 15. Extension cables from the closest 230V outlet (approximately 200m) were mounted in the ceiling to minimize obstruction for the LHD operation. The power fuse malfunctioned between and during trials and a regular on-site supervision was required to ensure that the equipment was activated at all times. This was later addressed to damages on the power cable. The damages likely occurred as a result of blasting OSBs in the muck pile in between filming sessions. Significant loss of data occurred due to this. The cable should be easily retractable/removed from the vicinity of the production front to avoid these problems. See Figure 16.

Roughly 700 loading sequences were captured on film during the field test in Fabian 905. The loading times were extracted manually beginning at initial penetration of the muck pile and ending when the bucket was in an upright position, ready to be hauled.

Figure 16: Camera mounting
In case of unmanageable OSBs in the muck pile, the camera and the external lightning would have had to be removed from the drift to allow for blasting. However, this never occurred during the field test.

With the above setup, cycle times could be accurately measured through the Giron data base and the loading time could also be accurately established through the filmed loading operation. However, in order to verify that cycle times can be used as an indirect measurement of loadability, loading and cycle times has to be well correlated, which requires that the hauling and dumping times is relatively constant.

The field test was also performed to determine what effect fragmentation has on diggability and what characteristics of the muck pile correspond to good respectively bad loadability. Further, the effect of fragmentation on bucket filling was visually evaluated to some extent in terms of tonnage hauled and volumetric bucket filling.

4 Results and discussion

4.1 Cycle times

Cycle times for equivalent LHD models with the same hauling distance have been extracted from the raw data to allow for a rough comparison in terms of LHD productivity. Figure 17 demonstrates the median cycle time for each ring in the adjacent drifts. All cycles above 200 seconds has been removed from the data (~20%) as these likely involve other activities such as road maintenance or extended material handling which does not reflect the loadability.

Figure 17: Cycle time comparison for drift 1450 and 1470
Drift 1470 has in general somewhat lower cycle times than drift 1450. There is a curve in drift 1450, that adds a few seconds to each cycle due to the reduction in hauling speed. Hence, drift 1450 is expected to have somewhat longer cycle times. However, the magnitude of this difference is hard to determine as it varies considerable amongst operators. Taking this in account, it is difficult to conclude whether the, on average, lower cycle times in drift 1470 is due to fragmentation/loadability or other factors such as operator efficiency and road conditions. A large dataset of historical data has been analysed with the same type of results. Two parallel drifts with the same hauling distance have on average significant differences in terms of cycle times and productivity although, in those cases, the same blasthole dimension is utilized.

The standard deviation of cycle times is roughly the same for drifts 1450 and 1470, see Figure 18. A good correlation can often be seen between cycle times and the standard deviation of cycle times. See Figure 19.

![Figure 18: Cycle time standard deviation](image1)

![Figure 19: Cycle times vs. Cycle time standard deviations in drift 1450](image2)
The standard deviations in this case are in the magnitude of 30-70 seconds. Outcherlony et al. (2010) have also showed that digging time varies with fragmentation but not in this magnitude. This may indicate that the standard deviations within a ring are not solely due to varying loading conditions but also due to large differences throughout the cycle addressed to other occurrences.

4.2 Causes for large time deviations

In order to understand what is causing these large variations in cycle times, three possible causes were analysed closer, namely; differences amongst operators, differences amongst LHDs and the impact of varying road conditions.

4.2.1 Operator dependency

Employees at LKAB states that the operator difference can reach 20% and potentially obstruct any attempt to use cycle times as an indicator of fragmentation and/or loadability. LHD operators in Malmberget mine works in shift divided into two sessions with a break in between. Each session is 2h 15min followed by a break of 2h 15min and then another session of 2h 15min after which the shift is complete. This means that there is a rotation of operator in any given LHD 4-5 times each day. There is also a rotation within each team i.e. an operator driving a certain LHD one day might drive another LHD the following day. There is no login or specific schedule giving information on which operator is operating a specific LHD at a certain time. Therefore it is impossible to analyse differences and variations of operators over time, unless a sign-in is introduced. Therefore this information cannot be obtained retroactively, inhibiting the use of historical data to assess loadability on a large scale for a given operator in terms of time requirements at the muck pile.

However, it is possible to extract data from each loading session i.e. each shift. This will provide a small dataset reflecting the cycle times of individual operators although no information regarding experience or skill of that operator along with loading condition is available.

Historical data from Fabian 880 indicates that the differences amongst operators are large throughout the extraction of a ring. See Figure 20.
It is clearly visible that there is a significant difference between operator 6 and 7. The cycle times spikes from one cycle to another when switching from one loading period to another. Cycle times can be expected to vary naturally as extraction progresses but the magnitude and clear session dependancy of these indicates that the main factor influencing cycle times of any LHD is the human factor.

Median cycle times varies roughly between 110-170 seconds for the analyzed rings, utilizing the same machine and dumping in the same orepass. This represents an operator difference of almost 64%. It is not known, in this case, if this difference in time is equally distributed over the course of the cycles or whetheher a specific stage is more prone to variations than another stage. For example, the transport time might be roughly the same for all operators but the digging time might be longer for some than others and vice verse.

Zooming in on loading session 6 and 7 in Figure 21 gives indications of a systematic difference between operators. It is highly unlikely that fragmentation or road conditions suddenly becomes unfavourable the minute operator 7 takes over.
Uncontrollable variations like this inhibits any attempt to derive information on fragmentation from cycle times alone. However, there might be information within the logged data that can indicate the quantity and severity of problems occurring during loading, hauling and dumping. Large time variations from cycle to cycle might indicate uneven fragmentation or problems with the gravity flow. This must be verified by visual observation to exclude other logical explanations such as continuous road maintenance or other occurrences.

If the standard deviation is high in a ring, a big time gap between operators likely exists. Hence, a high percentage of less experienced or “slower” operators have likely loaded during this period of time or vice versa. This consequently leads to higher median cycle times as seen in Figure 17.

4.2.2 LHD comparison

Assessing the LHD performance and comparing one machine to another is a difficult task. As stated earlier, the operator difference is the dominant factor influencing cycle times of the LHD operation. The utilized LHDs in Malmberget mine have a significant difference in breakout force in favor of the Sandvik loaders, See table 1. These differences seemingly influence cycle times and hence productivity to some extent.

When asked which LHD is the quickest i.e. has the lowest hauling time, 89% of the operators answered Caterpillar machines and only 11% answered Sandvik machines. On the other hand, 83% states that Toro machines do better during actual digging. When asked which LHD the operators believe is the overall most productive, 74% favoured for Caterpillar.
The interview study also indicates that most operators agree that the Sandvik machines penetrate the muck pile more efficiently than the Caterpillar machines. Logged cycle times indicate that the Cat machines are quicker than the Sandvik machines throughout the cycle, see Figure 20 and on average hauls roughly the same tonnage each round. In order to state that one machine is more productive than the other, every aspect of the LHD process has to be extensively tested and evaluated, for example when difficult loading conditions are encountered in the muck pile. However, such evaluation is outside the scope of this thesis.

If compiling the median cycle times for all machines operating in four drifts in Fabian 880 with the equivalent distance to dump; the trendlines shows interesting results. See Figure 22. The machines are utilized randomly at different extraction rates why the influence of extraction rate should be neglectable.

![LHD comparison](image)

**Figure 22: LHD comparison**

All Caterpillar machines show similar efficiency, relatively independent on production year and model. The Toro machines show more variations dependent on model and production year and are generally slower over the course of the cycle.

However, there is no information regarding what stage in the LHD cycle (loading, hauling or dumping) causes these differences and whether these differences are accurate measurements on productivity. If, as operator states, the Toro machines penetrates the muck pile better and enhance the flow of ore into the drift, it is misleading to say that Caterpillar machines are more productive solely because they have lower cycle times.

Further, operators have complained that the lower “power” in the Cat machines do not enable for good muck pile penetration, especially when the muck pile is compacted, consequently leading to “surface loading” where only the surface of the muck pile is extracted. This might
in turn lead to problems with gravity flow and earlier waste rock inflow than expected. However, this has yet to be proven.

4.2.3 Road conditions

When asked if there is any reason to why the operators hauls at a slower pace at certain times, 96% answered that road conditions controls the hauling speed. Many of these are concerned about injuries. 4% did not mention road conditions as a limiting factor but rather bucket filling and, in particular, OSB hauling. A majority of the operators also brought up situations with other personnel in the production area as a controlling factor.

It seems as if the hauling pace is dominantly determined by road conditions along with personal tendency to avoid physical strains. Hence, differences in hauling time might only partly be influenced by experience/skill.

Road conditions in front of the muck pile seem to attract different amounts of attentions from different operators. Some spend repetitive cycles, continuously fixing the road while others spend virtually no time at all doing that. It is not possible to see how road conditions along the drift changes over time by watching the video. It is therefore impossible to say whether road maintenance is performed based on the actual need of maintenance or on personal preferences.

Road deterioration over time and the presence of water often speeds up the road wear process. In Malmberget Mine the roads are casted with concrete. In cases of large water inflows the water forms channels underneath the casted road. See Figure 23. When the LHD repetitively drives across the “unsupported” part above the water channels the concrete starts to crack. (Personal communication, LHD operator LKAB, 2015-12-03)

4.2.4 Conclusion

The human factor dominates the length of cycles and has to be excluded in order to obtain valuable information unless a detailed observation is carried out for each operator. If a sign-in for each LHD was introduced it would be possible to follow-up on a certain operator in a certain machine to obtain information on productivity in different ore-bodies, levels, drifts and rings. This would allow for a rough estimates on loadability given that road conditions and other variables can be assumed to cause no more than marginal difference between the compared locations. However, no such system is in place as of today and factors like road conditions etc. rather seems to have a notable impact on cycle times.

Cycle times vary with distance to dump and fragmentation given that there is no difference between machines, no difference amongst operators and similar road conditions for the compared cycles. However, this is rarely the case. Road maintenance was, in the filmed rings,
one of the most reoccurring events resulting in prolonged cycle times except for operator difference. The differences amongst operators are also clearly visible in terms of loading strategies and handling of OSBs.

By analysing cycle times alone, it is very difficult, if not impossible to separate cycles involving road maintenance from cycles involving initiation of flow or prolonged material handling at the draw point. Visual analysis is required to determine which cycles are representable in terms of giving an indirect measurement of fragmentation and which involves events such as road maintenance etc. which is governed by other factors. When finer fragments are dominant in the muck pile operators often take the opportunity to use this material to fill holes in the road in front of the muck pile. When coarser fragments appear, they haul it straight to dump. This is one example of why cycle times alone to provide seemingly misleading information if not all facts are presented.

The most reliable method to “measure” loadability is to visualize the occurring problems, counting OSBs, observing the flow of material and measuring fragmentation along with digging time directly. This information would merge into a reliable dataset which can be used to map where and why loadability varies and give answer to the question: *What happens with loadability when 4” blastholes is utilized instead of the normal 4.5”?*

### 4.3 Loading times

An introduction campaign for new operators took place during filming and these cycles were excluded from the analysis along with some loading sequences with noticeably inexperienced operators. *Figure 23* demonstrates the distribution of loading times in drift 1450.

Loading times normally varies from 18-36 seconds if no other activities such as road maintenance in front of the muck pile, excessive material handling etc. are included. Loading times, and in particular time spent at the muck pile is heavily governed by operator efficiency. No other factor, unless fragmentation is very adverse, seems to cause time variations of the same magnitude. However, the limited quantity of data and the irregularity of the operator schedule in this period make it impossible to prove this statistically.
Figure 23: Distribution of loading time in drift 1450 (0-54% extraction ratio)

In Figure 24 loading time is compared for two seemingly experienced operators. Fragmentation is, based on visual judgment, roughly the same and compaction factor of the muck piles comparable. A systematic time difference is observed although muck pile compaction and fragmentation are seemingly similar.

Figure 24: Operator difference in digging times

Visual assessment give further support to this by comparing loading times to diggability and availability of loose material in the muck pile. Different operators have different techniques and loads differently from one another although no visual difference in terms of muck pile conditions is present. The frequency of reloads and overall skill varies substantially. When fragmentation is fine and a lot of available loose material is present in the muck pile there is no significant difference in loading time amongst operators. Although, when fragmentation gets coarser or if the muck pile is more compacted less experienced operators faces
substantially more difficulties than an experienced one, which is also noted by an increased standard deviation.

Interviews conducted with 62 operators indicate that operators approach their task differently. When asked if the operators believe that they have an influence on early waste rock intrusion, 36% answered that they do influence this to a great deal. 45% answered that they do to some extent (if they would load completely wrong) and 16% thinks that they have no impact on this.

When asked about the importance of side-to-side loading in the muck pile, 50% answered that it is very important and that the following operator will encounter greater difficulties than if loading is performed correctly. 44% answered that this is only partly true.

Combined, these variations in believes amongst operator will most likely influence the way they operate. An operator who thinks that he/she controls early dilution entry and that his/hers colleagues will experience difficulties if he/she does not pay full attention at all times will most likely spend additional time at the muck pile. To some extent, this can be confirmed in the filmed material.

Video footage indicates that some operators spend more time at the muck pile refusing to haul material obtained from surface loading. A full bucket is not always hauled if no additional material is flowing into the drift as a result of material removal. This seems to be heavily influenced by different loading strategies applied by different operators. Some operators seem to be more concerned about the flow of material than others whom keep a higher overall pace in the loading stage. Certain operators strictly loads from side to side in the muck pile which logically is beneficial for gravity flow and hence loadability at a later stage. Other operators ignore this method when loading is difficult etc.

4.4 Correlation between digging and cycle time

The correlation between digging time and cycle time is expected to be strong. Hauling and dumping is to a large extent not dependent on fragmentation and should therefore remain rather constant for each separate operator. However, road maintenance and other irregular occurrences may disturb this correlation.

The few outliers in Figure 25 indicates some sort of deviant occurrences which could be explained by road maintenance, OSB handling, people entering the production area or similar events. However, for this session these occurrences seem to be few. Cycle times are generally high when digging time is high and vice versa.
As previously shown, there is a substantial difference amongst operator in the digging phase although fragmentation and compaction factor of the muck pile is comparable. However, in order to use cycle times as an indicator on loadability, hauling and dumping times has to be taken into account as well. Hauling and dumping times is extracted by subtracting the loading time from the total cycle time obtained from Giron (LKAB database).
In *Figure 26* it is clear that the two compared operators hauls at a different pace. Operator X has in general lower loading times but significantly higher hauling times than operator Y. It is fair to say that loadability, in terms of muck pile compaction, is better for operator X (see table 2) but the total productivity is lower than that of Operator Y.

The loading time standard deviation of operator Y is higher (7.5s) than that of operator X (4s). This would indicate that loadability fluxuates more for operator Y than operator X. This correlates well with the fluxuations of digging scenarios i.e. differences in fragmentation and compaction factors during the same period. Visual judgement of compaction and availability of loose material in the muck pile is documented in *table 2*.

It seems like if more experienced operators are more predictable in the way they operate. A less experienced operator have more deviant cycles and less distinguished loading and hauling times. An analysis based on operators with below average experience is therefore not aimable.

*Table 2: Loadability for two loading sessions*

<table>
<thead>
<tr>
<th>Loadability / Operator</th>
<th>Operator X</th>
<th>Operator Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favourable loading condition</td>
<td>94%</td>
<td>34%</td>
</tr>
<tr>
<td>Neutral loading condition</td>
<td>6%</td>
<td>41%</td>
</tr>
<tr>
<td>Unfavourable loading condition</td>
<td>0%</td>
<td>25%</td>
</tr>
</tbody>
</table>

*Figure 27* illustrates the constant time difference in hauling and dumping between two different operators, although the same machine is utilized in both cases and the hauling distance is identical.
It is therefore appropriate to analyze loading times in terms of deviations rather than magnitude. However, varying road conditions and additional occurrences such as excessive material handling by some operators could alter the reliability of such analysis. The problems relating less experienced operators also remains i.e. if the operator is not predictable in all stages of the LHD operation it is impossible to verify that time deviations is related to loadability and nothing else. Figure 26 indicates that operator X has a significant standard deviation in hauling times, this indicates that the operator difference is not one dimensional i.e. certain operators are overall more efficient than others. It is rather a multi-dimensional difference where different operators are differently efficient at different stages of the LHD operations. A complete mapping of each separate operator is therefore required to validate that time differences is due to variations in loadability and not in hauling for example. This causes additional doubts of whether cycle times could be used to assess loadability.

In Figure 28 it is clearly visible that the hauling time is not dependent on the loading time (time spent at the muck pile). This also indicates that the hauling time is not dependent on fragmentation, bucket filling or bucket weight.

![Hauling time/loading time](image)

Figure 28: Hauling time compared to loading time

### 4.5 Digging time/fragmentation relation

Ouchterlony et al. (2010) concluded indirectly that the digging time and the standard deviations of the digging time increases as fragments gets coarser. However, that study was performed in an open cast quarry, where the material is allowed to swell almost unlimited. In underground blasting, under confined conditions, this is not the case. The material has a very
limited swell and only the material closest to the blast plane can swell sufficiently to be mobilized. The rest will become compacted. Therefore, in underground digging, the compaction factor has to be accounted as well as fragmentation. In the filmed rings, it appears as if digability is mostly governed by compaction of the muck pile rather than fragmentation which seems to be a secondary factor. This means that if compaction of the muck pile is comparable, fragmentation will affect digging time. If, however, the muck pile is compacted, it seems as if the degree of compaction governs the loading time rather than fragmentation. In Figure 29 and 30, fragmentation for both buckets are comparable. Although, digging time is substantially higher (50% increase) for Figure 30. The degree of muck pile compaction is judged to cause this difference.

![Figure 29: Short digging time](image1) ![Figure 30: Long digging time](image2)

The compaction factor is very difficult to measure. Unlike fragmentation measurements, it cannot be done utilizing digital tools or by visual assessment. Compaction seemingly increases with digging depth i.e. the longitudinal position of the bucket parallel to the drift.

*Figure 31* shows the digging times for 0-54% extraction rate in ring 12 in drift 1450. The first 25 buckets or so is loaded by one single operator. Fragmentation is in general fine and the muck pile compacted. Bucket 60 to 120 is loaded by operators of similar efficiency but the fragmentation is in general fine and compaction low. Loading times and the standard deviations of loading time are in this section low.
Diggability does not appear to be heavily influenced by fragment size but rather the availability of “loose” material in the muck pile. Independent on fragment size the compaction factor seems to cause prolonged loading times and an increased number of re-loading sequences. However, compaction appears to increase with the presence of very fine (clay-like) material “sticking” the larger fragments together. The friction angle of this clay-like material seems to be high and the presence increase with the depth of the muck pile (previous ring).

It appears as if a zone of loose material of varying fragmentation lies on top of a compacted pile of finer fragments. When the loose material have been loaded and hauled the compacted material appears. Sometimes smaller flows occur providing more loose material but often the underlying compacted material has to be mobilized to initiate the flow again.

In general, the muck pile was repetitively observed to undertake three different characteristics during the field test.

- A full muck pile of compacted character
- A full muck pile of loose character
- An empty muck pile of compacted character

Figure 31: Digging time
Diggability was best if the muck pile was full and loose, see Figure 32, and worst if it was empty and compacted, see Figure 33. At occasions, penetration of the muck pile was close to impossible and time requirements along with demands on operators, in terms of skill and effort, increased substantially.

Optimally new material should flow into the drift continuously to allow for quick, easy and safe extraction. Diggability and the availability of loose material is the highest after a larger flow has occurred. Quick and smooth production takes place until availability of loose material decreases. The operator generally has to struggle more to penetrate the muck pile up until a point at which a new flow of material takes place. A seemingly compacted wall with a high presence of fine (clay-like) material is often visible the cycles before a larger flow occurs and the muck-pile is longitudinal several meters further into the drift than normal. Larger fragments are commonly spotted in these larger flows and are most likely the cause of these smaller hang-ups in the first place by inducing arching effects. This tends to reoccur in a cyclic manner of varying length. An indicator of good fragmentation in terms of loadability would suggest a high occurrence of smaller flows and a low occurrence of larger flows which in turn indicates that a hang-up of some magnitude has occurred. However, larger flow normally indicates that the entire panel (full depth) is mobilized and hence production staff at LKAB (Personal communication, Peter Holmgren LKAB, 2016-04-21) preferable sees these large flows instead of many smaller flows which indicate that only a smaller portion of the panel is mobilized.
At one occasion during the field test a ring was loaded to 130% extraction rate before shutdown was initiated. During preparation of the muck pile i.e. trying to stop the flow, the entire panel came down and ore grade went up again. Production loading was commenced and the ring was instead shut down at 580%. This is one example indicating that material is not mobilized sufficiently to flow gravitationally down to the drift at all times. Large flows and extensive movement of the muck pile might be required to initiate the frozen material in the back of the ring. Hence, large flows causes problematic loading conditions but enhances production in terms of tonnage extracted. If flow disturbances occur at a high extraction rate it is difficult to judge whether the ore grade drops due to actual 100% extraction of the theoretical ring or due to frozen ore within the theoretical ring not being mobilized sufficiently. It is in most cases very difficult if not impossible to judge where the material appearing in the muck pile actually comes from. Hence, it is difficult to know whether the material in the muck pile is subjected to the blasting utilizing 4” boreholes instead of the conventional 4,5” from previous levels or rings. Measuring fragmentation in the muck pile might therefore in many cases be misleading in terms of addressing potential differences to variations in borehole dimension. A broader approach is likely required to spot these differences. If a reduced borehole dimension results in less frozen ore, a lower dilution is expected. Hence, an ore grade analysis is highly interesting in terms of identifying potential differences in gravity flow, although this entails uncertainties on its own.

Ring 17 in drift 1470 consists of ore alone, i.e no waste rock is identified during drilling. Hence, all waste rock extracted in this ring origin from outside the theoretical ring and material extracted during long loading periods with no considerable dilution can be assumed to origin from the theoretical ring. Fragmentation analysis should therefore be carried out for this material and not the diluted material as parts of it origins from earlier levels or rings where the conventional 4,5” boreholes is utilized.

Kvapil (2004) described this as: “We know of situations where the steep loading front does not terminate at the intersection with the roof of the extraction drift but is displaced toward the waste as is shown in Phase A,” see Figure 34. Further “In many cases, the arch of the roof cavity then collapses and the material flows into the drift as shown as Phase B. Beginning with the phase B geometry there are two possibilities. One is shown in Phase C in which the arched roof of phase B collapses and a new cavity develops at a higher level. The second possibility emerging from Phase B is shown as Phase D. Here a collapse of the wall of waste from the side (or front) occurs.”
Based on video footage it seems like these situations not only causes problematic loading conditions but also poses a direct danger to the operators and an increased risk of machine damage.

The hang-up with the largest resulting flow captured on film was the most dangerous situation and resulted in the coarsest fragmentation, see Figure 35 and 36, except for individual OSBs encountered sporadically. It seems as if the resulting fragments appearing in a flow is coarse, the greater challenges in initiating the flow are encountered. Likewise, the steeper the wall and the increased distance of which the wall is located longitudinally into the drift, the more intense and dangerous the flow is likely to be.
If the longitudinal distance parallel to the drift is high and the muck pile is steep and compacted, see Figure 37, a larger flow is expected. Loadability at this point is very difficult due to the compacted characteristics of the muck pile. The flow will likely be intense and a sudden release effect is expected as the arching effect collapses when supporting material below is removed, see Figure 38. Large fragments and OSBs can be expected in the consequent flow of material. The buckets hauled previous to the flow had an estimated ore grade of 60-70% and the bucket hauled directly after the flow had an indicated ore grade of 0%, see Figure 39. This causes uncertainties if whether the material comes from above i.e. waste rock from above blasted ring or from the previous blasted ring. This specific ring has a low general ore grade and is sub-optimal for analysis of where the waste rock might come from. However, Wimmer et al. (2008) concluded through various tests that iron-ore behaves like waste rock from a blasting point of view and that fragmentation should not vary substantially with ore-grade. This would, if correct, indicate that the waste rock enters from the front or from above and not from the current ring. However, significant nitrate leakage was visually observed before the current ring was blasted and there is a possibility that the OSB comes from within the blasted ring.

![Diagram showing compaction and flow](https://via.placeholder.com/150)

**Figure 39: Dilution entry (10% extraction rate)**

Loading times tend to increase when the compacted wall is reached. However, it is not certain that the operator requires more time to satisfactorily fill the bucket. It seems as if the operators is keen on restarting the flow as soon as possible and therefore empty seemingly full buckets to have another go at the muck pile. The decrease in ore-grade seems to change the priority and logically loading times goes up. This has nothing to do with fragmentation in terms of diggability but rather a larger issue related to gravity flow and fragmentation on a larger scale.

The fact that this phenomena occurs at 10% extraction rate in this ring indicates that fragmentation is suboptimal. The presence of coarser fragments after this flow indicates that boulder blockage is the plausible cause.
Following this large flow, no new flow of material occurred for 15 cycles at which point the steep and compacted wall was encountered yet again at roughly the same longitudinal distance parallel to the drift. Loadability successively worsened during this period until a new large flow occurred. See Figure 40, 41, 42, 43 and 44.

(Figure 40: Before large flow)  (Figure 41: After large flow)

(Figure 42: Hangup)  (Figure 43: Cavity formation)  (Figure 44: Dilution entry from previous blast)

(Kvapil, 2004).

Material could either come from above or from the waste rock in the front. The ore grade before the flow was 51% and after the flow 0% for a few cycles before the ore grade increased again.

(Figure 45: Before medium flow)  (Figure 46: After medium flow)
In *Figure 45* and *47* the longitudinal distance parallel to the drift is “medium”. The muck pile wall is steep and rather compacted, loadability is worse than normal. A medium intense flow is expected and the fragments are coarse but generally no OSBs are present, see *Figure 46* and *48*.

In *Figure 49* the longitudinal distance parallel to the drift is short and the steepness of the muck pile rather low. Generally the clay-like wall is not encountered and loadability is still good. A gentle, yet significant flow of material occurs and loadability remains good. The fragments are generally in the size range of fine to medium. These kinds of flows are preferred in terms of LHD operations as the availability of material never drops to levels where muck pile penetration becomes difficult. However, less experienced operators might struggle more with coarser fragments than finer ones; hence for some operators, loadability and loading times may even worsen after a flow of this magnitude.
4.7 Bucket filling/fragmentation relation

Since no comparison of drifts with different hole dimension was performed due to production delays, there is no data available to evaluate if bucket filling is affected by hole dimension or not.

However, bucket filling during the field test was in general high, certain operators seem to care more than others about whether the bucket is completely full or not. Less experienced operators struggle more with coarser fragmentation and bucket filling sometimes suffers slightly from this. However, the angle of the camera was sub-optimal for analyzing this and further filming is required to analyze this more closely.

When asked, 57% of the operators states that they strive to fill the bucket maximally each cycle while 24% attempts to fill it to 100% of the theoretical bucket volume, but no more. About 8% claims that they do not bother much as long as the bucket is filled more than 75%. Some operators answered that they try to fill the bucket maximally without surface loading, i.e. they are satisfied if the material loaded is loaded properly and not hasted. One operator said that “you get what you get each time” i.e. bucket filling is not very important and another went on saying that certain machines are too weak and in those cases it takes too much effort trying to completely fill the bucket.

67% of the operators state that if loadability is difficult, one might need to settle with a lower bucket filling. The rest claims that it is very rare that the bucket is not full when hauling or that they never leave the muck pile with a bucket that is not 100% full. It was noticed on many occasions during filming that OSBs (>1m) was loaded together with other material and hauled directly to dump.

4.8 Mapping of the LHD operation

Based on information obtained through analysis of historical and present data along with the filmed material a mapping of the LHD operation is attainable. Figure 50 demonstrates the identifiable factors affecting the LHD operation in terms of time requirements. Out of the identified causes for large time deviations, operator efficiency is the dominant and primary factor. The magnitude of time variations caused by differences in experience, skill and individual preference inhibits a reliable analysis of loadability derived from cycle times. It is clear that the operator factor has to be removed from the analysis to obtain amiable results of which to draw conclusions from.
Figure 50: Map of the LHD operation

4.9 Sources of inaccuracies

The initial analysis cannot be supported by filming. The indications of large operator differences cannot be directly proven. However, the filmed material supports and indicates that these differences are real and significant. However, the limited view of filming (the muck pile only) leaves a lot of uncertainties during the hauling phase. It cannot be verified that the road conditions are not heavily altered at certain times. During the field test, no large variations of road conditions were spotted but it is impossible to say what happened in between visits. However, operators have given no indications that something abnormal should have occurred during the period of filming.
4.10 Future work

Further filming should be conducted to obtain a large, reliable dataset to answer the question if the borehole dimension affects loadability. A visual fragmentation study should be conducted to spot differences in the two drifts. Loadability should also be classified visually and not based on time requirements at the muck pile but rather obstacles faced independent on operator experience etc. The LHD operation should be excluded from the analysis to provide reliable data which is easy to evaluate and discuss.

Removing the LHD operation from the analysis by visually observing fragmentation, compaction factor and flow disturbances would provide a more accurate and reliable dataset. Figure 51 illustrates the remaining factors which is visually obtainable by filming.

To allow for gathering of large quantities of filmed material at the draw point, an enhanced camera setup should be utilized to remove the current around-the-clock stand-by approach in case required blasting of unmanageable OSBs in the muck pile. A camera with zoom-function and remotely controllable pitch in combination with a “blast proof” protective box, preferably utilizing a high-quality plexiglas would enable a self-sufficient gathering over an extended period of time with very little interference and no stand-by required. The camera should be firmly mounted in the ceiling at a safe distance from the muck pile and the plexiglas would provide the necessary protection in rare cases of excessive blasting debris. The problem faced during production blasts is not debris but rather the excessive shock wave which can be managed by an intelligent positioning of the equipment. An ethernet cable should be extended to the entrance of the production area to allow for easy access and data handling with no stress of ongoing production. Such a setup would allow for filming of the draw point months of time.
with minimal human interference. Optimally someone should control that the power supply is stable and that no excessive dust on the plexiglas or camera lens is hindering the view at a regular basis, suggestively once a week. The focus of the camera should also be controlled to ensure that the draw point is in view. All of this can be performed from outside of the production area at any given time since ongoing production will not interfere. The time requirements of such a control will be less than 10 min and can be performed by virtually anybody working in the mine.

5 Conclusions

The conclusions obtained from this project is that cycle time is not a very reliable indicator of neither loadability or fragmentation. This is due to the significant time difference amongst operators which is difficult to account for. The time difference is not limited to the loading phase of the LHD operation but also extends to the hauling phase. The irregularity of these differences and the fact that they are not only magnitudinally but also divergently affected by the operators causes great uncertainties when trying to interpret cycle or loading times without visual backup. It is not possible to give a reliable answer to the problem statement due to this. However, lots of information on how the stated problem can be answered was provided along with general information on the loading phase.

Fragmentation can visually be judged to cause variations in loading time. However, this is heavily dependent on the operator. An experienced operator will be more consistent throughout the loading phase and have lower time deviations than a less experienced operator. The muck pile compaction seem to be the primary factor influencing loading time. Independent on fragmentation, the shape and looseness of the muck pile generally governs the loadability and hence time requirements to fill the bucket. Fragmentation seem to be a secondary factor which affect loadability if compaction of the muck pile is comparable for two loading sequences. Obviously, if fragmentation is very adverse, additional time is required to handle larger boulders separately.

Loading techniques, such as side-to-side loading and OSB-handling is also heavily affected by the operator. Hauling times seem to remain rather constant for each operator although they vary amongst different operators. Larger deviations in hauling times are observed for some operators than others. The interview study conducted indicates that the operators view their role in production differently which well could explain the above described variations.
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