RESEARCH REPORT

Loading Procedure and Draw Control in LKAB's Sublevel Caving Mines

Baseline Mapping Report

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Preface

This research report serves as a baseline mapping of Loussavaara-Kiirunavaara AB's (LKAB) sublevel caving operations for the project 'Improved Resource Efficiency through Dynamic Loading Control'. The authors would like to thank the staff of LKAB's Kiirunavaara and Malmberget mines for their invaluable support, ideas and guidance. Agio System och Kompetens AB, Boliden Mineral AB and ABB AB are also acknowledged for their valuable input into the project. The authors gratefully acknowledge LKAB, Vinnova, the Swedish Energy Agency and Formas for financing this project through the SIP-STRIM program.

Abstract

Sublevel caving (SLC) is an underground mass mining method used to extract iron ore from the Kiirunavaara and Malmberget mines. Although both mines use SLC as the mining method, their implementation varies in terms of mine design, ring design and draw control strategy. The Kiirunavaara mine has a continuous and massive ore deposit which allows a standard mine design layout, while the Malmberget mine has scattered ore bodies with varying mine design parameters. The two mines also employ different opening techniques for production drifts.

Luossavaara-Kiirunavaara AB (LKAB) uses different information systems to run these highly mechanized mines. The information generated by the various systems is transferred between the different unit operations and is used to optimize the mining process. The mines use GIRON to create, store and display different information related to the mining operation. Information on all unit operations is stored in a number of databases inside GIRON. The two loading related information systems which support the loading operation are the Wireless Loader Information System (WOLIS) and the Loadrite system. The Loadrite system measures the bucket weights being loaded by the Load Haul Dump (LHD) machines at the draw point. This information, along with information on planned ring tonnage etc., is displayed to the LHD operator inside the LHD machine using WOLIS. WOLIS provides online data on the ring performance such as grades, tonnage extracted etc. to the LHD operators and the production team.

In SLC, the different aspects of loading at the draw point include loading procedures, loading issues, loading criteria and loading constraints. Loading procedures include the practices and precautions taken during loading at the draw point. Loading issues include events observed at both mines, such as brow failure, ring freeze, hang-ups etc. Although most loading issues are handled in a similar manner, hang-up handling techniques are different at the Kiirunavaara and Malmberget mines. Loading criteria and constraints along with the nature of material flow collectively provide a complete understanding of the draw control strategy. Loading criteria comprise a set of rules or guidelines for loading and closing a draw point. LKAB uses WOLIS to enforce the loading criteria for its SLC operations. Loading constraints include production constraints, grade control and mining constraints which must be followed for a safe and sustainable mining operation.

A baseline analysis of the draw control and loading operations at the Kiirunavaara and Malmberget mines is summarized in this report using information collected through internal documents, meetings, e-mails and manuals.

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1 Introduction

1.1 Background

Sublevel caving (SLC) is the mining method practiced at the Kiirunavaara and Malmberget mines. Luossavaara-Kiirunavaara AB (LKAB) uses sublevel caving (SLC) to operate the two largest underground iron ore operations in the world while maintaining a high degree of productivity and safety (Järvholm, 2013). The mine design and layout have evolved at both mines with advances in mining technology and a push to increase the mining scale (Hustrulid & Kvapil, 2008).

With more advanced machines being used for different unit operations, the mines have developed a detailed network of information systems and applications to assist the various departments in performing their tasks. Now, large amounts of data are being shared by such diverse unit operations as drilling, charging, blasting and loading. The information generated by the systems is used by the mines for planning, scheduling and decision making.

The scaling up of the mine design has resulted in new mine optimization challenges for all the unit operations (drilling, blasting, loading and transporting). Understanding and optimizing draw control is one such challenge. The two mines use different draw control strategies that have been developed and upgraded over the years to accommodate changes in mining conditions and mine requirements. Draw control deals with the issue of when to stop loading from a draw point and the amount of material to be extracted from a ring (Shekhar et al., 2016). The decision to close a production ring in sublevel caving mines is irreversible. The mines currently have certain fixed criteria for closing a draw point. An ideal loading criterion should stop the loading at the draw point such that dilution can be minimized while maximizing ore recovery.

1.2 Aim

The aim is to describe the loading procedures and draw control at LKAB's SLC mines.

1.3 Scope

The report focuses on the different aspects of loading at the draw points in LKAB's SLC mines. It enumerates the loading criteria and loading constraints at the Kiirunavaara and Malmberget mines and summarizes details of mine design, layout and geology affecting the draw control. The report covers the use of information systems (Loadrite system, GIRON and WOLIS) in the loading process and offers a brief description of the organizational structure and practices of the loading operation.

1.4 Limitations

The report is limited to the loading operation and draw control at the Kiirunavaara and Malmberget mines. It does not provide a detailed description of the overall mining process. The report does not cover information systems used for other unit operations such as drilling, blasting, mine planning etc.

2.1 The Kiirunavaara mine

The Kiirunavaara ore body consists of magnetite ore with magmatic intrusions. The ore body stretches about 4km along the strike in the N 10° E direction with an average width of around 80m, dipping at about 60° SE towards the Kiruna city (Nordqvist and Wimmer, 2014). The average iron content for the ore body is 64% (Nordqvist and Wimmer, 2014), but the grade varies, and the iron content can reach up to 69% (Rutanen, 2011). In general, the ore quality is better in the middle part of the ore body and poor near the hanging wall and footwall contact (Henrikki Rutanen, personal communications, 2015).

2.1.1 Ore reserve estimation

Core logging is done using inclined downwards holes from the footwall and the hanging wall. The resulting information is used to construct a model of the ore body and provide details on the ore dimension and grade. Core drilling is performed in a square grid pattern on the ore body from both hanging wall and footwall side. The grid interval is 100m by 100m from the footwall side and 300m by 300m from the hanging wall side (Henrikki Rutanen, personal communications, 2015). A grid interval of 100m by 100m means that holes are drilled at an interval of every 100m both along the dip direction and along the strike of the ore body (Henrikki Rutanen, personal communications, 2015). Figure 2.1 shows the drill profile of a typical core drilling program for the southern part of the ore body.

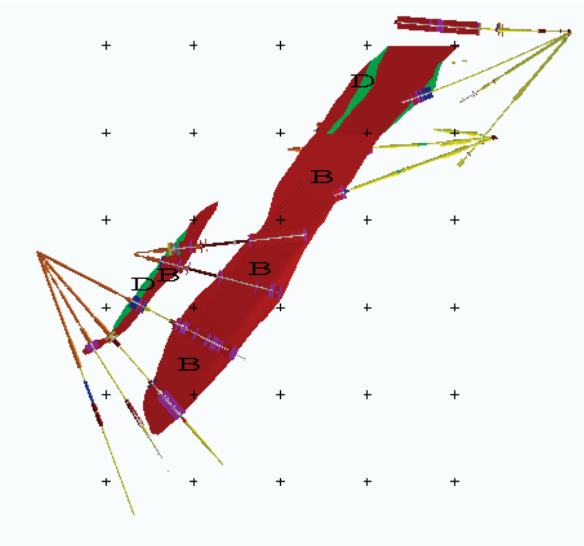

Figure 2.1 Drill profile for core logging (Rutanen, 2011)

Simple Kriging is used to extrapolate the grade of the ore body. A spherical variogram is used for grade estimation and ore reserve estimation (Rutanen, 2011). The generated block model is transferred to the mine planning team for drill design planning. The geology department communicates any major intrusion or structure to the drilling team. However, details on intrusion and internal dilution are sometimes not present in the block model as it is not detected by the space drilled core holes. Information gathered on intrusions during production drilling is updated in the block model (Henrikki Rutanen, personal communications, 2015). The width and inclination of the ore body varies, so a level wise delineation of the ore body is performed and used for the drill design. As per the recommendations of the Swedish Association of Mines, Minerals and Metal Producers (SweMin), the proven mineral reserve is 521MT and the probable mineral reserve is 161MT for the

Kiirunavaara ore body (LKAB, 2014). The measured mineral resource is 13MT (LKAB, 2014), and the indicated mineral resource is 208MT (LKAB, 2014). Exploration is on-going, and the extent of the ore body is being determined by exploration projects.

2.1.2 Mine design and layout

Most of the mining at the Kiirunavaara mine is done via transverse SLC layout; i.e. cross cuts are oriented perpendicular to the strike of the ore body. Longitudinal SLC is practiced in some areas where the ore width is narrow; i.e. the drifts and cross cuts are parallel to the strike of the ore body. The general mine layout at the Kiirunavaara mine has evolved over a long period; its hybrid layout can adapt to ore width and shape. Some transverse drifts transform into longitudinal drifts near the hanging walls, allowing better recovery. Other transverse drifts branch to accommodate either the ore shape or to handle disturbed mining areas with the objective of reducing development costs. In general transverse SLC layout is preferred over longitudinal SLC layout due to rock mechanics related issues (Patricia Boeg-Jensen, Personal communication, 2015). Figure 2.2 shows the top view of a typical production area; Figure 2.3 gives a three-dimensional view of the Kiirunavaara mine.

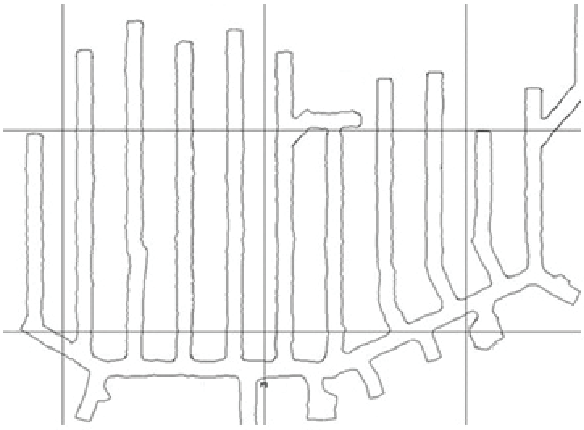

Figure 2.2 A typical layout of the Kiirunavaara mine (Courtesy LKAB)

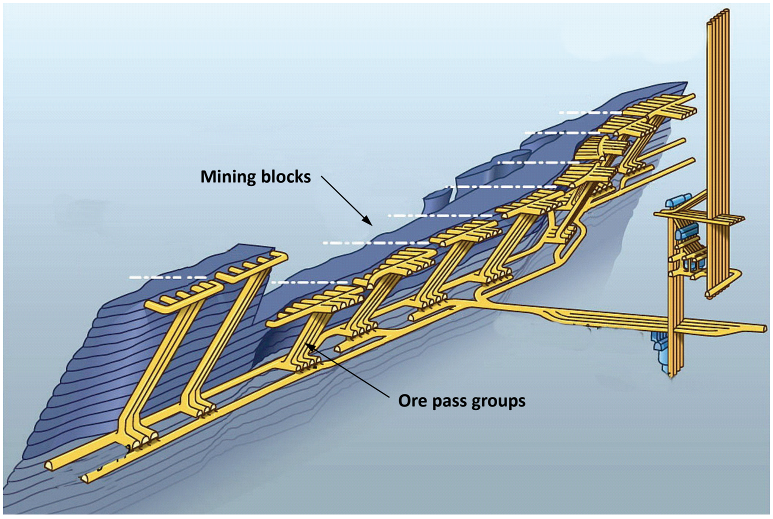

Figure 2.3 3D layout of Kiirunavaara mine (Rutanen, 2011)

The sublevel interval in the Kiirunavaara mine is 29m (floor to floor) and drift spacing is 24.7m (centre to centre) (Susanne Karppinen, personal communication, 2015). The drift spacing is 21m (centre to centre) for blocks 38 and 41 (Susanne Karppinen, personal communication, 2015). The production drift is 7m wide and 5.2m high (Jonsson, 2015).

2.1.3 Ring design -the norm and variation

The Kiirunavaara mine uses a standard SLC 'silo-shaped' ring design; it has normally 8 drill holes with 54m long mid holes (60m in some cases) and side holes with a side angle of 73° (Wimmer, 2014). The diameter of production holes is 115mm (Wimmer, 2014). The distance between two adjacent holes at the end of the bore hole can be a maximum of 4m (Susanne Karppinen, personal communications, 2015). Boreholes are detonated in pairs with a delay of 25ms (Kristina Jonsson, personal communication, 2015). Figure 2.4 shows the shape of a typical production ring at the Kiirunavaara mine.

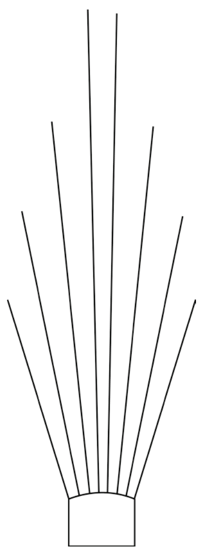

Figure 2.4 Typical production ring (Shekhar et al. 2016)

Two types of drill designs are used for openings (first blast in the production drift) at the Kiirunavaara mine; both serve the purpose of adjusting the drill design to suit the ore geometry near the hanging wall (Wimmer et al. 2012). The first consists of four rows of rings; the burden between the first, second and third rows are 2m, followed by a burden of 3m between the third and fourth row, as shown in Figure 2.5 (Susanne Karppinen, personal communications, 2015). The drill design also contains three boreholes drilled midway between the first-second and second-third rows of opening rings. These rows form the first blast, with the central uncharged hole acting as a free face (Susanne Karppinen, personal communications, 2015).

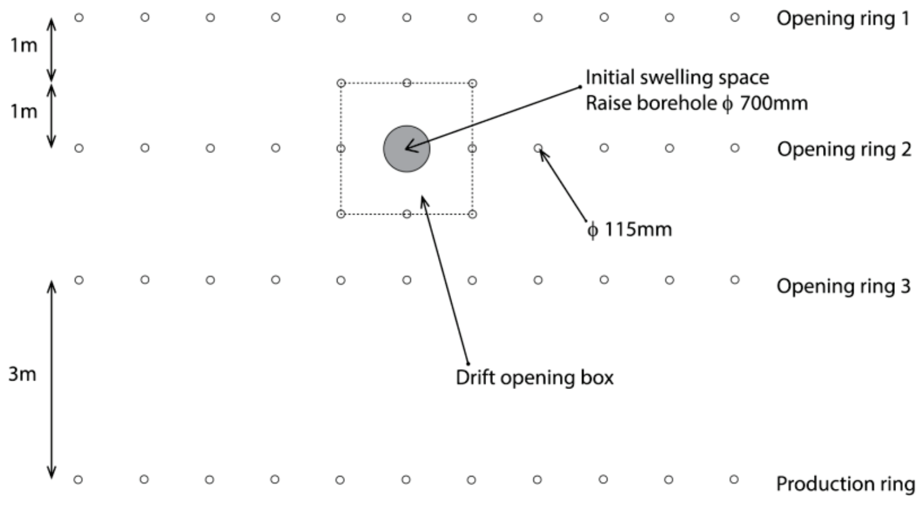

Figure 2.5 Top view of the first production blast at Kiirunavaara (Modified from Falksund, 2015)

The relative position of the opening holes along the production drift is shown in Figure 2.6. The following rings are drilled and blasted at 3m burden intervals with a front angle of 70° and a side angle of 60° until the holes start connecting to the cave of the level above (Susanne Karppinen, personal communications, 2015). The ring location where the drill holes connect to the cave of the upper level is called ‘rasinbrott’ (Susanne Karppinen, personal communications, 2015). At this particular location, two double rings are drilled. The first double ring is drilled at a front angle of 70° and 75° and the second is drilled at a front angle of 75° and 80° (Figure 2.6). This practice achieves better fragmentation for the transition zone, as it increase the specific drilling for the zone (Chakraborty et al. 2004). After rasinbrott is reached, the drill holes follow a standard ‘silo-shaped’ ring design with a front angle of 80° (Susanne Karppinen, personal communications, 2015). The last two rings drilled in the production drift are double rings with their drill collar in the footwall. The first double ring has a front angle of 80° and 85° and the second has a front angle of 85° and 90° (Figure 2.6). The last ring in the production drift is designed to have an ore-to-waste ratio of 1:1 (Susanne Karppinen, personal communications, 2015). This change in design permits the recovery of a maximum amount of ore near the footwall contact.

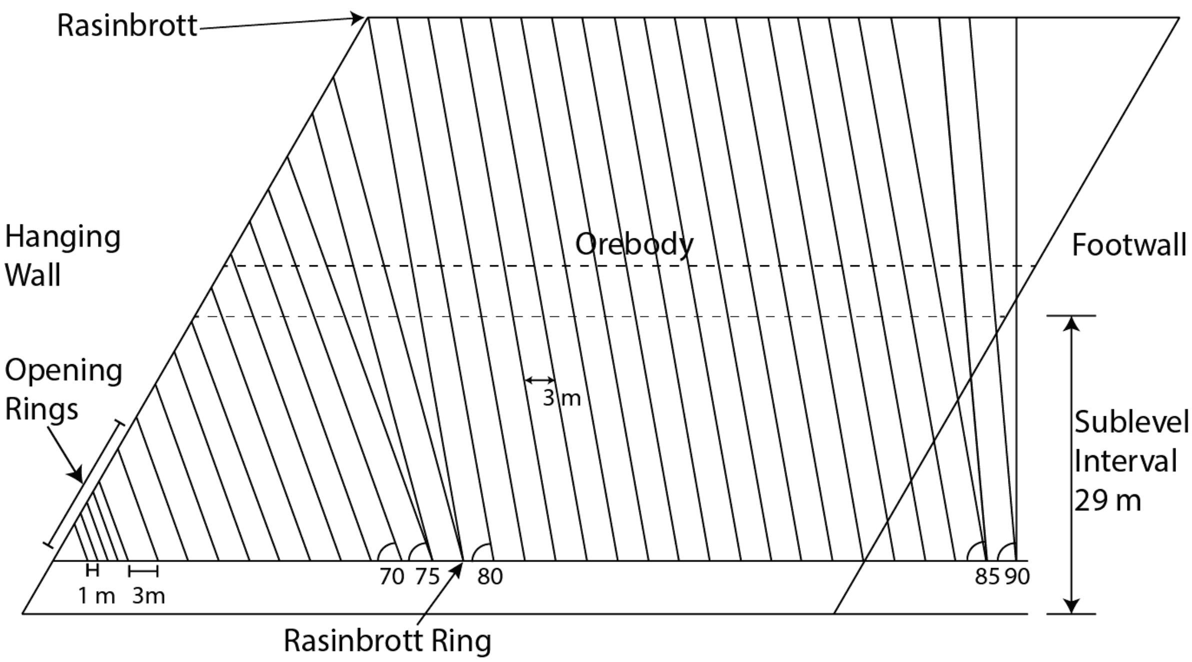

Figure 2.6 Side view of a transverse production drift (Shekhar et al. 2016)

If the ore body is relatively thinner near the hanging wall, the opening rings can have boreholes with lengths less than 10m. An opening design called Grovhålsöppning (Large-hole opening) is used in such production drifts (Falksund, 2015). This design is similar to the drill design used when drilling production drifts but the holes are drilled vertically on the production drift roof instead of horizontally, as shown in Figure 2.7. Production drill rigs are used to drill the rings (Figure 2.7).

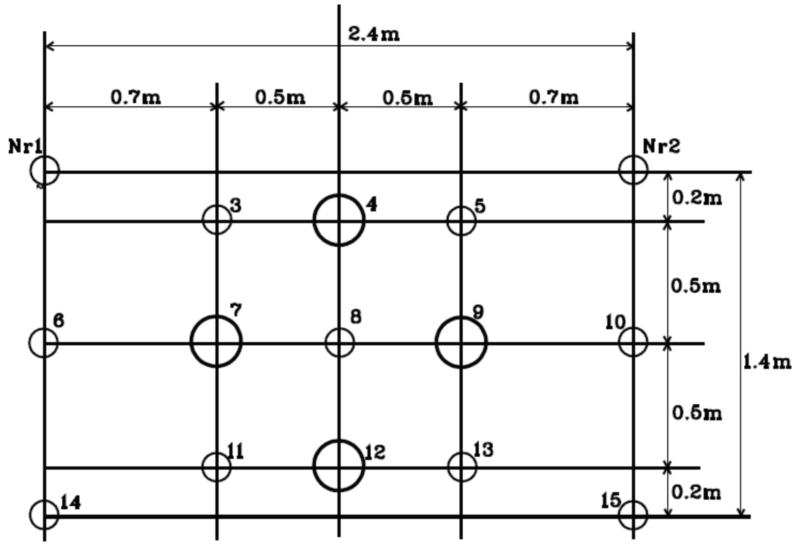

Figure 2.7 Opening borehole design (Grovhålsöppning or Large-hole opening) (Falksund, 2015)

In general, a blasted ring contains around 10000 tonnes of ore, but the ore produced from a ring can vary between 8000 to 12000 tonnes depending on the location of the ring along the drift. The volume and tonnage for a ring changes with drill design and ore geometry and can be seen in GIRON (Palm, 2013). In the case of double ring blasts, the ore tonnage details are stored in one of the rings of the double ring in GIRON. The width of the draw is assumed to be around 60% of the drift spacing (Matthias Wimmer, personal communication, 2015).

2.2 The Malmberget mine

The Malmberget mine consists of about 20 orebodies (Figure 2.8), of which 12 are currently being mined with varying degrees of tonnage (Savilahti and Jonsson, 2013). The mining area stretches 5km in the E-W direction and 2.5km in the N-S direction (Lund, 2013). The ore is composed of magnetite (95%) and hematite (5%), and the grade for the different ore bodies varies from 49% to 63% (Lund, 2013). The width of the ore bodies varies from 20 to 100m, and the tonnage varies from 5MT to 250MT (Savilahti and Jonsson, 2013). The mine is divided into two parts: the western and eastern fields. The ore bodies in the eastern fields are composed of massive magnetite ores with a current known depth of 1600m and provide 80% of the total production (Lund, 2013). The western fields consist of small magnetite-hematite deposits with a current known depth of 950m (Lund, 2013). The ore bodies in the eastern field are Alliansen (Al), Fabian (Fa), Kapten (Ka), Dennewitz (De), Parta (Pa), Printzsköld (Pr), Östergruvan (Og) and Vitåfors-Riddarstolpe (Vi-Ri). The western field includes the Välkomman (Vä), Baron (Ba), Johannes (Jh), Hens (Hn) and Josefina (Js) ore bodies.

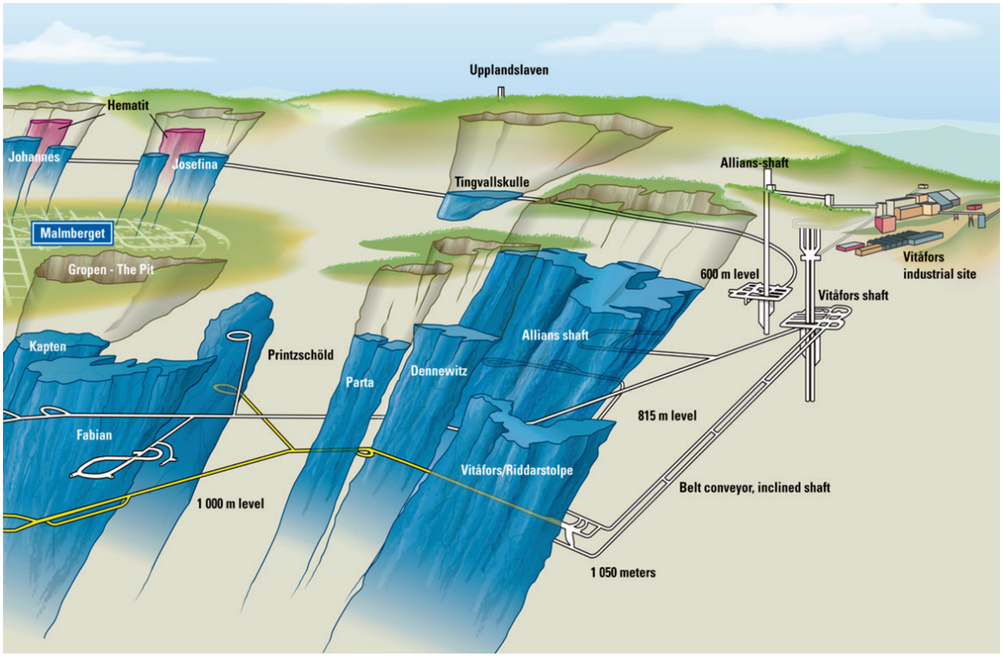

Figure 2.8 3D view of the Malmberget deposit (Savilahti and Jonsson, 2013)

2.2.1 Ore reserve estimation

The mine uses two sources of input data for the ore reserve estimation: drill core logs and grade control drilling (Personal communications, 2015). Drill cores are drilled at a 60m grid interval which translates into one hole per 3600m^2 of ore surface area (Jyri Meriläinen, personal communications, 2015). Grade control drilling is done to estimate the ore boundary towards the hanging wall. This type of drilling uses susceptibility measurements for magnetite and gamma ray method for hematite ore (Jyri Meriläinen, personal communications, 2015). The drilling creates about 40m long holes and uses them to delineate the ore boundary more accurately. The details from drill cores and grade control drilling are used to create a horizontal section of the ore body. The horizontal sections are then extended and joined digitally to create a three-dimensional model of the ore body. The ore model is validated to create a three dimensional digital model known as 3DM (Jyri Meriläinen, personal communications, 2015). The mine does not use block models for drill design purposes. The 3DM is used for drill design and loading operations. Ore reserve estimation is also performed for the rings using the 3DM model. In addition to the 3DM creation, geological mapping records joints and structures, GSI, lithology and rock type. As per the recommendations of the Swedish Association of Mines, Minerals and Metal Producers (SweMin), the proven mineral reserve is 303MT and the probable mineral reserve is 35MT for the Malmberget ore body (LKAB, 2014). The measured mineral resource is 10MT (LKAB, 2014), and the indicated mineral resource is 96MT (LKAB, 2014).

2.2.2 Mine design and layout

The mine design and layout at the Malmberget mine vary from one ore body to another. The Malmberget mine uses both transverse and longitudinal layouts for production, depending on the width of the ore body. This provides the mine with the flexibility to employ different mine layouts to reduce ore loss. The layout at one level can be longitudinal and the level below can be transverse, making the layout more complicated than a typical SLC operation. In most cases, levels up to 780m (below surface) have a longitudinal SLC layout, while levels from 805m and below have a transverse layout (Kristina Jonsson, personal communications, 2015). Figure 2.9 shows levels 780 and 805 for the Fabian ore body; black outlined drifts are level 780 (longitudinal drifts), and coloured drifts are level 805 (transverse layout).

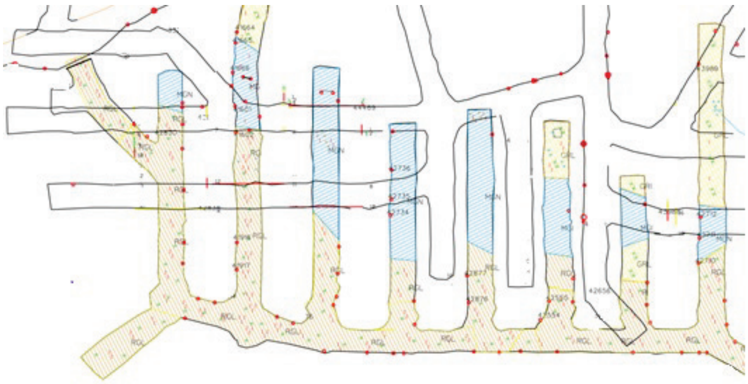

Figure 2.9 Mine Layout for Level 780 (black outline) and 805 (coloured drifts) for Fabian orebody (Courtesy, LKAB)

A drift´s orientation is guided by ore geometry and ore geology. The production drifts are planned to avoid weak zones and zones with major waste intrusions (Sven-Erik Wennebjörk, personal communications, 2015). Longitudinal SLC accounts for 10% of the production and transverse SLC accounts for 90% (Sven-Erik Wennebjörk, Personal communications, 2016). The sublevel interval varies from 20 to 30m (floor to floor) depending on the ore body. The drift spacing stays constant at 22.5m (centre to centre) for all ore bodies. The overall orientation of the production drifts is optimized to minimize ore loss, as the ore body shape and size varies. But this variation results in a complex network of production drifts, and drifts at the upper levels are not parallel to those at the lower levels. Table 1 shows the variation of sublevel intervals for different ore bodies. The production drifts are 6.5m wide and 5m high.

Table 1 Sublevel intervals for ore bodies in the Malmberget mine (Jonsson, 2015)

Field	**Eastern fields**					**Western fields**		
Ore Body	**Al**	**Fa, Ka**	**De, Pa**	**Pr, Og**	**Vi-Ri**	**Vä**	**Ba, Hn, Js**	**Jh**
Sublevel Interval	30m	25m	20m	25m	24m	25m	20m	22m

2.2.3 Ring design -the norm and variations

The ring design follows the standard fan shaped production ring, but the dimensions vary for different ore bodies. As the sublevel interval and burden vary, the shape and size of production rings also vary, along with the number of production ring boreholes (Jonsson, 2015). The diameter of the boreholes is presently 4.5” (115mm), but tests with both 4” and 3.5” holes are done today to try to limit surface vibrations. The number of boreholes in a ring varies from 7 to 15 and is dependent on ore geometry and mine layout (Sven-Erik Wennebjörk, personal communications, 2015). The length of the boreholes can go up to 45m, while the distance between two adjacent holes at the end of the bore hole can be a maximum of 4.2m (Sven-Erik Wennebjörk, personal communications, 2015). Delay detonators with a 100ms delay are used for blasting, and a single hole is blasted per delay (Kristina Jonsson, personal communication, 2015). Table 2 shows the variation in drill design for the different ore bodies.

Table 2 Mine design parameters for ore bodies in Malmberget mine (Jonsson, 2015)

Field	**Eastern fields**					**Western fields**			
Ore Body	**Al**	**Fa, Ka**	**Pr**	**Vr, Og**	**De, Pa**	**Vä**	**Ba, Js**	**Jh**	**Hn**
Burden	3.5m	3 m	3.5m	3.5 m	3.5m	3 m	3.5m	3m	3m
Side angle	65°	71°	65°	71°	71°	60°			

The first production blast starts near the hanging wall; it is designed differently from its counterpart in the Kiirunavaara mine. The opening for the production drift can be one of three types: raiseborrhålsöppning (raise bore openings), slitsöppning (slit opening) or ny öppning (new opening) (Falksund, 2015). Raiseborrhålsöppning is similar to the common opening pattern used in the Kiirunavaara mine, with a slight variation. The first three rows of production drill holes have a distance of 1.2m between rings, with the raise bore holes in the second row having a diameter of 700mm (Figure 2.10). The fourth row of production boreholes has a burden of 3 or 3.5 m depending on the ore body in which the opening is being made (Falksund, 2015). This design is used when the longest hole in the first production blast is more than 30m (Falksund, 2015).

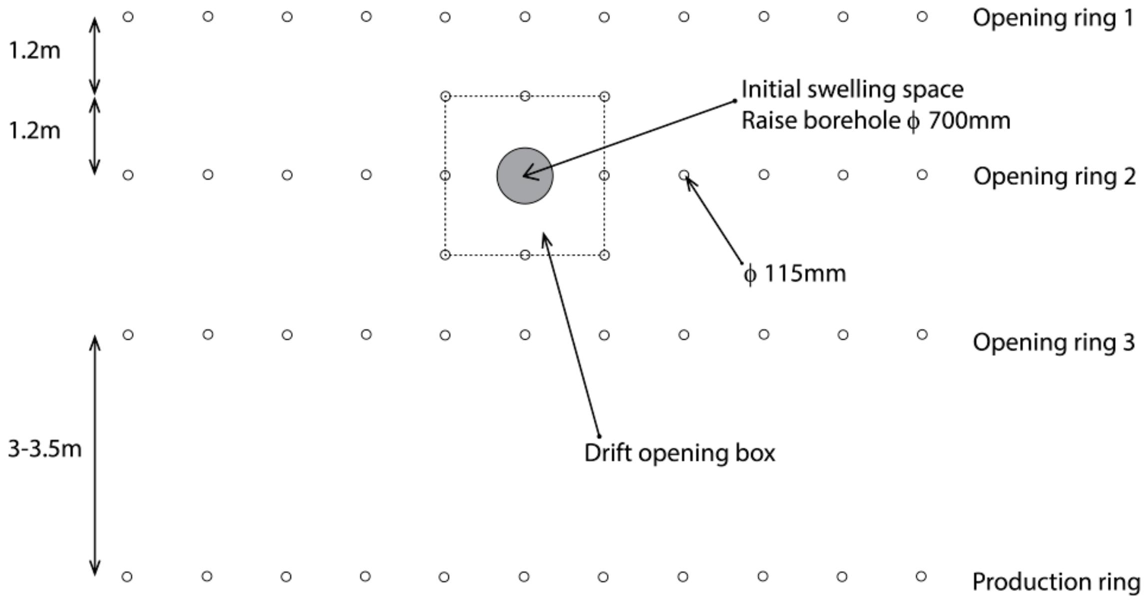

Figure 2.10 Raiseborrhålsöppning drill design (Top view) (Modified from Falksund, 2015)

In slitsöppning, the first three set of production boreholes are drilled with a distance of 1.2m between them and a borehole diameter of 4.5” (115mm) (Falksund, 2015). Between these rows of boreholes, two slits are constructed by drilling five 165mm diameter holes next to one another, as shown in Figure 2.11. The fourth set of boreholes is drilled at a distance of 3-3.5m depending on the ore body (Falksund, 2015). This design is used when the longest hole in the first production blast is between 23 and 30m (Falksund, 2015).

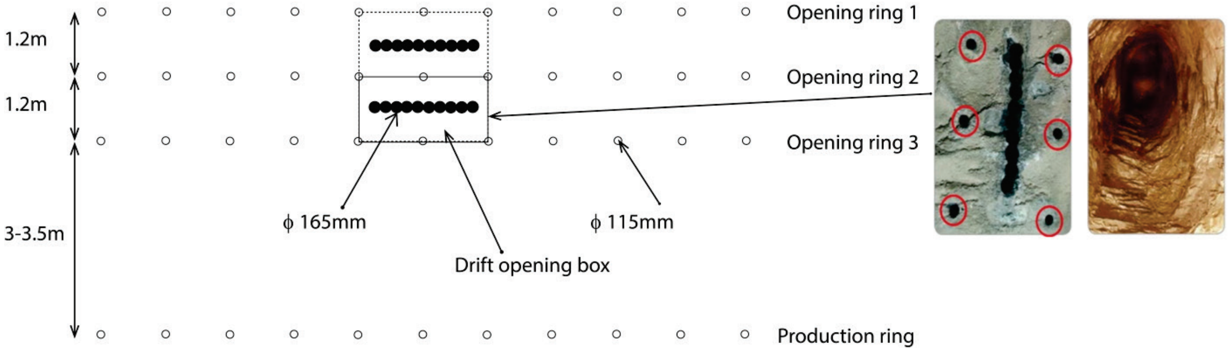

Figure 2.11 Slitsöppning design for opening (Top View) (Modified from Falksund, 2015)

Ny öppning is a new opening type introduced in March 2014. The design uses production drill rigs to drill all the boreholes required for opening a production drift, hence reducing the drilling cycle time for operation (Falksund, 2015). The design uses electronic detonators were the total time span of the blast is 15 seconds. As shown in Figure 2.12, five sets of boreholes are drilled. The second and fourth sets are not drilled for the entire width of the drift (Figure 2.12). The red holes shown in the Figure 2.12 are uncharged holes; these provide a free face similar to the raise hole and the slits in the two previous methods (Falksund, 2015). Two primers are used for certain holes in the middle, as marked in the figure. The delay design for the blast is shown with the numbers above each borehole representing the delay sequence. This design is used when the longest hole in the first production blast is less than 23m (Falksund, 2015).

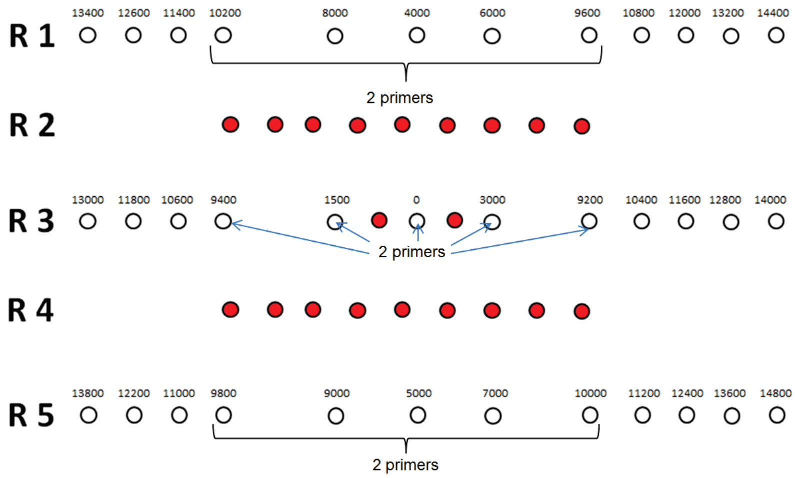

Figure 2.12 New opening design for Malmberget mine (Falksund, 2015)

The front angle for the first production blast for all three designs is maintained at 70° (Sven-Erik Wennebjörk, personal communications, 2015). After this, the next rings are drilled and blasted at a specified burden interval, depending on the ore body, with a front angle of 70° and side holes with a side angle of 60° until the holes reach the hanging wall contact (Sven-Erik Wennebjörk, personal communications, 2015). This drill pattern is followed until the boreholes start connecting to the cave of the upper level. As noted above, the ring location where the drill holes connect to the cave of the upper level is called “rasinbrott”. Similar to the Kiirunavaara mine ring design, at the Malmberget mine, two double rings are drilled at rasinbrott. The first double ring is drilled at a front angle of 70° and 75° while the second double ring is drilled at a front angle of 75° and 80°. After rasinbrott is reached, the boreholes follow a standard fan shaped ring design. As the rings approach the footwall, the drill design is altered to recover ore near the footwall. The last ring in the production drift will have an ore to waste ratio of 1:1. Two double rings are also drilled at the foot wall. The first double ring has a front angle of 80° and 85° and the second double ring has a front angle of 85° and 90° (Sven-Erik Wennebjörk, personal communications, 2015). The side angle varies along the production drift; it first increases after rasinbrott and then decreases near the footwall to restrict the waste inflow (Sven-Erik Wennebjörk, Personal communications, 2015). Different side hole angles are used for different ore bodies (Table 2) but there is no specific rule guiding the magnitude of the side angle, and the angles vary depending on ore geometry (Sven-Erik Wennebjörk, personal communications, 2015). For rings with a sublevel interval of 30m, the side holes do not reach the preferred standard design in which the side holes reach the proximate drift. This could lead to poor fragmentation and low final extraction ratio (Chakraborty et al. 2004). In order to optimize the mine design, the production drifts are curved, as shown in Figure 2.13. Under such conditions, the burden varies to increase the ore recovery. The rings in these or similar cases need to maintain a minimum burden of 1.2m (Sven-Erik Wennebjörk, personal communications, 2015). Enforcing this limit keeps the boreholes from collapsing and allows them to maintain an effective burden.

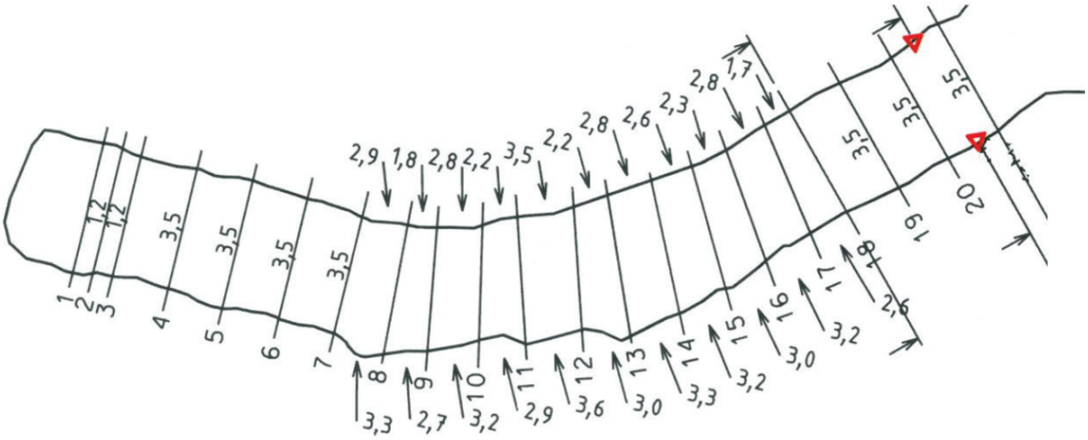

Figure 2.13 Drift bending in Malmberget mine (Courtesy LKAB)

In the case of adjacent rings, no correlation needs to be maintained, but a gap of 1.5m is maintained between the rings to avoid a collapse of boreholes (Sven-Erik Wennebjörk, personal communications, 2015). The time lag between when the holes are drilled to when they are blasted varies from three months to five years (Sven-Erik Wennebjörk, personal communications, 2015). A drill buffer of two years is the practice at the Malmberget mine; this means the production rings equivalent to the next two years of production are drilled and available (Sven-Erik Wennebjörk, personal communications, 2015). However, production areas are constrained by issues related to seismicity and caving (Sven-Erik Wennebjörk, Personal communications, 2016). Hence, drilling sometimes needs to be done in new production areas which do not have seismicity or caving issues.

3 Organizational Structure

Material loading from the draw point is a continuous process at LKAB and requires the proper use of both manpower and machines. The production team controls the loading process and determines the procedures and criteria for loading at the draw point.

3.1 The Kiirunavaara mine

The organizational map for the production and loading section of the Kiirunavaara mine is shown in Figure 3.1. The production and loading section, headed by a sektionschef (section manager) is divided into the following departments: byggledare externa (construction manager external), byggledare konsuln (construction manager Konsuln), teknikutvecklare (technology developer), processingenjör (process engineer), laddning (charging), skivservice (production area maintenance), gruvstaben (loading control), lastning (loading), and schaktrenovering (ore pass restoration).

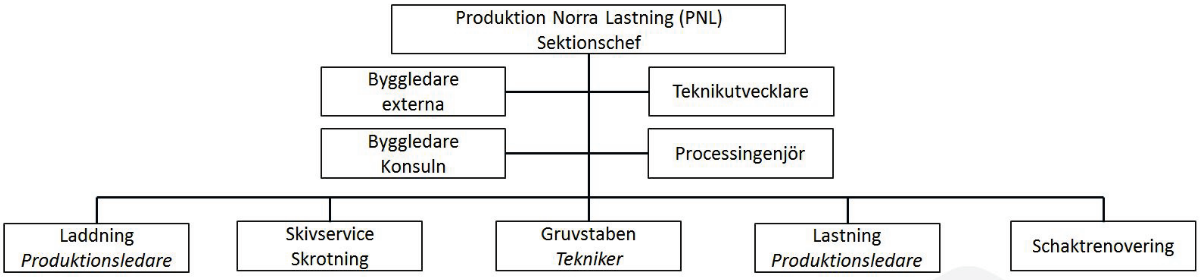

Figure 3.1 Organizational map of the Kiirunavaara mine (production and loading) (Courtesy LKAB, 2015)

Mine personnel involved in loading include the following:

- **Loading Control (Gruvstaben)**: They provide information about which draw points should be loaded and which draw points should be closed (Kjell Olovsson, personal communications, 2016). They also deal with short term mine sequencing and scheduling.
- **Production Managers (PC) Loading**: They are in charge of the LHD operators and assign them to different production areas (Kjell Olovsson, personal communications, 2016). Two production managers (PCs) head the loading operation in the Kiirunavaara mine.
- **Production Leaders (Produktionsledare)**: They are deployed in the shifts with LHD operators and provide directions to LHD operators based on information from the production manager (PC) loading and loading control (Kjell Olovsson, personal communications, 2016). The production leaders have a work rotation with two people on work and one off work every week (all seven days). Two production leaders are deployed in the morning and afternoon shifts at the mine (Kjell Olovsson, personal communication, 2016).
- **LHD Operators**: They load the material at the draw point. The Kiirunavaara mine has 81 LHD operators (Kjell Olovsson, personal communication, 2016).

3.1.1 Manpower deployment

The LHD operators work in four shifts: morning (05:00-13:48), day (7:18-16:06), afternoon (14:30-23:12) and evening (16:00-01:00) (Figure 3.2). The operators work in a staggered pattern so that the shifts overlap to use the LHD machines as much as possible. Each LHD is usually operated by two LHD operators who take turns to operate the machine. The duration of the loading period of the operators varies, as shown in Figure 3.2.

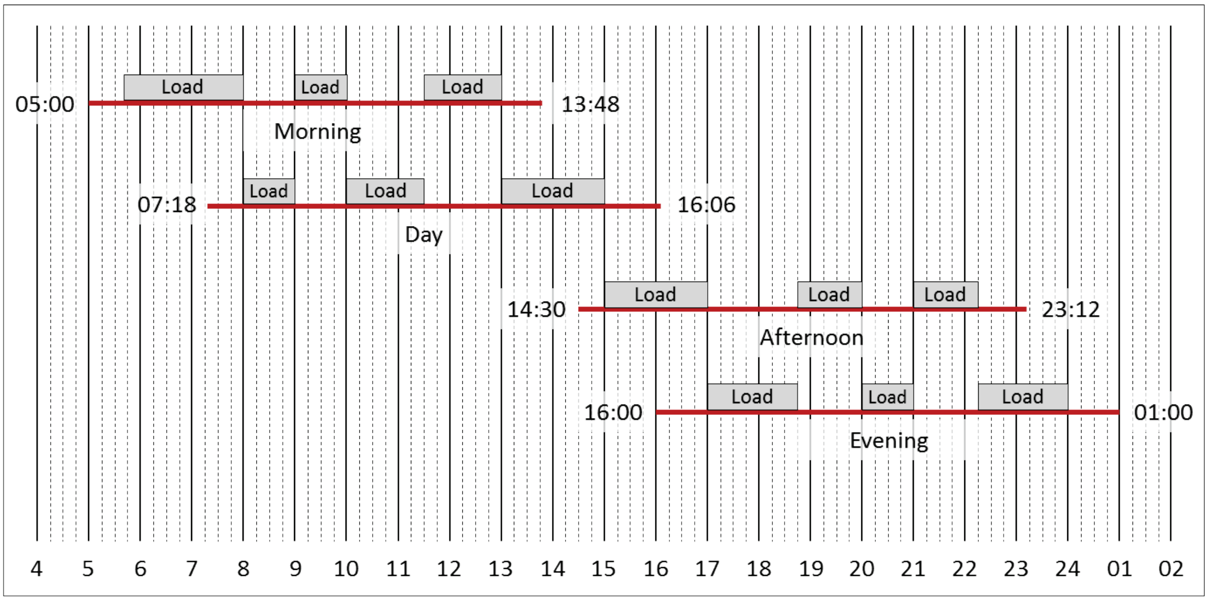

Figure 3.2 Shift design at Kiirunavaara mine (Kjell Olovsson, personal communication, 2016)

The morning shift starts at 05:00 but the LHD operator starts loading from the draw point at around 5:45 (time to travel from surface to underground) and continues loading until 08:00. The LHD operator from the day shift takes over the loading until 09:00 and the first LHD operator resumes the loading at 09:00, relieving the operator from the day shift, and creating the overlapping pattern mentioned above. The practice of continuous machine operation is followed for the first three shifts, as shown in Figure 3.2, but the evening shift runs at reduced manpower capacity (Kjell Olovsson, personal communication LKAB, 2016). Overall, the LHD operators are divided into seven groups. The first five groups are assigned to work in morning, day and afternoon shifts (Kjell Olovsson, personal communication, 2016). The groups rotate in a morning-afternoon-week off-day-week off pattern, so in any given week three groups are working and two groups are not (Kjell Olovsson, personal communication, 2016). The remaining two groups work alternative weeks in the evening shift (Kjell Olovsson, personal communication, 2016).

3.2 The Malmberget mine

The organizational structure and manpower distribution in the Malmberget mine are slightly different. Figure 3.3 shows the organizational structure for the production and loading section. The production and loading section is headed by a sektionschef (Manager) and is divided into the following departments; processingenjör (process engineer), produktionsstab (loading control), samordning/byggledning (coordination and building), productiontekniker (production technician), teknik/utvecklare (technology developer), laddning/förråd (charging/storage), lastning (loading) Fabian, lastning (loading) Alliansen, bergtransport (ore transportation), resursstyrka (resource group) and utbildning (education).

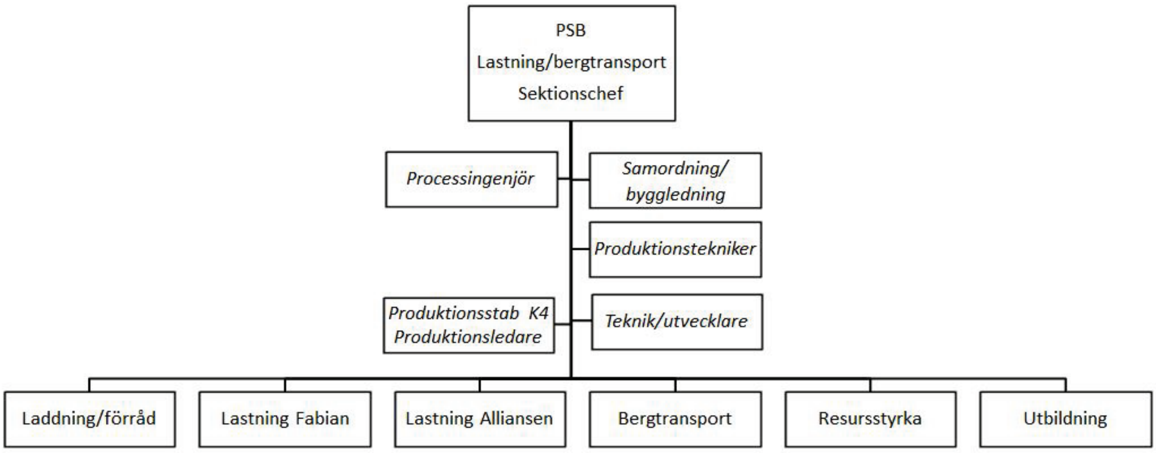

Figure 3.3 Organizational map of Malmberget mine (production and loading) (Courtesy LKAB, 2015)

Mine personnel involved in loading at Malmberget include the following:

- **Loading Control (Produktionsstab)**: They provide information about which draw points should be loaded and which draw points to be closed (Patrik Johansson, personal communications, 2016). They also deal with short term mine sequencing and scheduling. Loading control consists of four production leaders working in rotation, with three people working the morning, day and afternoon shift and one person is off.
- **Production Manager (PC) Loading**: They are in charge of handling the LHD operators and assigning them to different production areas (Patrik Johansson, personal communications, 2016). Fabian and Alliansen are the two nodal points in the eastern field of the mine; from here, the operators are deployed to different parts of the eastern field (Patrik Johansson, personal communications, 2016). The western field is contracted to an external company.
- **LHD Operators**: They perform the loading of the material at the draw point. In the Malmberget mine, LKAB has 59 LHD operators (Patrik Johansson, personal communication, 2016) not counting those working for the contractor.

3.2.1 Manpower deployment

Figure 3.4 shows the shift design at the Malmberget mine. The LHD operators work in five shifts: morning (05:00-13:12), day (07:00-15:12), afternoon (13:54-22:00), evening (15:54-24:00) and night (22:00-06:00). The LHD operators operate the LHD machines in a staggered pattern. The duration of the loading period by the two alternating operators is constant (2 hours 15 minutes) in the Malmberget mine, except for the first and last loading period of the day, each of which is 2 hours, as shown in Figure 3.4.

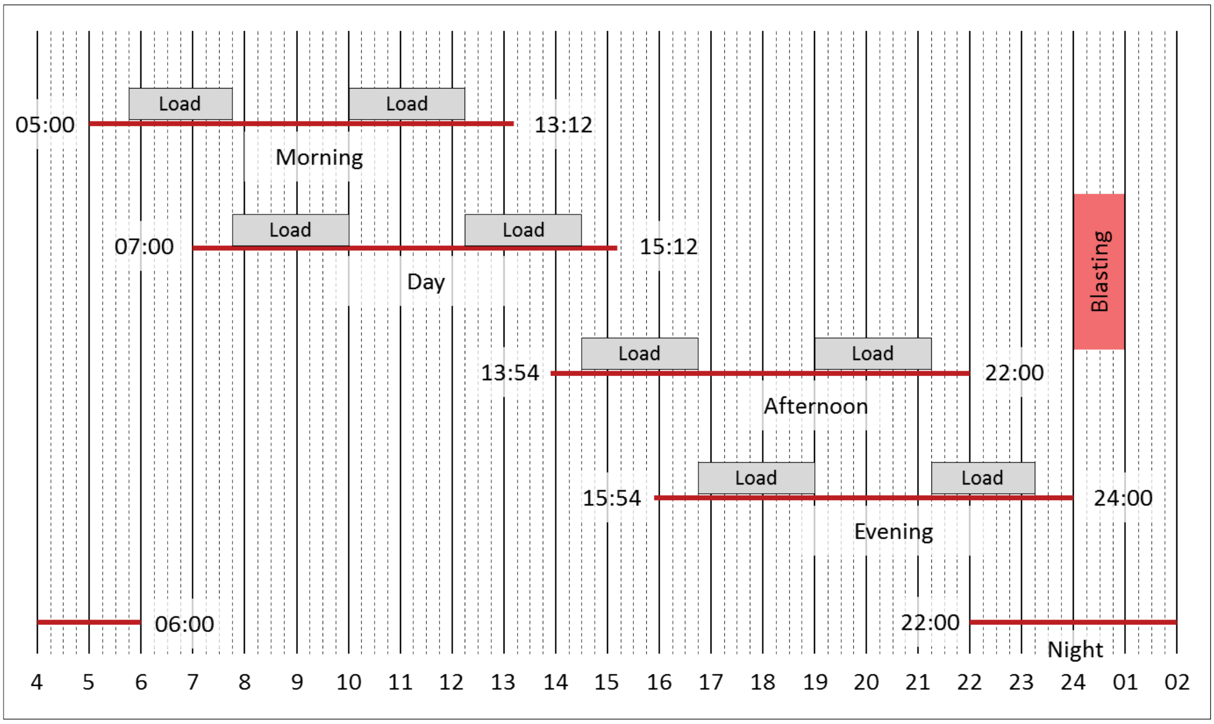

Figure 3.4 Shift design at Malmberget mine (Patrik Johansson, personal communication, 2016)

The morning shifts starts at 05:00 but the LHD operator starts loading from the draw point at around 5:45 (time to travel from surface to underground) and continues loading until 07:45. At this point, the second LHD operator from the day shift takes over the loading until 10:00 when the first LHD operator resumes the loading, creating an overlapping pattern (Patrik Johansson, personal communication, 2016). The practice is followed for the first four shifts as shown in Figure 3.4. The night shift consists of two operators who work between 23:15 and 06:00. The LHD operators are divided into eight groups. The first six groups are assigned to work in morning, day, afternoon and evening shifts (Patrik Johansson, personal communication, 2016). The groups rotate in a morning--afternoon--week off--day—evening--week off pattern, so in any given week, four groups are working and two groups are not (Patrik Johansson, personal communication, 2016). The remaining two groups work alternative weeks in the night shift. The night shift consists of only two operators (Patrik Johansson, personal communication, 2016).

4 Loading Support Functions

Sublevel caving consists of a number of unit operations, including drilling, blasting, ventilation, loading and transportation of material. Each unit operation generates a large amount of data; these data are used to plan the subsequent processes and to monitor the mining operation. A systematic recording, storing and delivering of mining related information is vital for a mechanized mining operation. LKAB uses different information systems to support the mine´s unit operations and employs these systems to monitor and record geotechnical properties of the mine and mechanical outputs from the machines. The three support systems used for the loading operation are the Loadrite system, WOLIS (Wireless Loader Information System) and GIRON.

4.1 Loadrite system

The Loadrite scoop weighing system is installed in the LHD machines to measure the bucket weight of a loaded bucket (Davison, 1996). It measures the hydraulic pressure in the lift cylinders of the LHD's arms connecting the machine to the bucket. It then converts this hydraulic pressure into a weight (Davison, 1996) which is displayed for the operators inside the LHD machine through WOLIS. Loadrite consists of an electronic trigger device which ensures that the weight measurements are taken at the same position on every lift (Davison, 1996). A transducer measures the hydraulic pressure in the lift cylinder. Two transducers are used for a lift cylinder; one is placed on the return side of the cylinder and the other on the input side of the cylinder (Davison, 1996). These transducers are connected to a pressure transducer which measures the difference in the pressure of the input and return side of the hydraulic jack and transfers this into a weight value (Davison, 1996). A data logger allows the transfer of data from the system to a WOLIS-computer installed in the LHD.

The first Loadrite weighing system was purchased in October 1996 to be used at LKAB's Kiirunavaara mine. This was done on a rental basis for three months; the installation included the Loadrite system, a printer and a data transfer system (Davison, 1996). The initial goal was to assess the possibility of using bucket weights to classify the amount of ore and waste in the system (Davison, 1996). The ore and waste density are significantly different, with an average ore density of 4.6 - 4.8tonnes/m^3 and an average waste density of 2.7 - 2.8tonnes/m^3 (Klemo, 2005). The results from the initial installation and testing (see Appendix 1 and Appendix 2) showed that the Loadrite system was accurate to 2.5% in the upper weight range (30tonnes) and to less than 1% in the lower weight range (10-20tonnes) (Davison, 1996). In other words, the Loadrite system serves the purpose of providing the input weight of a loaded bucket to the mine for bucket grade calculation (ore - waste composition of a loaded bucket) and grade control.

4.1.1 Loadrite Pro weighing system

The Loadrite Pro Weighing System is an improved version of the originally installed Loadrite system and has several features to handle different types of loading conditions. The system is installed in LHD machines in both the Kiirunavaara mine (except for two new LHDs) and the Malmberget mine. The system is built for use in material transportation (hauling), loading and blending operations (Loadrite Pro, 2002). It can handle different units of measurement for weight. The system has several built-in functions for handling different scenarios (loading, transportation and blending) and for handling different materials simultaneously. It provides functions for calibration, machine setup and data collection. The important functions from the Loadrite Pro (2002) relevant to the loading process in sublevel caving mines can be categorized into weighing setup, machine setup, calibration and diagnostics (see Appendix 3). The accuracy of the Loadrite system depends on the calibration of the system.

Four types of calibration can be performed by the Loadrite Pro weighing systems:

- Rotary trigger position calibration
- Speed compensation calibration
- Zero calibration
- Span calibration

Appendix 4 discusses the procedure for performing these calibrations for a LHD.

4.1.2 Calibration practices at the Kiirunavaara mine

During new installation of Loadrite system in a LHD, the Loadrite manual is followed which recommends to perform speed compensation calibration (see Appendix 4), followed by zero calibration (see Appendix 4) and span calibration (see Appendix 4) with 20tonnes is performed (Gustaf Blomberg, personal communication, 2016). Either after a bucket change or when the operator suspects a calibration issue, zero calibration followed by a span calibration using 20tonnes weight is performed (Gustaf Blomberg, personal communication, 2016). Zero calibration is performed every 20 bucket loads and at the start of the shift (Gustaf Blomberg, personal communication, 2016). Schedule maintenance for LHD is performed every 500 hours for LH625 (capacity 25 tonnes) and every 250 hours for the LH621 (capacity 21 tonnes) (Gustaf Blomberg, personal communication, 2016).

4.1.3 Calibration practices at the Malmberget mine

During new installation of Loadrite system in a LHD, a speed compensation calibration (see Appendix 4) is performed on the machine, followed by the zero calibration (see Appendix 4) and span calibration. After a bucket change, the zero calibration and then the span calibration are performed.

4.2 GIRON

GIRON is an application tool which creates, stores, and displays mine related data from many different unit operations at LKAB. The application also communicates with other mine systems by sending and receiving data. The GIRON application is built in Developer Studio 2003 in a three layered structure, with an output display module termed the client, the business logics and algorithms built in a Distributed Component Object Model interface (DCOM) and a database management system Oracle 10g which stores the mine data (Adlerborn and Selberg, 2008).

The database in GIRON consists of many different datasets and stores a wide range of information, such as material loading data, machine oil consumptions etc. The application is online 24 hours a day and can be used simultaneously by different users (Adlerborn and Selberg, 2008). Figure 4.1 shows the functions handled in GIRON.

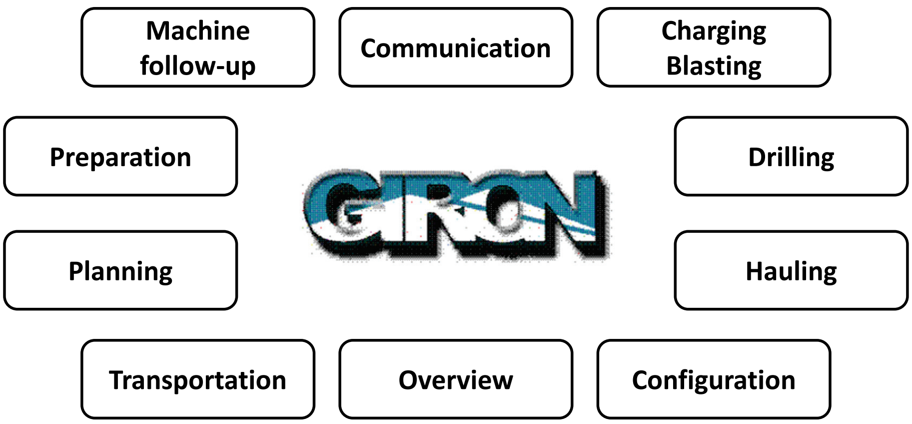

Figure 4.1 GIRON functional overview (Adlerborn and Selberg, 2008)

As shown in Figure 4.1, GIRON is used for planning, drilling, hauling and transportation operations at LKAB. The drift planning and ring design handled in GIRON are important for draw control, as they are the basis for the calculation of planned tonnage from a production ring. The drill planning tool takes information from the geology model/block model and profile data of production drifts (Palm, 2013).

4.2.1 Ring geometry

Ring geometry is designed using drill planning tool. The ring geometry created by the drill planning tool is used during drilling to guide the boreholes and control the length and angle of the production boreholes. Three reference planes (two on either sides and one vertically below) that controls the borehole length by limiting the area, above and around the drift, which can be drilled are created in the Raise bore planners tool (Figure 4.2a). The limiting boundary for the ring design (Figure 4.2b) is formed by connecting the two limiting surfaces for the given ring with the limiting surfaces and drift profile limiting surfaces from the nearby drifts (Palm, 2013). In case that no nearby drifts are detected, the limiting surface can be made by free triangulation drawn in the raise bore planners tool (Palm, 2013).

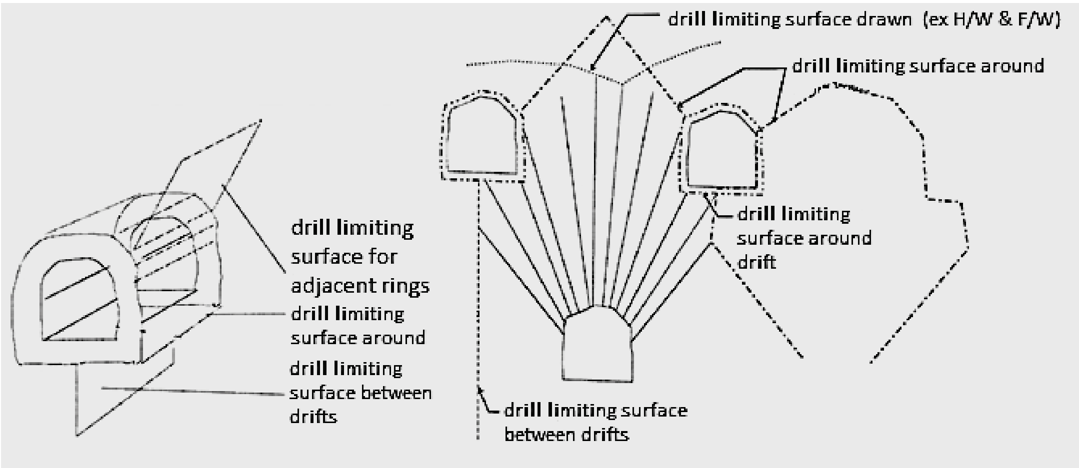

Figure 4.2 a) Three limiting surfaces for drill design; b) Limiting boundary for drill design (Palm, 2013)

The ring design boundary is then used to guide the drill rig by controlling the length and angles of the boreholes so that holes are drilled within the defined area in an accurate manner (Palm, 2013). Drill limiting surfaces can also be created around a drilled production ring by maintaining a predefined distance between the tip of the boreholes and the limiting surfaces, as shown in Figure 4.3. This is done manually in the raise bore planning tool when no drill limiting surface can be detected around the ring (Palm, 2013).

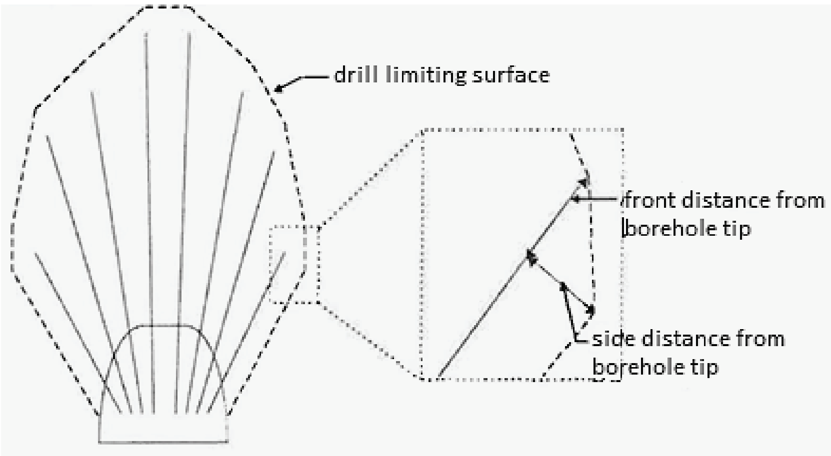

Figure 4.3 Drill limiting surface around a drilled ring (Palm, 2013)

4.2.2 Ring volume creation

For a production ring, 3D ring geometry is created by the raise bore planners (RBP) tool. Volume limiting surfaces are formed by extending the drill limiting surfaces around the ring and the ring surface plane (formed by drill limiting surfaces around the ring) (Palm, 2013). The volume created by combining the nearest volume limiting surfaces is the ring volume for a production ring, as shown in Figure 4.4 (Palm, 2013). The RBP tool detects the volume limiting surfaces from the tip of the drilled boreholes up to 6m; if the surfaces are not found, the RBP tool requests a further search. If there is a further search, the RBP tool tries to find a limiting surface for the longest borehole and to create a volume using the detected volume limiting surfaces. If further search turns up no results or if further search for the limiting surface is denied, the system creates a volume from the tip points of the boreholes (Palm, 2013).

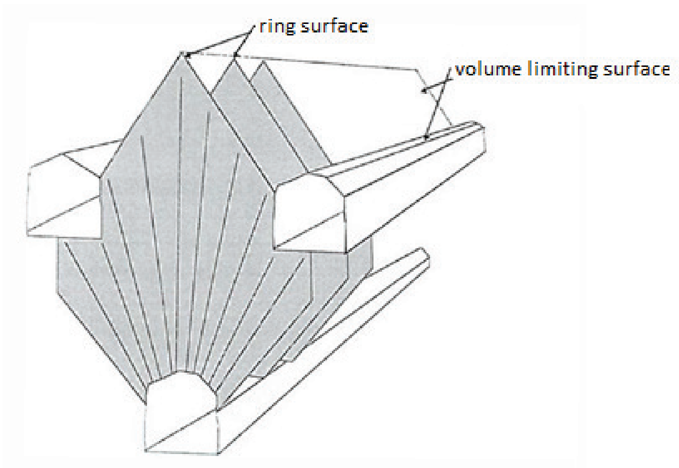

Figure 4.4 Volume creation (Palm, 2013)

4.2.3 Detection of neighbouring drifts

The drifts detected by the RBP tool when the volume of the ring is created by using the volume limiting surfaces are called the neighbouring drifts for a production ring. Figure 4.5 shows an example of the neighbouring drifts detected. From the ring plane, two coordinate points are cut with the neighbouring drifts and are stored in GIRON. The midpoint of the two coordinate points is also created and stored in GIRON. The number of neighbouring drifts depends on the ore geometry and ring location in the drift. A production ring near the hanging wall might not have any neighbouring drifts at all.

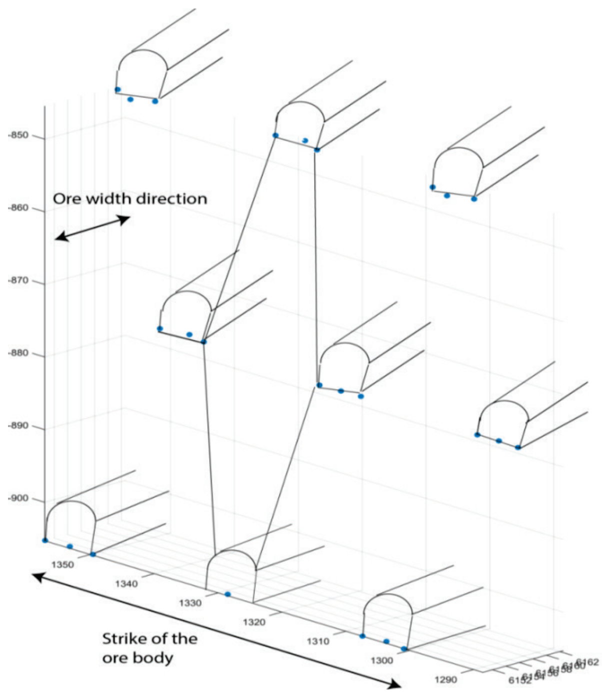

Figure 4.5 Example of neighbouring drifts in SLC

4.2.4 Detection of neighbouring rings

For each neighbouring drift detected, GIRON also detects and stores a corresponding neighbouring ring. The coordinates of the mid-point for the neighbouring drift detected are used as a reference point. The corresponding neighbouring ring is then searched for 10m on either side (forward/backward) of the reference point along the axis of the neighbouring drift (Daniel Eliasson, personal communication, 2016). Any neighbouring ring detected, along with its corresponding neighbouring drift, is displayed in the WOLIS system, as are the final extraction ratio details for the neighbouring ring.

4.3 WOLIS

The WOLIS system was developed by Agio system och kompetens AB (previously Kiruna Softcenter AB) and LKAB to improve the efficiency of the mining process (Adlerborn and Selberg, 2008). It is a control, decision and support system used in the loading and hauling process (Adlerborn and Selberg, 2008) and can be divided into three parts:

1. **Information collection**: Each LHD has a computer installed in it, along with a WLAN antenna. The bucket weight information is collected by the Loadrite system. The RFID scanner in the LHD, along with RFID tags mounted in the drifts and ore passes, gives information on the LHD's position in the mine (Adlerborn and Selberg, 2008). Information collected from the RFIDs and the Loadrite system is used in the WOLIS system to track the loading operation.
2. **Information transfer:** The information collected from the different LHD computers is transferred by the WLAN antenna through the WLAN router to GIRON, the main system for storing and displaying different databases (Adlerborn and Selberg, 2008).
3. **Information display:** The information on the rings, including ring position, number of buckets loaded, ore grade etc., can be displayed on computer screens for the operators and production team (Adlerborn and Selberg, 2008).

During the loading and hauling process, each time the onboard RFID scanner detects an RFID tag, it sends a signal to the WOLIS client computer giving the position of the LHD. Similarly, every loaded bucket is tagged so that information related to the drift from which it was loaded and the ore pass where it is unloaded is stored in the system. Figure 4.6 shows the layout of the WOLIS system installed in the mine.

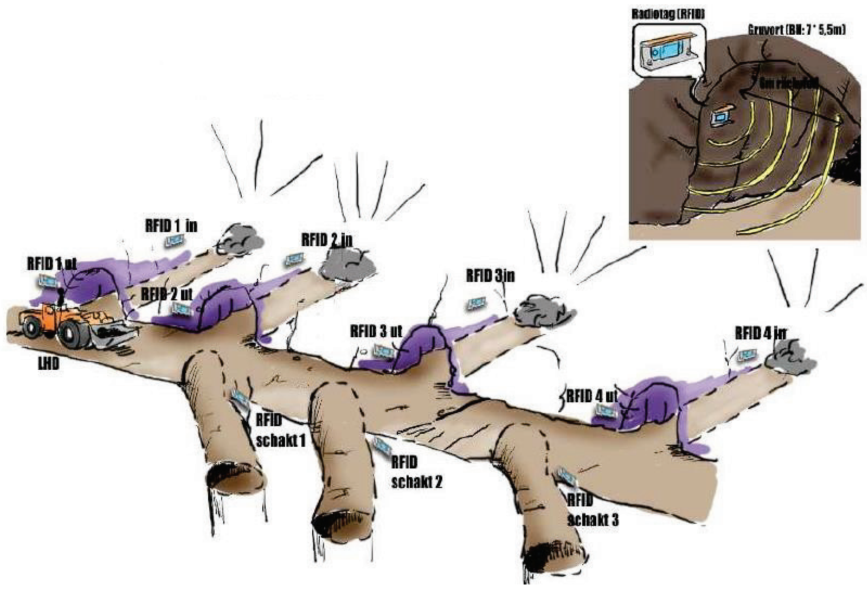

Figure 4.6 RFID position layout by WOLIS (Courtesy Agio system & kompetens AB)

The bucket data are transferred from the Loadrite system to the WOLIS system when the operator presses the weight button on the WOLIS screen inside the LHD (Siikavaara, 2004). The WOLIS system stores the data and transfers it to GIRON via WLan routers placed at designated locations in the mine (Siikavaara, 2004). When WOLIS and GIRON are connected, information related to drilling, ore geology and loading data is exchanged between the two systems.

Figure 4.7 shows one example of the details displayed to the LHD operator by WOLIS. The operators can change the visualized graph if they want to see, for example, iron ore content, extraction ratio, waste rock content, bucket number, tonnage etc.

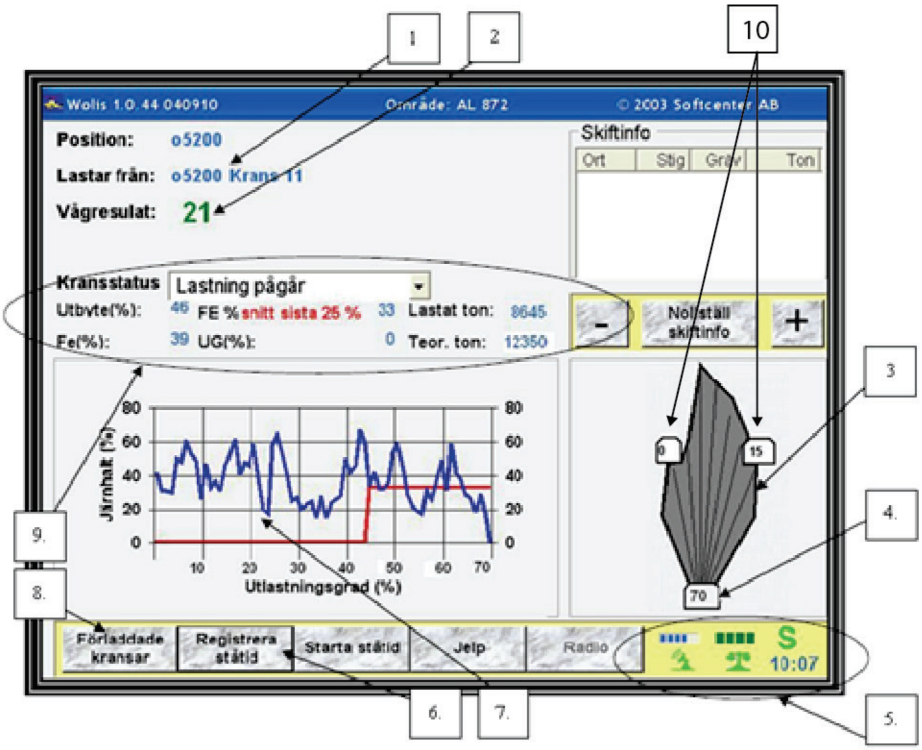

Figure 4.7 WOLIS display screen (modified from Adlerborn and Selberg, 2008)

The loading properties displayed on the WOLIS screen shown in Figure 4.7 are the following:

1. The location from where the material is taken, including the drift and ring number (Adlerborn and Selberg, 2008).
2. Last bucket weight recorded by the system (Adlerborn and Selberg, 2008).
3. A graphical representation of the current ring being loaded showing the drill holes, along with the neighbouring rings (Adlerborn and Selberg, 2008).
4. The current extraction ratio of the ring being loaded, in percentage (Adlerborn and Selberg, 2008).
5. Status indicators showing if the system is connected to the weighing system, if it is connected to the WLan, and an indication of upload/download transfers (Adlerborn and Selberg, 2008).
6. A new window to register down time, i.e. the duration and cause of system being down or unusable (Adlerborn and Selberg, 2008).
7. A graphic representation of the total loading from the current ring (Adlerborn and Selberg, 2008). The system has four modes for graphical representation. The graph can plot:
   a) Iron % (Y axis) vs Extraction ratio (X axis)
   b) Waste % (Y axis) vs Extraction ratio (X axis)
   c) Bucket weight (Y axis) vs Number of buckets loaded (X axis)
   d) Waste % (Y axis) vs Number of buckets loaded (X axis)

In Figure 4.7, the blue line shows the moving average property (iron percentage or bucket weight) and the red line shows the iron percentage of the last 25% (by units) of the extraction ratio. These two lines guide the driver's decision when to stop loading from a ring.

8. A new window showing if any charged holes are close to the current ring (Adlerborn and Selberg, 2008).
9. Additional data about the current ring is displayed on the operators screen (Adlerborn and Selberg, 2008). It includes the present status of the ring, the iron % for the last 25% of the extraction ratio, tonnage loaded, planned tonnage, iron percentage for bucket etc.
10. The final extraction ratio of the neighbouring drifts in the level above the present draw point.

4.3.1 Grade calculation in WOLIS

WOLIS uses the bucket weight from Loadrite together with an assumed theoretical volume of the loaded material to calculate the grade of the material in each bucket, i.e. the percentage of iron and waste present in the bucket. The iron percentage for a pure magnetite ore is 72.36% and for a pure hematite ore is 69.90%. However, the assumed iron percentage in WOLIS for a bucket completely filled with ore is 71% (Daniel Eliasson, personal communication, 2016). The formula for iron percentage used by WOLIS is described in Equation 5.1:

$$Fe\,\%\,for\ a\ Bucket = \big((Bucket\ weight - Y) \div (X - Y)\big) \times 0.71 \qquad (5.1)$$

where X is the weight of a bucket completely filled with ore and Y is the weight of the bucket completely filled with waste for the given LHD machine (Daniel Eliasson, personal communication, 2016). As LKAB has machines with different bucket sizes, the WOLIS system has different X and Y values stored in it for grade calculation.

5 The Loading Operation

The four aspects of loading (Figure 5.1) at the draw point are defined as:

- **Loading procedures:** Practices followed by operators for safe and efficient operation.
- **Loading issues:** Hang-ups, brow failure etc. which can result in temporary or permanent stoppage of loading from the draw point.
- **Loading criteria:** Rules and guidelines controlling the loading and closing of draw points in SLC. These can be static or dynamic and are aimed at increasing ore recovery and reducing dilution.
- **Loading constraints:** Prerequisites or preconditions to be followed during mine planning and loading for safe and efficient mine operation.

Loading criteria and loading constraints along with the nature of material flow together provides a complete understanding of the draw control strategy employed in the mine. The Kiirunavaara and Malmberget mines have different ore geology, mining conditions and capacities, leading to different loading criteria and constraints.

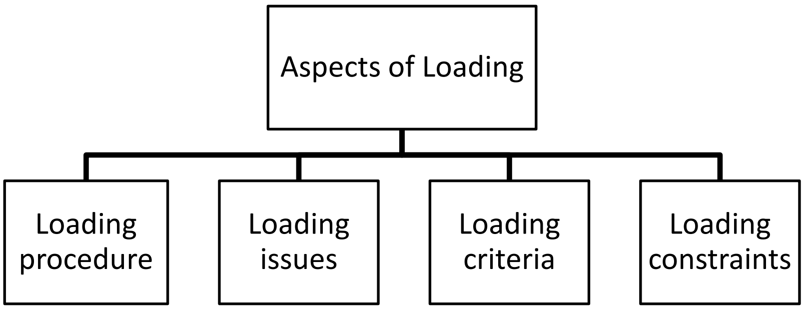

Figure 5.1 Loading process in SLC

5.1 Nature of loading at the draw point

The process of loading in sublevel caving is difficult, as a large amount of material is loaded from a small cross section known as the draw point, while, simultaneously, material from above flows into the draw point to replace the loaded material (Figure 5.2). The material is loaded and then transported by LHD machines to ore passes in Kiirunavaara mine while at Malmberget the material is transported by the LHD machines either to the ore passes or to trucks depending on the production conditions and mine infrastructure. Loading starts at the draw point after a production ring is blasted and clearance for loading is given.

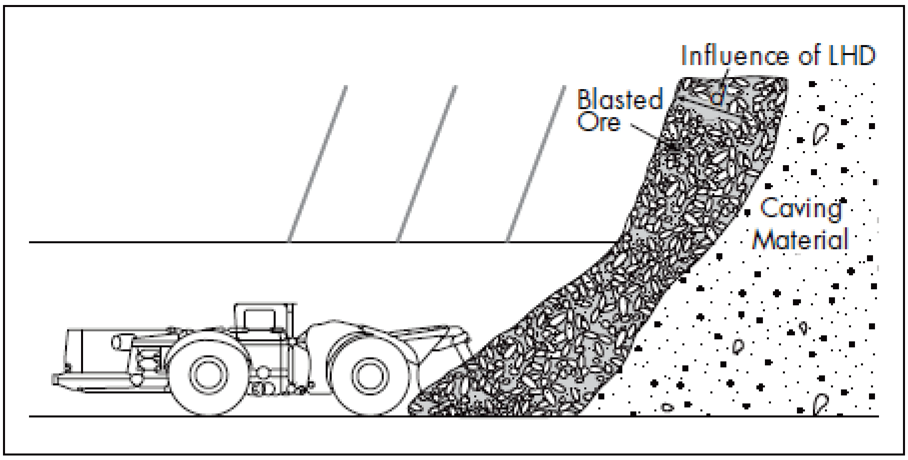

Figure 5.2 Loading at a draw point (Dunstan and Power, 2011)

The blasted material swells and fills the draw point to form a muck pile; the spread and angle of the muck pile slope varies during loading. According to Kvapil (2004), for good extraction, an ideally blasted ring creates a muck pile which fills the draw point as shown in Figure 5.3.

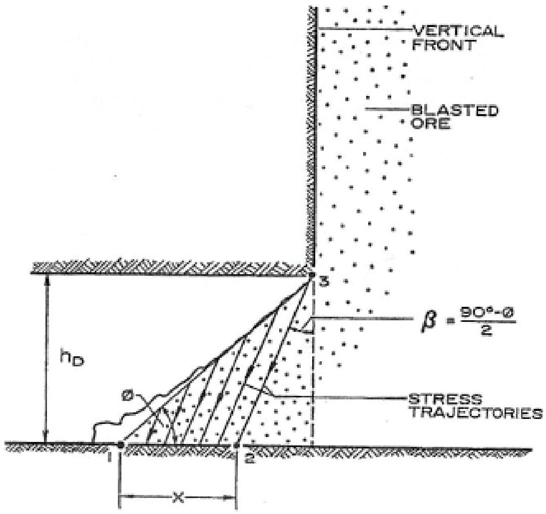

Figure 5.3 Muck pile spread for a vertical ring (Kvapil, 2004)

Theoretically, the initial muck pile slope is equal to the natural angle of repose (Φ), as a slope of coarse material is stable when the inclination is equal to the natural angle of repose (Φ) (Kvapil, 2004). As the material is loaded, the slope moves from plane 1-3 to plane 2-3 (Figure 5.3), after which the slope fails and fresh material from the blasted ring fills the draw point. However, practical experience shows that the muck pile behaviour is not always uniform.

Another aspect of the muck profile is the digging depth for the LHD. During marker trials at Kiirunavaara mine, Nordqvist and Wimmer (2014) measured bucket positions and depth penetration for 30 loading cycles. They found the maximum penetration depth was 2.2m in the muck pile based on depth measured by laser scanners; this was less than the ring burden (3m).

5.2 Loading procedures

Loading procedures in SLC mines include practices for safe and efficient loading. These can be summarized as follows:

- During loading, the operator's cabin should always be under a supported roof (Patrick Klasér, personal communications, 2015).
- Operators should try to push the LHD bucket into the muck pile as much as possible to stimulate a uniform material flow at the draw point (Patrick Klasér, personal communications, 2015).
- Operators should try to alternate the bucket loading from the left and right side of the muck pile, as shown in Figure 5.4 (Dunstan and Power, 2011). This practice helps to manipulate the muck pile and create uniform material flow.

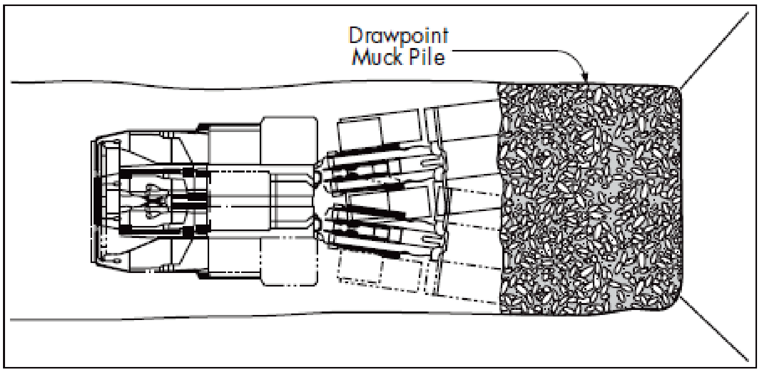

Figure 5.4 Side to side loading at draw point (Dunstan and Power, 2011)

- Operators should try to fill the bucket completely. In practice, filling the bucket can be difficult in the first attempt if the muck pile is compacted or contains many boulders, so operators make multiple attempts by pushing the bucket into the muck pile until sufficient material is loaded.
- At LKAB, operators weigh the bucket near the ore pass to get an accurate reading of the weight of the material being transported by discounting material lost during hauling (Davison, 1996).
- During weighing, the bucket is lifted in one smooth cycle to get an accurate weight reading and to avoid errors because of hydraulic spikes in the cylinder arms of the LHD (Davison, 1996).
- In Malmberget, after the loading of a ring is stopped, the draw point is closed by the operators; they construct a protective wall from the muck pile to provide a safe area for the charging of the next ring (Jan Holmlund, personal communications, 2016). The charging and blasting team is informed when the draw point is closed. If the muck pile is still active, loading is continued for some time to stabilize the muck pile by removing the excess material at the draw point (Jan Holmlund, personal communications, 2016). A scattered and unstable muck pile is unsafe for the charging team; the scattered material must be removed from the draw point, and the muck pile must be stable.

5.2.1 Instructions for using WOLIS

In LKAB, each LHD operator can see information, such as extraction ratio, and ore grade for the last 15 buckets, total planned tonnage, and tonnage extracted from the ring, on the WOLIS screen installed in the LHD, see figure 4.7. The information is used by the LHD operator to decide if loading should be continued or discontinued at a particular draw point (Patrick Klasér, personal communications, 2015). The operator uses the information displayed on the computer screen to determine if more material can be excavated from the draw point based on the loading criteria. If the information on the screen indicates loading should be continued, it is continued; otherwise, the draw point is closed. However, if loading cannot be continued because of loading issues, such as hang-ups, brow failure etc., the operator enters the reason for loading stoppage in WOLIS and moves to the next active draw point for loading (Patrick Klasér, personal communication, 2015).

5.3 Loading issues at LKAB mines

Loading at the draw point is sometimes stopped early because of loading issues such as hang-ups, brow failure, pillar failure, intrusions, poor fragmentation or ring freezing. The loading procedure changes when such an event takes place; loading is stopped if or when a draw point encounters a brow failure, pillar failure or ring freeze (also known as 'tak kvar').

Material with poor fragmentation is still loaded. The boulders are broken by a rock breaker at the Kiirunavaara mine before the material is dumped passing a grizzly before entering the ore pass (Patrick Klasér, personal communications, 2015). Still, large fragments are encountered in the ore pass and in the output of the ore pass frequently. This causes problems when loading the material onto the train from the ore passes and is handled either by blasting or by using water (Patricia Boeg-Jensen, Personal communication, 2015). In Malmberget mine, no grizzly is present and the boulders are broken by drilling and blasting (Krister Taivalsaari, personal communication, 2016). Poor fragmentation could be caused by poor drilling and blasting or by geological conditions. The loading criteria are followed for draw points with poor fragmentation, but an inefficient filling of the bucket may cause inaccurate grade estimations.

5.3.1 Handling hang-ups at the Kiirunavaara mine

The handling of hang-ups differs for the Kiirunavaara and Malmberget mines. When a hang-up is encountered at the draw point in the Kiirunavaara mine, it is initially handled by the LHD operator. The operator directs the LHD bucket to penetrate the muck pile and release the hang-up by disturbing the muck pile at the draw point (Patrick Klasér, personal communications, 2015). The ability of the operator to handle the hang-up depends on the nature of the hang-up and the operator's experience (Patrick Klasér, personal communications, 2015). A high hang-up is difficult to manipulate using the LHD bucket, but a low hang-up can be handled. If the operator is unable to handle the hang-up, water jets are used to release it (Patrick Klasér, personal communications, 2015). In other cases, low hang-ups of big boulders are drilled and blasted (Patrick Klasér, personal communications, 2015). If the hang-up persists, the next production ring is drilled and blasted.

5.3.2 Handling hang ups at the Malmberget mine

In the Malmberget mine, each LHD has two draw points assigned to it with priority one and priority two (Anna Johansson, personal communications, 2016). If a hang-up is encountered, it is first handled by the operator using the LHD bucket to resume the material flow (priority one). If the operator is unable to release the hang-up, the machine starts loading from the priority two draw point. When the hang-up is reported by the operator, it is inspected by the operator or the production leader (Fredrik Tano, personal communications, 2016). Depending on the inspection, the hang-up is classified as a high hang-up or a low hang-up. Material is loaded from the adjacent drift to loosen and release low hang-ups, while the production ring is blasted in the adjacent drift to release high hang-ups (Krister Taivalsaari, personal communications, 2016). Low hang-ups of big boulders are sometimes drilled and blasted by a special crew (Krister Taivalsaari, personal communications, 2016).

5.3.3 Handling waste intrusions at the Malmberget mine

The ore body in Malmberget has waste intrusions in the ore body. If a production ring has a very high waste intrusion percentage (something seen in the WOLIS system), the production ring is not drilled and is left intact (Kristina Jonsson, personal communication, 2015). The next production ring is drilled and blasted instead, and loading can be continued. The mine is contemplating changing this practice, as it causes issues with reinforcement and caving (Kristina Jonson, personal communication, 2015). In future, the mine plans to drill and blast the ring but not load the material.

5.4 Loading criteria

Loading criteria are a set of rules and guidelines that control the loading and closing of draw points in SLC. The loading of material at the draw point in both the Kiirunavaara and Malmberget mines is assisted by the WOLIS system. As noted previously, WOLIS displays bucket weight and bucket grade, among other ring properties. The information displayed by the WOLIS system is used by the mine to communicate the loading criteria.

5.4.1 Loading criteria at the Kiirunavaara mine

In the Kiirunavaara mine, extraction ratio is used as loading criterion, which is the ratio of total tonnage of material loaded from the draw point to the planned tonnage of the ring. Loading is started for a blasted ring and is continued until the extraction ratio for the ring has reached the target final extraction ratio as communicated by loading control (Patrick Klasér, personal communications, 2015). If a draw point performs poorly from the start, loading is continued until a relatively higher extraction ratio can be reached, after which, based on the ore grade trend shown in the WOLIS system, the draw point is abandoned (Patrick Klasér, personal communications, 2015). The decision is subjective depending on the assessment of loading mine personnel.

There are special loading conditions near the ore boundaries; hence, loading is performed differently as described below:

- **Loading near the hanging wall and footwall**: The loading process and draw control near the hanging wall are guided by safety concerns (Patrick Klasér, personal communications, 2015). Draw points near the hanging wall have an open cavern at later stages of the draw; i.e. the hanging wall has not yet caved or has just started to cave, creating an open cavern above the draw points. Keeping this in mind, LHD operators load the material under the supported part of the drift. The current loading procedure dictates that no loading can be performed in an open cavern situation; i.e. loading is stopped when an opening is encountered at the draw point because of a gap between the muck pile and the supported part of the draw point (Patrick Klasér, personal communications, 2015). The final extraction ratio for rings near the hanging wall can vary from 35% to 70%. Poor blasting or other operational issues can result in final extraction ratios even less than 35%. High final extraction ratios can occasionally be observed for rings near the hanging wall. This issue is resolved gradually as the production reaches rasinbrott rings where the drill hole is connected to the caved upper level. The rings can then be loaded normally. Another exception to the loading criteria is for rings which are partly drilled in the footwall and partly drilled in the ore body. The last few rings in a production drift are partly drilled in the footwall which resulting in internal dilution. Because of this, the loading procedure for these rings is different. The initial inflow of waste is neglected, and final extraction ratio targets are higher than 105% to recover ore that may have accumulated in the above levels (Patrick Klasér, personal communications, 2015). Based on bucket weight trends, the extraction ratio for these rings can go beyond 200% to recover more ore near the footwall and ore from the above levels.
- **Loading the last ring of a production drift**: For the last draw point of a production drift, a second phase of loading known as 'restmalmslastning' (residual ore loading) is sometimes done (Patrick Klasér, personal communications, 2015). This is a separate process which assumes that heavy finer ore flows faster than caved material (Kvapil, 2004) and accumulates along the footwall. Based on mine experience, loading is done for certain draw points to recover the ore remnants in the cave, often many years after the draw point has been closed. The production from the rings is based on final production targets and accounts for approximately 13% of the total production in 2015 (Patrick Klasér, personal communications, 2015).

5.4.2 Loading criteria at the Malmberget mine

The loading criteria at the Malmberget mine are different. The mine has three loading criteria. The operators should continue loading until:

1. The extraction ratio > 80%;
2. The average Fe content for the last 25%-units of the material loaded (extraction ratio wise) goes below 30%; and
3. The trend of the Fe% for the last 40%-units of the material loaded (extraction ratio wise) is negative.

Currently, the third criterion cannot be displayed in the LHD cabin for the operators. Loading is stopped when all three loading criteria is fulfilled. If a draw point performs poorly from the start (low moving average grade), the draw point is closed as 80% extraction ratio is reached (Kristina Jonsson, Personal communications, 2015). There are special loading conditions near the ore boundaries, so the loading is done differently as described below:

- **Loading near the hanging wall and footwall**: The loading near the hanging wall is guided by safety, and the average final extraction ratio for the first three rings is around 70-80% (Torulf Johnson, personal communications, 2016). Loading is stopped once an open cavern is formed at the draw point. It is important to note that loading should not be stopped when a small gap is formed at the draw point between the brow and the muck pile (Torulf Johnson, personal communications, 2016). Instead, it should be continued until a reasonably large open cavern has developed at the draw point. A small gap left at the draw point creates the possibility of sudden material flow, creating a risk to the charging team (Jan Holmlund, personal communications, 2016). Generally, rasinbrott is reached after first 10 to 12 rings after which the production rings are connected to the caved material. Once the rings are connected to rasinbrott, the normal loading criteria are followed. The loading criteria change for rings near the footwall that have drill collars in the footwall. In such cases, the initial waste inflow is neglected, and a higher final extraction ratio is targeted to recover ore from the upper levels left near the footwall (Mattias Nilsson-Mäki, personal communications, 2016).
- **Loading the last ring of a production drift**: A second cycle of loading for the last draw point of a production drift, called ‘restmalmlastning’, was previously practiced in the Malmberget mine (Mattias Nilsson-Mäki, personal communications, 2016). The procedure was the same as in the Kiirunavaara mine, and the selection of a draw point was decided based on experience. Between 2010 and 2014, a total of 7.5Mtonnes was loaded using ‘restmalmlastning’, with about 15% of production in 2014 coming from this operation (Mikael Eriksson, personal communications, 2016). The mine stopped using ‘restmalmlastning’ in 2015 for economic reasons (Patrik Johansson, personal communications, 2016).

5.5 Aspects of loading constraints

For an SLC operation, the different loading constraints usually include production requirements, grade control and mining constraints (Figure 5.6):

1. **Production requirements**: Mine planning and production for SLC operation is dependent on tonnage capacity in the ore bodies, ore pass capacity, development of drifts and capacity of the drilling and loading teams (Brown, 2007). Mines have a planned yearly, monthly and weekly production target which must be reached for mine operation to be profitable. The target needs to be achieved using existing machine and manpower resources. A draw control strategy should be able to meet the production targets using the available resources. Hence, a clear understanding of the production requirements and the available resources is important to develop a new draw control strategy.
2. **Grade control**: Caving operations define the average mine and shut-off grades based on ore grade, metal prices and cost of operation (Laubscher, 1994; Bull and page, 2000). Average mine grade deals with the overall grade of the run of mine output; shut-off grade regulates the grade of material loaded at the draw point. Grade control is vital in improving mine profitability and should be addressed in the draw control strategy.
3. **Mining constraints**: The sequence of mining is dependent on the relative position of the cave front, draw of the neighbouring draw point, ore geometry and mine stability (Laubscher, 2000; Brown, 2007). Caving operations are also constrained by issues such as seismicity and non-caving hanging walls. These aspects govern the draw control strategy for a mine and must be understood to develop a new draw control strategy.

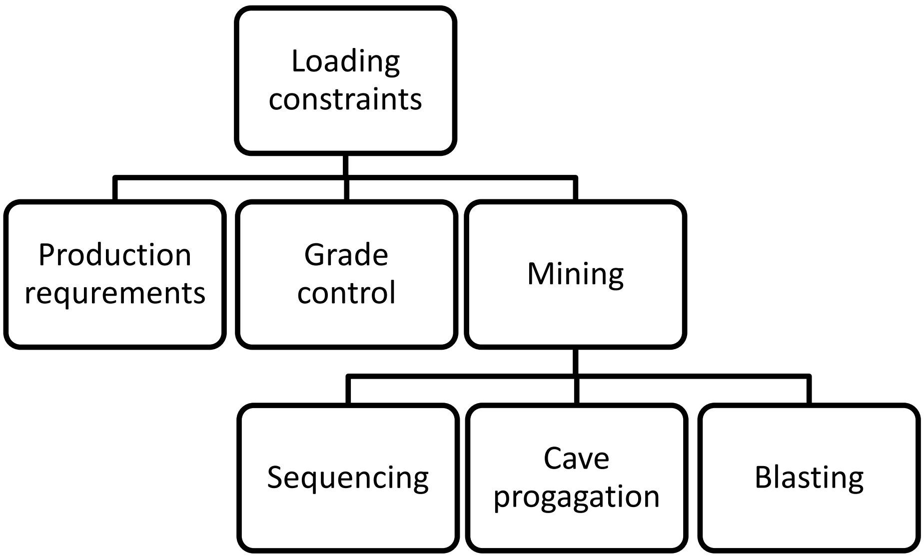

Figure 5.5 Loading process in SLC

5.6 Loading constraints at the Kiirunavaara mine

Loading constraints at the Kiirunavaara mine are split into production requirements, grade control and mining constraints. The mining constraints are defined by the mine based on company polices, mine requirements, geotechnical conditions and market conditions. A brief description of the constraints binding for the loading process at the Kiirunavaara mine is given in the following sections.

5.6.1 Production requirements

The Kiirunavaara mine produces 27Mtonne of crude ore per year; the production for 2016 is around 27Mtonne of crude ore. Average tonnage of a production ring at the mine is 10,000tonne which translates into approximately 2500 to 2900 production rings per year.

5.6.2 Grade control

The average mine grade and shut-off grade for the Kiirunavaara mine varies and is decided by the mine. Its current average mine grade is 45% Fe, and its current shut-off grade is 30% Fe (Patrick Klasér, personal communications, 2015). This means the target average grade for crude ore mined throughout the year is 45% Fe, and a draw point should be closed when the average grade of the material being loaded goes below 30% Fe. The average mine grade and shut-off grade values can change depending on mine conditions and mine management. The ability to change grade values is essential to maintain a profitable mine operation, but the changed value should be described in the draw control strategy, and necessary changes should be made in the draw control to accommodate the change in grade values.

5.6.3 Mining constraints

Draw control strategy in sublevel caving is constrained by the mining sequence, geotechnical conditions, operational limitations, seismicity and ore geometry. In the initial mining sequence for a mining level at the Kiirunavaara mine the cave front is kept flat, i.e. the cave front is moved uniformly along the adjacent drifts of the mining level (Patrick Klasér, personal communications, 2015).
As the production advances, the flat front pattern changes to a V-shaped cave front. The shape of the V-shaped cave front can change depending on mining sequence in nearby mining blocks, seismicity, and structural stability of the drifts in the block. The cave front can either converge towards the entrance cross cut or it can be the opposite depending on these mining conditions. Figure 5.6 shows an example for a mining sequence at Kiirunavaara mine (Patrick Klasér, personal communications, 2015). Mining blocks with structurally unstable areas are prioritized in the drifts for blasting and loading (Susanne Karppinen, personal communications, 2015). In vertical sections of the ore body, a V shape pattern of extraction is followed, such that the lowest level on which extraction is being carried out is always the vertex of the V shape (Patrick Klasér, personal communications, 2015). This is done to maintain overall mine stability in the mine.

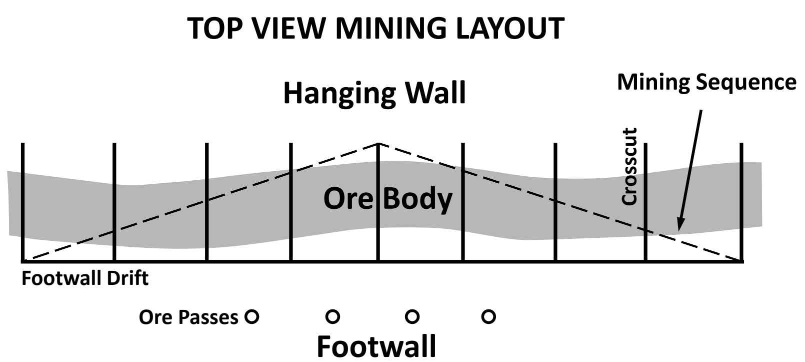

Figure 5.6 Example of a mining sequencing (Patricia Boeg-Jensen, personal communication, 2015)

To achieve the current production target at the Kiirunavaara mine, 12 active production areas are required (Patricia Boeg-Jensen, Personal communication, 2015). Each production area needs two to three active draw points.

Kiirunavaara mine is also constrained by vibration and blasting. The mine has limits on vibration that it can generate in the nearby Kiruna city. The number of blasts in a particular mining block is also constrained which can vary from mining block to mining block. Mine seismicity at Kiirunavaara mine is a constraint during operations and affects the sequence of mining in mining blocks. The mine is monitoring mine seismicity. Ore pass availability is another mine constraint that effects the production scheduling in the mine. Issues related to seismicity and ore pass availability is taken into account while mine planning scheduling.

The Kiirunavaara mine also has area specific constraints which guide the draw control for certain mining blocks to handle delayed caving. These might be below cave areas which have not yet propagated to the surface i.e. sill pillars. Delayed caving can also occur because of other mining conditions. For such areas, there is a low fixed final extraction ratio target for rings near the hanging wall and a relatively high fixed final extraction ratio for rings near the footwall, while the average material grade of ore being loaded is ignored (Wetterborn, 2008). The practice is followed to achieve a steady state caving in blocks with delayed caving. The operators are guided by the loading control and are prohibited from loading if an open cavern is formed at the draw point. Figure 5.7 shows the plan for block 9 at mining level 716. The first few rings (yellow) near the hanging wall have a low final extraction ratio target (35-60%). Thereafter, the next few rings (blue) have a final extraction ratio target between 60 and 90%, while the remaining rings (green) can be loaded normally.

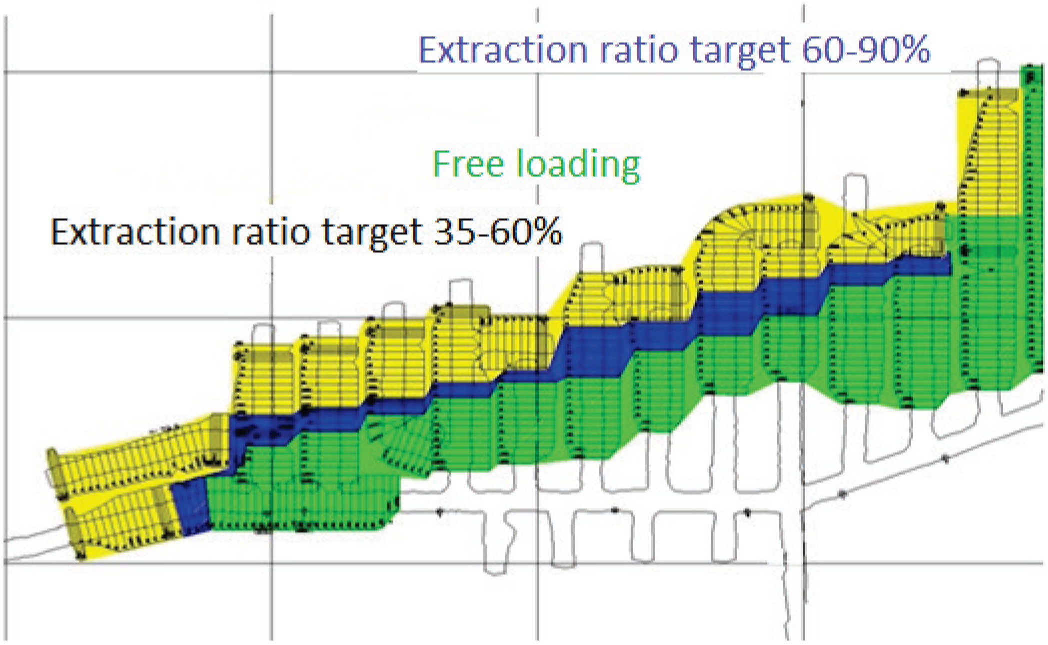

Figure 5.7 Final extraction ratio target for Bl 9 Level 716 (Wetterborn, 2008)

A summary of site specific loading criteria is provided in Sormunen (2005), Sormunen (2007) and Wetterborn (2008).

5.7 Loading constraints at the Malmberget mine

Like the Kiirunavaara mine, the Malmberget mine has loading constraints which must be met. The different ore geology and mining conditions at the Malmberget mine create a different set of constraints.

5.7.1 Production requirements

The current yearly production for the Malmberget mine is 17Mtonne of ore of which total magnetite production is 14.5 Mtonne and the rest is Haematite (Kristina Jonsson, personal communications, 2016). The mine production and scheduling are controlled by short term plans (three months) discussed in monthly meetings between production and mine planning personnel (Veronica Wikström, personal communications, 2016). Based on the production details of the past month, the short term plan is revised to meet the future production targets. The planned tonnage of a production ring at the Malmberget mine varies, as the mine design varies for different ore bodies and ore geometry. Hence, the total production target is divided into approximate targets for individual ore bodies using the planned tonnage data from the drill design and resource availability (Veronica Wikström, personal communications, 2016).

5.7.2 Grade control

The average mine and shut-off grade for the Malmberget mine varies and is decided by the mine. The average mine grade target for 2015 was 42% Fe, and the shut-off grade target was 30% (Veronica Wikström, Personal communications, 2016). The average final extraction ratio for the mine in 2015 was 120% with an average grade of 40.6% Fe (Patrik Johansson, personal communications, 2016). The mine has now raised the shut-off grade from 30% Fe to 35% Fe to reach the overall average grade of 42% (Patrik Johansson, personal communication, 2016). The mine uses a constant grade of 45% for production planning in both short term and long term plans to simplify the planning process (Veronica Wikström, Personal communications, 2016).

5.7.3 Mining constraints

Draw control at the Malmberget mine is constrained by the mining sequence, blasting constraints and mine induced seismicity. The mining sequence at the Malmberget mine varies at different ore bodies and mining levels. It is primarily guided by the development situation of the level below. If there is no development at the lower level, a production ring can be blasted and loaded (Mattias Nilsson-Mäki, personal communications, 2016). However, if partial development is underway, mining cannot be done in that production drifts. For areas with completed development at the lower level, the mining sequence is similar to the one used in the Kiirunavaara mine. In general, an interactive draw is maintained; this transition into a V shaped sequence with the vertex pointing away from the entry point into the ore body at that mining level (Mattias Nilsson-Mäki, Personal communications, 2016). Yet the mining sequence is different for different ore bodies and is decided by the mine. A minimum distance of 30m is maintained between production faces for two levels such that the lower production level lags by a distance of 30m from the upper production level (Mattias Nilsson-Mäki, personal communications, 2016).

The mining sequence is also changed if there is mining induced seismicity. Mining induced seismicity at the Malmberget mine causes seismic events which can be harmful for the mine’s infrastructure, the personnel working inside the mine, and the infrastructure cause vibrations in the city near the mine (Veronica Wikström, personal communications, 2016). Loading at draw points in active seismic areas is not safe, so the mining sequence is changed by either halting the loading process in seismically active areas or by not blasting production rings in such zones until the situation is stabilized. Seismicity is assessed to determine areas that are safe for operations (Veronica Wikström, personal communications, 2016).

To achieve its production target, the Malmberget mine needs 11 active production areas in the eastern fields and from between two to five active production areas in the western field (Veronica Wikström, personal communications, 2016). Each production area needs two to three active draw points. To keep nine LHD machines available for production, the mine currently has between 18 and 25 active draw points (Veronica Wikström, personal communications, 2016).

Draw control is also constrained by grade variations between ore bodies. The Parta and ViRi ore bodies have relatively poor iron content, so less ore is targeted (Veronica Wikström, personal communications, 2016). Fabian sometimes has poor iron content as well. Ore pass availability can also constrain the draw control. The Alliansen ore body has four ore passes and sometimes faces ore pass availability issues. Other ore bodies may lack the required number of active ore passes because of blockage or damage in ore passes or may not have any ore passes present close to the ore body. LHDs load trucks in these situations in ore bodies Valkomman, Hens, Johannes, Dennewitz and Baron.

Blasting constraints at the Malmberget mine are designed to reduce the number of seismic events and are used to regulate the number of active draw points (Table 3). They are designed to reduce the number of seismic events. Each night, five to six blasts are conducted (PSR, 2016).

Table 3 Blasting constraints at the Malmberget mine (PSR, 2016)

SN	Ore Body	Constraints (Maximum number of blasts)
1	Dennewitz	De1012: 1 blast per day (BPD); De1034: 1BPD Total : 1BPD (But not the same day as Parta)
2	Fabian	Fa855: 2BPD; Fa880: 2BPD; Fa905: 2BPD Total: 3BPD
3	Kapten	Ka855 cannot be blasted before loading Fa 880/1460-1860
4	Johannes	1 BPD
5	Josefina	1BPD
6	Parta	Pa986: (Blasting completed); Pa1006: 1BPD (Not the same day as Dennewitz) Total: 1BPD
7	Printzsköld	Pr945: 1BPD; [Left side of the ore body is divided into area1 (o3670-o3850) and area 2 (o3870-o4070). Blasting is done alternately in the two areas. Near the boundary of the two areas, blasting is done alternately with a space of four drifts. Drifts 2410, 2390, 2370 and 2350 are not to be opened] Pr970: 1BPD; Pr996: 1BPD Total: 2BPD
8	Vitåfors-Riddarstolpe	VR1050: The level is divided into two areas from drift o7760-o7520 and o7920-o7780. Blasting should be spaced between the two areas. VR1075: Drifts o7770-o7890 in area 1 may be opened. Maximum blasting of 1 blast per day per area and total of maximum 2 blasts per day from ViRi. Blasting of nearby drifts should not be done at the same time.

6 Concluding remarks

The draw control strategy at the Kiirunavaara and Malmberget mines is guided by a bucket weight based draw point monitoring system, but this is only part of the overall framework. Draw control incorporates the sequencing and scheduling of a development, production and material handling system with the objective of minimising both mining costs and dilution (Smith and Rahal, 2001). Hence, the draw control strategy is not one piece of knowledge at the mine but a collection of overlapping pieces of knowledge.

LKAB’s two sublevel caving operations, the Kiirunavaara and Malmberget mines, have different ore geology, mine design and layout, but they use the same loading support functions (Loadrite, GIRON, WOLIS) with minor adjustments. The Loadrite system provides the bucket weights which are used by WOLIS to predict the iron content in the bucket and guide the operator in decision making.

The loading procedure at LKAB has been streamlined to increase mine safety and productivity. LHD operators are given clear instructions on the loading process. The safety of operator and machine is maintained by following clear guidelines for different loading conditions. The LHD operators also communicate with the production leaders and other mine personnel to exchange information on the loading process. Two operators are assigned for each LHD to maximize machine use in a shift.

As the draw control strategy is affected by ore geology, ore geometry, mine design and layout, the Malmberget and Kiirunavaara mines have differences in their draw control strategies. Draw control aims at achieving an efficient mine operation. It takes production requirements, mining constraints and average mine grades as its input variables and provides a solution in terms of a set of rules and guidelines for loading at a draw point regulated by a shut-off grade. The present draw control strategy at LKAB considers the production requirements, grade control, loading criteria and mining constraints. Special loading conditions are practised near the ore boundaries both near the hanging wall and the footwall for increasing ore recovery and improving safety. The loading criteria at the Kiirunavaara mine use the extraction ratio as the primary input information for draw control. The Malmberget mine has slightly more flexible loading criteria and uses both extraction ratio and trend of bucket grade as the primary input information for draw control. However, both mines employ a draw control strategy which considers the production requirements and mining constraints and regulates the loading process through a sound draw point monitoring system.

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Personal communications

The Kiirunavaara mine, LKAB

Year	Name	Position
2016	Gustaf Blomberg	Technician, PNL Loading
2015-16	Henrikki Rutanen	Geologist, PNG Mine planning
2016	Kjell Olovsson	Section Manager, PNL Loading
2015-16	Matthias Wimmer	Senior Research Engineer, RGB R&D Mining technology
2015-16	Patricia Boeg-Jensen	Research Engineer, RGB R&D Mining technology
2015	Patrick Klasér	Planner, PNG Mine planning 2015
2015	Sandy Doull	Maintenance Engineer, PNM Maint. mobile machines
2015	Susanne Karppinen	Planner, PNG Mine Planning

The Malmberget mine, LKAB

Year	Name	Position
2016	Anna Johansson	PC loading Fabian, Mine production
2016	Fredrik Tano	Production leader, Mine production
2016	Jan Holmlund	PC Production charging, Mine production
2015	Jyri Meriläinen	Senior mine geologist, Mine planning
2016	Kenneth Henriksson	Process engineer, Mine production
2016	Krister Taivalsaari	PC loading Alliansen, Mine production
2015-16	Kristina Jonsson	Research engineer, R&D Mining technology
2016	Mattias Nilsson-Mäki	Production coordinator, Mine production
2016	Mikael Eriksson	Production Technician, Mine production
2016	Patrik Johansson	Manager, Mine production
2015	Sven-Erik Wennebjörk	Planning engineer, Mine planning
2016	Torulf Johnson	Production leader, Mine production
2016	Veronica Wikström	Long term planning, Mine planning

Agio System och Kompetens AB

Year	Name	Position
2015-16	Daniel Eliasson	Solution Architect

Appendix 1 Initial testing and calibration of the first Loadrite system

An internal report by Davison (1996) describes the testing and calibration conducted during the initial installation of the Loadrite system. A series of tests were performed on the system by using different test weights and by varying the lifting speed of the LHD bucket. Lifting speed refers to the speed at which the bucket is lifted; it is measured as a unit-less number in the system. In the tests, the LHD bucket was raised slowly and then quickly, and the bucket weights were recorded. The two lifting speeds were used as upper and lower limits for lifting speed. Calibration was performed for six equally spaced lifting speeds. A ‘Zero weight’ calibration was performed to adjust the weight of the bucket so that the weight of only the material was shown by the system. A ‘Span’ calibration was done using a 10tonne test weight. The purpose of the span calibration was to establish a relationship between the hydraulic pressure and the weight. The weight used for the span calibration should be at least 20% of the maximum weight weighed by the machine. Davison (1996) concludes that to achieve accurate weight readings, each bucket must be weighed while driving to the ore pass. The lifting arms should start from the bottom of the lift cycle and move up towards the trigger point in a uniform motion. As the lifting arm passes the trigger point, a beeper sound is made, after which lifting can be stopped and a weight reading can be taken by pressing a button. The completion of the weight reading is signalled by a beeper sound, after which the bucket can be unloaded. Weight readings can be taken while driving, but the machine should not drive over a rough surface; hence, a relatively flat surface near the ore pass is preferred.

Appendix 2 Loadrite statistical tests

A series of statistical tests was conducted to measure the accuracy of the system. The following are Davison's (1996) procedures and conclusions:

1. Testing calibration at different weight values: The system was tested against three different weights (30tonne, 25tonne and 17tonne) using a truck and weighbridge. The results showed a 0.8tonne difference (2.5% error w.r.t weighbridge) for the 30tonne weight, 0.2tonne difference (less than 1% error w.r.t weighbridge) for the 25tonne weight and the 17tonne weight. Increased error at high weight may have occurred because Loadrite was calibrated with a 10tonne weight.

2. Testing calibration at different lifting conditions: A number of readings were taken during driving and shaking of the machine to simulate the worst case scenario for the Loadrite. The greatest standard deviation observed was 1.1tonne. Therefore, lifting the bucket under different conditions provided almost similar bucket weight readings. The test concluded that Loadrite can be trusted when being used by different operators in different loading conditions.

3. Testing calibration near the ore pass: The aim of the test was to monitor the difference in weight readings when the machine was moving. The largest difference measured between average weights when standing still and while driving to the ore pass was 0.7tonne. The test concluded that the system works when readings are taken during transportation.

4. Testing the influencing factor in the weighing process: The aim of the test was to assess which factors influence the bucket weighing accuracy and to determine the degree of their influence. The results showed that the distance between the starting position of the lifting cycle and trigger point affected the weighing process the most. The trigger point is the bucket position at which the hydraulic pressure in the arm cylinder is measured by the transducers. A difference of 4.1tonne -4.5tonne was observed when the lifting cycle was started near the trigger point.

5. Testing the effect of a hydraulic spike on the accuracy of weighing: The aim was to study the extent of the effect of a hydraulic spike and establish an optimal distance from the trigger point to start the lifting cycle to get accurate readings. The test concluded that lift arms should be initiated more than 20cm below the trigger point, and the lifting cycle should be uniform for better accuracy of the bucket weight reading.

6. Comparison of weighing on the move and weighing in a stationary position: A series of readings were taken on the road to the ore pass and at the ore pass. A difference of less than 1tonne was observed (confidence level 95%). The test recommended weight readings should be taken near the ore pass as no extra time or effort is required by the driver.

Appendix 3 Loadrite pro Functions

The important functions relevant to the loading process as stated in the Loadrite pro manual 2002 are:

1. Weighing setups: The functions in the weighing setups deal with the weight related initial inputs required for installation and maintenance of the Loadrite system. These details are entered when Loadrite is installed in a new machine or when the machine goes through scheduled maintenance. It sets the range of weights which can be measured accurately by the system. During setup, a maximum payload weight limit is entered into the system using the full scale (F/Scale) function. Weighing material greater than the full scale value will give unreliable results. The setup can also be used to regulate the increment size of the weight reading. It is advised to select an increment size larger than the minimum value allowed to mask small instabilities when repeatedly weighing the same material.

2. Machine setups: A number of machine related functions are built into the Loadrite system to improve the machine compatibility of the system. Most of the details are entered when Loadrite is installed on the LHD or when the machine goes to scheduled maintenance. The installation of Loadrite on a LHD requires cylinder rod size and bore size as input details for internal calibration. Multiple controls are present in the system to regulate and control errors in the weight reading. In order to increase the accuracy of the system, hydraulic pressure is measured on both the input and the return side of the cylinder. The system gives a warning if the lifting is not steady and the difference between the hydraulic pressures is larger than allowed. Accuracy of the system is increased by taking multiple readings during a lift. With the multiple trigger mode, more than one weight and lift speed reading can be taken and compared by the system. If the weight and speed errors are within acceptable limits (75%), the average weight of the weight values is displayed. If the errors are not within the set limits, lift is rejected and no weight is displayed. The setup contains other functions such as Filter (to filter hydraulic spikes), Interlock (to fix the triggering position of the machine) etc.; these are used to control the machine related aspects of the Loadrite system.

3. Diagnostic setup: The Loadrite system has several diagnostic related functions, for example, to check pressure gauge status and to find errors in the system, as well as to restore, back-up and print the calibration history of the system.

Appendix 4 Calibrations in the Loadrite Pro weighing system

The four calibrations which can be performed in the Loadrite Pro weighing system as described in the Loadrite Pro (2002) are as follows:

- **Rotary trigger position calibration**: The purpose of this calibration is to fix the position of the cylinder arm at which the weight reading should be recorded, i.e. the arm position for triggering the transducer to measure the hydraulic pressure. In the desired trigger position, the bottom of the bucket is horizontal to the main lifting arm pivot pin. The highest possible arm position, the lowest possible arm position and the arm position for the trigger are entered into the Loadrite system. The trigger position should be set approximately in the middle of the limits. The calibration for all three points should always be done together during installation of the system but should also be done if any arm cylinder related repairs are done.
- **Speed compensation calibration**: The purpose of this calibration is to provide accurate weight readings at different lifting speeds. As the load gets heavier, the lifting speed reduces; i.e. with different percentages of ore and waste, the lifting speed will vary. The calibration accommodates variations in the speed by calibrating the system against six different speeds (set at equal intervals, such as 6, 10, 14, 18, 22 and 26). The calibration is done by lifting an empty bucket at the six different speeds; the system then generates an internal corrective algorithm to convert hydraulic pressure at different speeds to weights. The system will give no weight reading for lifting speed less than 3% or greater than 20% of the highest calibrated speed.
- **Zero calibration**: The Loadrite system is calibrated to know the hydraulic pressure for an empty bucket. An empty bucket is lifted at a medium speed and the weight reading is displayed. The weight represents the weight of an empty bucket; this is zeroed to correct the zero offset. The empty bucket is lifted again to check if a zero weight reading is displayed and the calibration is completed. Zero calibration is performed during installation and also during the loading process. A secondary function called 'zero prompt' advises the operator to perform a regular zero calibration during the loading process. After a machine has been switched off for longer than an hour, zero calibration should be performed every 15 minutes for the first hour of operation, after which it should be performed every 30 minutes. The Loadrite does not allow the zeroing of weights beyond 10% of the full scale weight for the system.
- **Span calibration**: The purpose of this calibration is to determine the relationship between hydraulic pressure and weight. A zero calibration must be performed before the span calibration. A test object with a known weight is measured by the Loadrite system (Figure A4.1). The weight of the test object is entered into the system, and the test object is lifted by the LHD at normal lifting speed. If the lift is 'good', the enter key is pressed, and calibration is complete. The process of lifting is repeated until a good lift is achieved. The system then adjusts the internal scaling factor and saves the calibration in its internal memory.

Figure A4.1 Test weight used for span calibration (Courtesy LKAB)