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A review of the High-Performance rock-bolting method and its application in a Nordic mine.

School of Engineering
Thesis, which has been submitted as a thesis for examination for a Master of Science degree in Engineering.
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Abstract

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Abstract

Installing rock reinforcement in underground mines is one of the most time-consuming process steps. Rock-bolts are one of the most common methods of rock reinforcement. Rock bolts are increasingly installed by fully mechanized rock-bolting equipment. Commonly used bolting methods are rebar bolts with resin cartridges or cement as grout. These methods are compared with the newly developed ‘High Performance’ method from Epiroc. The ‘High Performance’ method uses self-drilling hollow bolts with a fast curing epoxy resin as grout. The aim of the case study is to determine if Boliden should switch to the ‘High Performance’ method. For this, the rock-bolting productivity of the current and ‘High Performance’ methods was estimated. In order to estimate this observations and time studies were conducted. The operational capacity of the current rock bolting operation at Kristineberg is believed to be 7.8 bolts per hour. With the ‘High Performance’ method this could increase to 9.4 bolts per hour. The calculation methods showed an improvement in the range of 3% to 9%. This while productivity of the ‘High performance’ method is believed to be 20% faster than the current method. The financial analysis has shown that if the price of the bolts doubles a 6% increase in production is necessary. If the price increase per bolt is below the limit set by the production increase than it is advised to invest in the ‘High Performance’ rock-bolter.

Keywords Rock bolting, Mine productivity, One-step bolting, Pumpable resin

I. Summary

Installing rock reinforcement in underground mines is one of the most time-consuming process steps. Rock-bolts are one of the most common methods of rock reinforcement. Rock bolts are increasingly installed by fully mechanized rock bolting equipment. Commonly used bolting methods are rebar bolts with resin cartridges or cement as grout. These methods are compared with the newly developed 'High Performance' method from Epiroc. The 'High Performance' method uses self-drilling hollow bolts with a fast curing epoxy resin as grout. The epoxy resin is pumped through the bolt into the hole, the mixing happens just before the resin enters the bolt. This method can also be used with conventional pre-drilling and hollow bolts. The comparison is done for the following aspects; health, safety, environmental, productivity and costs. The HSE aspects of the 'High Performance' method are focused on the resin components that are used. One of these components contains isocyanates, the release of isocyanates is limited if the resin remains below 20°C. With the appropriate measurements in place, this risk should stay within regulation limits. The 'High Performance' method requires fewer process steps to install a rock-bolt. It has a lot of potential for automation, if self-drilling bolts are used. The installation process goes from 3 consecutive process steps to 1 process step.

The aim of the case study is to determine if Boliden should switch to the 'High Performance' method. For this, the rock-bolting productivity of the current and 'High Performance' methods was estimated. In order to estimate this observations and time studies were conducted. These data were analyzed and the productivity of the current and 'High Performance' methods was calculated. The operational capacity of the current rock bolting operation at Kristineberg is believed to be 7.8 bolts per hour. With the 'High Performance' method this could increase to 9.4 bolts per hour. The operational capacity is defined as the productivity the bolter can reach when we exclude the standby-time, logistic delay, maintenance and dinner/lunch breaks. In the operational capacity, all operations directly needed for a functioning bolting cycle are included. With the productivity of the 'High Performance' method the increase in mine production was estimated with different methods. Different methods were used in order to include possible other bottlenecks. The calculation methods showed an improvement in the range of 3% to 9%. This while productivity of the 'High performance' method is believed to be 20% faster than the current method. This difference in productivity and production gains is likely due to other bottlenecks, scheduling difficulties and amount of work available. This difference leaves more time for machine maintenance and other auxiliary activities. This could result in a higher availability of the equipment when needed, potentially further increasing the production. It is believed that the not yet developed automation function could add another 15% in bolting productivity. SimMine is used to create a discrete event simulation model of the current and new method. The most likely case of replacing 3 rock bolters resulted in an average production increase of 10.7%, this is seen as a bit optimistic. The actual improvement is most likely between the values calculated and simulated. The financial analysis has shown that if the price of the bolts doubles a 6% increase in production is necessary. If the price increase per bolt is below the limit set by the production increase than it is advised to invest in the 'High Performance' bolter.

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V. Glossary

List of definitions used throughout the report.

Blast cycle	- Drill and blast cycle is an excavation cycle used in the mining and tunnelling industry. This cycle includes all the steps necessary for a continuing operation.
Boom	- Hydraulic powered arm that carries the feed rail for the drilling equipment or bolt inserting equipment.
Face	- The surface where the mining work is advanced, commonly used as a replacement for the working area.
Fan	- Fan shaped drill-hole layout in underground mining and tunnelling.
Grout	- Medium that is used to secure rock bolts in their hole, this medium transfers stress from the rock mass to the bolt.
Mesh	- Iron wire mesh that is installed at the rock interface to capture falling blocks.
Nordics	- Nordic countries that include; Denmark, Finland, Iceland, Sweden and Norway.
Rock bolt	- Anchoring bolt that is used for the stabilization of rock excavations.
Shotcrete	- Spray-able concrete that is used to reinforce rock excavations.

Part I – Theoretical comparison of the 'High Performance method

1.1 Introduction

As existing mines increase in depth to continue mining, rock mechanical stresses start to increase (Nordlund, 2013). In order to ensure that these mines are safe and productive, it is likely that some sort of roof support must be installed. One of the most common methods of roof support in the Nordics is rock bolting. Rock bolting is the operation of installing rock bolts into the rock mass. The Nordics are the Scandinavian countries plus Finland and Iceland. Rock bolts provide support against the uncontrolled deformation of the rock mass. The installation of rock bolts is a time-consuming process in underground mining which does not add direct value. New methods are being developed to enhance the installation of rock bolts, these methods focus on operator safety and productivity. The shorter the installation time is, the more productive a mining operation can be (Archibald, 2000). One of these new methods is called the 'High Performance' method, this is developed by Epiroc in cooperation with industry partners. The 'High Performance' method uses hollow rock-bolts with a pumpable two- component resin. This method can be used in combination with self-drilling bolts, adding the benefit of not having to take the drill out of the rock. Self-drilling bolts are rock bolts with a drill bit attached to it, the bolt and drill bit are left in the rock. These methods are called 'High Performance' methods because it is expected that they are a lot more productive than current rock bolting methods. The aim of the first part of this study is to compare two widely used rock bolting methods with the 'High Performance' methods.

1.2 Study approach

This study will be divided into two parts; the first part will be a theoretical comparison of the 'High Performance' methods with two commonly used methods, the 'High Performance' methods have the possibility to replace these methods. The installation methods and possible workflow will be discussed, these will be based on the standard operating procedure seen at Boliden's Kristineberg mine. The methods will be compared for the following aspects; health, safety, environment and quality of installation.

The second part of the study will go into depth on how rock-bolting productivity can be linked to mine production, this will be done for the Kristineberg mine. This study will look at replacing the rock bolters that use cement as grout with the 'High Performance' bolters. These methods will be compared for productivity impact, costs and automation potential. The aim of comparing these two methods is to analyse if switching to the new method will result in a higher net present value for the life of mine plan. The result of this analysis is then used to provide a fact-based recommendation to the Kristineberg mine whether they should convert to the 'High Performance' bolting method.

In order to get insight into the bolting methods and standard operating procedures, these bolting operations have been followed for 94.6 hours underground, this has been done for the Kristineberg mine of Boliden in Northern Sweden.

1.3 Research Questions and Objectives

The objective of this thesis is to provide Boliden with a fact-based recommendation whether the 'High Performance' rock bolting method compares positively with the current bolting method used at Kristineberg.

The main research question of this project is:

Does the 'High Performance' method result in a higher mine production that will outweigh the increased capital and operational costs of this method?

In order to answer this question several sub-questions have to be answered:

- How does the 'High Performance' method compare on health, safety and environmental aspects with the current bolting methods?
- Is there a productivity improvement with the 'High Performance' methods compared to current methods used in Kristineberg?
- Will this improvement in productivity result in production improvement that outweighs the extra capital and operational costs of the 'High Performance' method?
- What are the near-future automation options for the 'High Performance' bolting process?
- Are there particular problems concerning the 'High Performance' methods that would make the implementation of this method not feasible?

To reach this final goal the following objectives are going to be assessed.

- Mapping and describing the current rock-bolting process.
- Mapping and describing the 'High Performance' rock-bolting process.
- Provide a qualitative comparison of the current and 'High Performance' bolting methods.
- Provide a quantitative comparison for the cement grouted bolting method and 'High Performance' bolting methods in terms of rock-bolting productivity at Kristineberg.
- Compare the mine production of the current and possible future situations with discrete event simulation.
- To assess and compare the operational costs, capital costs, cost per tonne, expected revenue and net present value of the methods.
- Asses what impact the 'High Performance' bolting productivity has on the number of number of blasts per year.

1.4 Scope

In this subchapter is stated what will and won't be included in the thesis, this is done separately for the first and second part of the thesis. It is divided into two parts in order to be more specific.

Table 1. Scope of theoretical comparison.

In scope	Out of scope
Health and safety aspects of cement grouted, resin cartridges and 'High Performance' bolting methods. (hollow and self-drilling) Qualitative and quantitative comparison between; cement grouted, resin cartridges and 'High Performance' bolting methods (hollow and self-drilling)	Review of different rock reinforcement methods

Table 2. Scope of case study in Kristineberg.

In scope	Out of scope
Quantitative comparison between; cement grouted and pumpable resin grouted bolting methods (hollow and self-drilling) Productivity influence of rock bolting on the overall mine production Financial comparison between bolting methods (confidential)	Rock mechanical parameters Review of different simulation techniques Review of different measures to improve bolting productivity

1.5 Chapter review

The structure of the report with a brief description of each chapter is given below:

Part I: Theoretical comparison of the 'High Performance' method

Chapter 1: Introduction, study approach and research objectives
A brief introduction into rock-bolting and the current challenges faced by the industry. An outline of this studies approach and objectives.

Chapter 2: Literature review
A review of how rock-bolts work, their most important anchor mechanism. A brief list of the most commonly used rock bolts and installation methods. And finally a review of the state of the art rock-bolts and installation methods.

Chapter 3: Mechanical installation methods
This chapter includes how mechanical rock bolters install bolts for the cement grouted, resin cartridge grouted and 'High Performance' bolting methods. Based on the data from Epiroc, Sandvik and personal observations.

Chapter 4: Health, safety and environmental aspects
This chapter analyses the health, safety and environmental aspects of the 'High Performance', cement grouted and resin cartridge method. Protective measures and handling requirements are also listed.

Chapter 5: Quality of installation
A brief review of the quality with which rock bolts are installed and encapsulated.

Chapter 6: Automation
This chapter reviews the potential for automation of the rock bolting process with the 'High Performance' bolting methods.

Chapter 7: Rock bolting productivity
This chapter includes definitions and methods to compare rock bolting productivity. And figures of rock bolting productivity in Nordic countries.

Chapter 8: Summary of the methods
A summary of the methods that are discussed in the previous chapters.

Part II: Case study – Rock bolting productivity at Kristineberg

Chapter 9: Methodology
This chapter includes the different methods used to gather and process the data. It also lists the assumptions made and the limits of the data gathered.

Chapter 10: Data collection
A review of how the data were collected, categorized and processed. This is done for both the cement grouted method as for the 'High Performance' method.

Chapter 11: Data analysis
This chapter includes the analysis of the data that have been gathered. The collected data gathered from observations are compared with data gathered by the onboard systems.

Chapter 12: Results
A detailed review of the results of the rock bolting productivity for the current and 'High Performance' methods. And how this rock bolting productivity possibly translates into an improvement in ore production.

Chapter 13: Simulation
This chapter includes a review of the simulation software that is used together with the results of the simulation.

Chapter 14: Financial analysis
This chapter includes the costs and potential financial benefits of the 'High Performance' method compared with the current method.

Chapter 15: Discussion
A review of the main findings of the 'High Performance' method, including HSE risks and potential production improvement.

Chapter 16: Conclusion
A brief review of the main conclusion of this thesis.

Chapter 17: Further research
In this chapter potential further research topics are discussed.

1.6 Introduction

1.6.1 Epiroc

Epiroc is a leading global provider of solutions for rock drilling and excavation, Epiroc has demerged from the Atlas Copco group in 2018. The head office is based in Stockholm, Sweden their manufacturing units are located in Sweden, Canada, China, India and the United States. They are active in 150 countries employing more than 13,000 people, in 2017 Epiroc had a revenue of 3.7 billion USD. Epiroc tries to stay ahead of the market by innovation and creating highly efficient products. Epirocs' main focus is equipment for drilling and rock excavation, they also provide related consumables and services (Epiroc, 2018a). Epiroc has developed the 'High Performance' method in cooperation with mining companies and a rock reinforcement supplier.

1.6.2 NewBoliden

Boliden is a base and precious metal company with its own mines and smelters. Its operations are based in Sweden, Finland, Norway and Ireland. The company its roots date back to 1924 when a gold deposit was discovered at the place which is now Boliden. Nowadays Boliden employs around 5,500 people in its operations. The company is not only focussed on the production of primary metals but it is also present in the metals recycling industry, this shields it from the cyclic commodity market. The mines of Boliden are among the world's most productive mines in terms of tonnes per hour of labour. In 2017 the mines produced 42,000 ton copper, 78,000 ton zinc and 3,300 ton nickel, the revenue of the whole group was around 5.4 billion USD (NewBoliden, 2017). Boliden tries to be in the front of automation in the mining industry, in order to increase the productivity and eliminate accidents. Boliden operates both underground and open-pit mines.

1.6.3 Underground mining cycle

In underground mining, multiple operations need to be completed in a set order to ensure steady production and a safe working environment. The most common mining method in hard-rock is drilling and blasting, a typical drill and blast cycle consist of 7 steps. This drill and blast cycle is illustrated in Figure 1. The first step that is done is the drilling of the blast holes, once these are drilled they are charged with explosives. The explosives are blasted, fracturing and loosening the rock. The toxic fumes created by the explosion have to be ventilated. After the area is cleared from dangerous gasses, the ore is loaded into trucks. The roof and face of the new area are scaled, this is the operation of removing partially loose rocks with a jackhammer. Once the area is cleaned it is time to install rock support, the first step is the installation of shotcrete on the roof and walls. Rock-bolts are installed to reinforce the rock mass, they are installed after the shotcrete in order to complement the shotcrete. The installation of rock support is an important step to ensure a safe work environment.

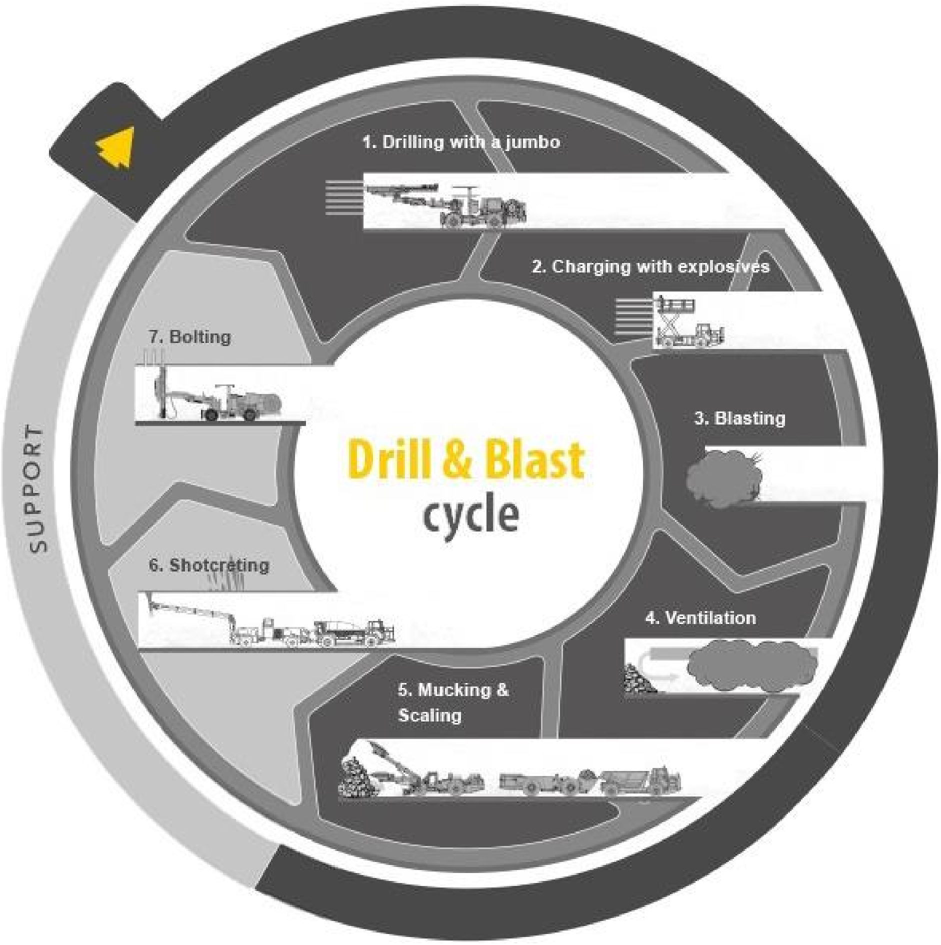

Figure 1. Drill and blast cycle adapted from (Bestsupportunderground, 2016).

1.6.4 Rock reinforcement

With underground mines increasing in depth, securing the working area becomes a bigger challenge (Ranjith, 2017). In most cases, rock reinforcement is needed to provide a safe working environment. In the mining and tunnelling industry rock bolts, meshing, shotcrete and concrete or steel arches are the most common long-term support methods. These methods can be classified as passive and active support methods. Active support imposes a predetermined load to the rock surface, this load is applied at the time of installation. Passive support methods rely on the displacement of the rock mass to develop their resistance load (Brady, 2004). Rock support does not increase the productivity but is necessary to ensure a safe work environment. The aim of rock support is to conserve and improve the strength of the rock mass and maintain the load-bearing capacity of the rock mass (Barret, 2006).

1.6.5 Rock bolting

Rock bolting is a reinforcement method which can both actively and passively reinforce the deforming rock mass. This depends on the kind of bolts that are installed. Rock bolts are steel or fibre rods which are installed inside the rock mass, they can be encapsulated with cement, resin or uncovered (Hoek, 2000). A detailed description of different rock bolts and installation methods is given in chapter 2.

2. Literature review

This chapter will give an introduction to rock bolts and installation methods. This is done by reviewing the: main mechanics behind rock bolts, different types of rock bolts and the common installation methods. Last the current state-of-the-art rock bolts and methods are discussed.

2.1 Introduction on rock bolts

Some underground mines rely on ground support methods to stabilize man-made openings. Rock reinforcement can provide a safe working environment, a common reinforcement method is rock bolting. Rock bolts are steel or fibre rods that are installed inside the rock-mass. The main purpose of the support is to conserve and improve the tensile and shear strength as well as maintaining the load-bearing capacity of the rock mass (Li, 2017b). Rock bolting has been around from the early 20th century, it started with mechanical anchored bolts. Cement and epoxy encapsulated bolts were introduced in the 1950s. These were intended for weak rocks where mechanically anchored bolts tend to slip. From the 1960s onwards rock bolts improved in terms of costs, installation requirements and reliability (Barret, 2006). Rock bolts have become one of the most popular forms of rock reinforcement due to their effectiveness, installation time and cost (Archibald, 2000).

There are a few limitations to the effectiveness of rock bolts. They can only be applied in areas with relatively small deformation, up to 50mm for fully grouted bolts. Larger movements can be accommodated when using special bolts, such as energy absorbing yield bolts or cable bolts (Barret, 2006). Although rock bolting is one of the most common methods of roof support it is in most cases one of the longest operations in the blast cycle.

Rock bolts can be active and passive reinforcement methods, this depends on the fact of a predetermined load is applied to the bolts. If a bolt is pre-tensioned then it is said to provide active support. If a bolt is not pre-tensioned and the load develops as the rock mass deforms then it is said to provide passive support (Brady, 2004; Eberhardt, 2013).

2.2 Rock bolt design

Rock bolts can be used in multiple ways to support the rock mass, the three most common applications are discussed below.

- Single block

Individual blocks or wedges can be secured by installing single bolts under an angle. In this case the bolt is used to suspend the weight of the loose block, the total maximum load is the weight of the block (Chen, 1994; Li, 2017b). This method relies heavily on the experience of the geologists and operators, this is an older method which is not in favour anymore due to safety concerns.

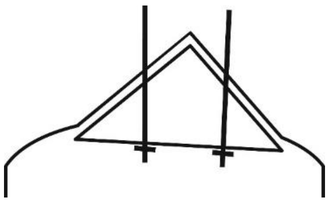

Figure 2. Schematic of single block installation (Li, 2017a).

- Beam effect

This bolting method is designed to support a horizontal weak layer of rock. The bolts must be able to hold the weight of the layer, they are secured into the stable rock mass above the weak layer. This is mostly applied in coal mines and is also installed in a pattern but the mechanics behind the method are different (Luo, 1999; Oliveira, 2016).

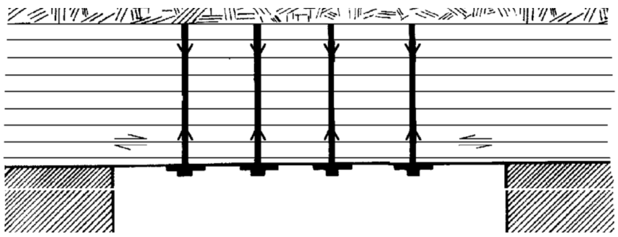

Figure 3. Schematic of suspension bolting (Luo, 1999).

- Pattern bolting

Pattern bolting is used to support the creation of an artificial pressure arch in the rock mass, like a stone arch bridge. In this case the bolts are installed in a predefined pattern, all the bolts have the same spacing in between them. The bolts create a zone of compression which reinforces the rock mass (Chen, 1994; Li, 2017a). The rock bolting pattern is predefined, the correct installation of the reinforcement is less dependent on the operators' skill. This method increases the safety in the mine as fewer errors can be made by inexperienced operators. This method is the most common one in the Nordics and has the potential to be automated in the future because of the predefined patterns.

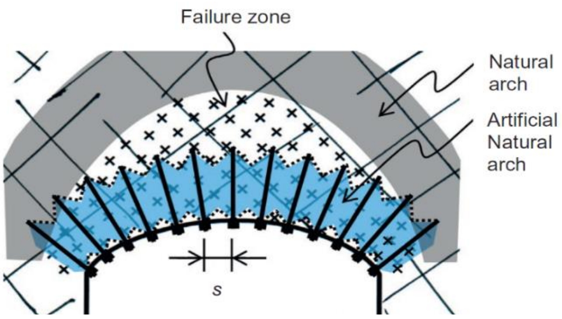

Figure 4. Schematics of pattern bolting (Li, 2017b).

The main parameters of rock bolt design are the spacing, length, strength and stiffness. The length of the bolt relies on the height of the opening and the failure zone of the rock. The length should be larger than the failure zone but from the operational side not more than half the height of the opening. The spacing between the bolts depends on the rock joint spacing and on the length of the bolt if an artificial pressure arch is created. The spacing and length of the rock bolt give the thickness of the interaction zone (Brady, 2004; Li, 2017a; Li, 2017b; Mark, 2001). If these data are not yet available in the design stage of a project, empirical methods are used to estimate the length and spacing. The rock mass quality index and the excavation height can be used to give a good estimate of the required length and spacing, this is done with the Q-system of rock mass classification (Barton, 2014).

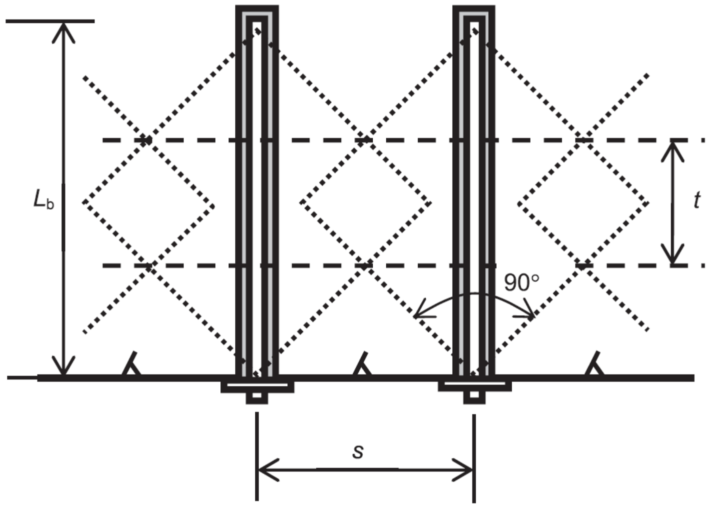

Figure 5. Interaction zone of rock bolts (Li, 2017a).

2.3 How rock bolts work

Rock bolts reinforce the rock mass by restraining the deformation, they are installed to control the displacement of the rock mass. This displacement is a direct result of the excavation: the rock wants to expand into the opened space. The behaviour of rock bolts is characterized by their stress-strain relationship (Li, 2017b). This is given by the stiffness, strength and anchoring method of the bolt. In Figure 6. Load-displacement curves of rock bolts a few examples of different kinds of rock-bolts are shown.

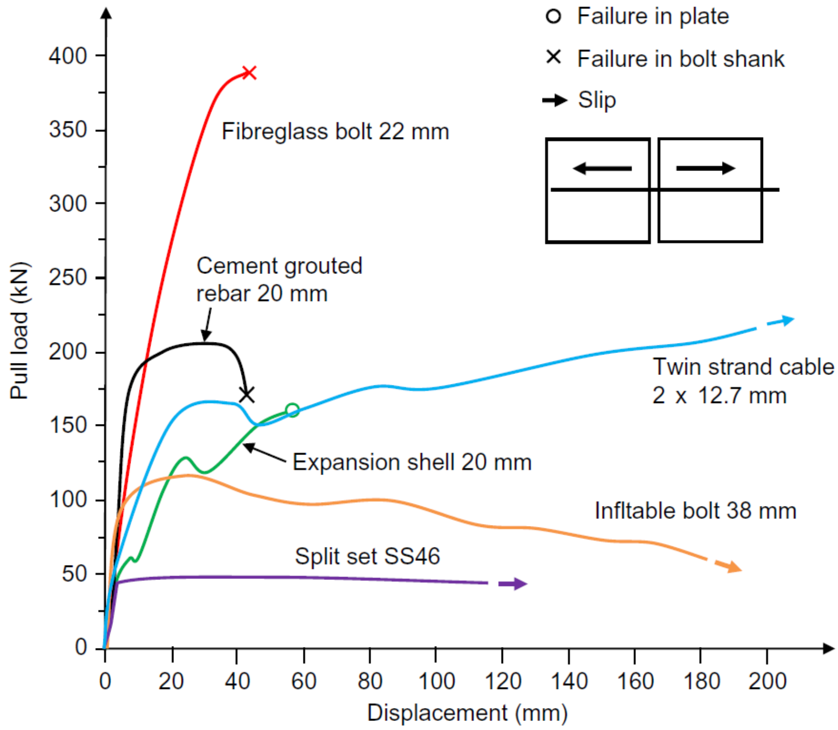

Figure 6. Load-displacement curves of rock bolts (Li, 2017b).

2.4 Anchor mechanisms

Rock bolts can be classified into 3 categories depending on their anchoring mechanism: discrete point anchored bolts, fully encapsulated bolts and frictional bolts.

- Discrete point anchored bolt

Discrete point anchored bolts work by retaining the deformation of the rock mass by dividing the load over the whole bolt length. The maximum load capacity of the bolt is in general determined by the frictional resistance of the expansion shell or the friction between the resin and the bolt. These bolts are pre-tensioned and give therefore immediately support after installation, these bolts fall under the active support method (Li, 2017b; Mark, 2000).

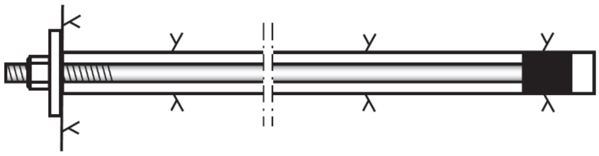

Figure 7. Discrete point anchored bolt (Li, 2017b).

- Fully encapsulated bolt

The load on a fully encapsulated bolt is transferred from the rock mass through the grout to the bolt surface. Fully encapsulated bolts divide the displacement of the rock mass over a part of the bolt, the length of this part is dependent on the place of the bond failure. The maximum axial stress is equal to the tensile strength of the bolt when it is loaded by a deformation in the rock mass (Li, 2017b; Ma, 2014; Maidl, 2013). Depending on the settling time of the grout that is used are these bolts active of passive, cement grouted bolts are seen as passive support.

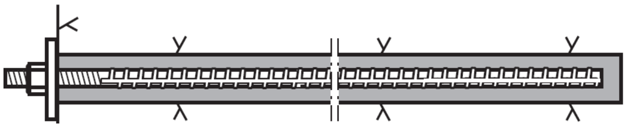

Figure 8. Fully encapsulated bolt (Li, 2017b).

- Frictional bolt

The load of a frictional bolt is dependent on the friction between the rock mass and the bolt. The bolt is allowed to partially slip, this allows a friction bolt to accommodate large displacement in the rock mass. The load capacity is relatively low because it is dependent on the friction between the rock mass and the bolt. These bolts provide immediate support and are therefore an active support method (Li, 2017b; Maidl, 2013).

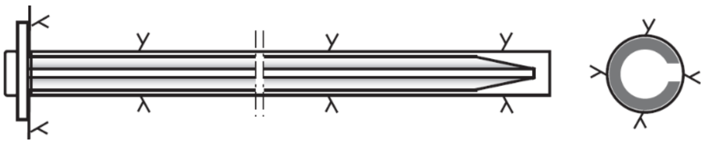

Figure 9. Frictional bolt (Li, 2017b).

2.5 Sorts of rock bolts

Over the past years, the range and applications of rock bolts have increased. The factors that are used to choose a rock-bolt include the following: application requirements, rock type, life expectancy, presence of water, corrosive behaviour, extraction height, required displacement and load-bearing capacity. The length of most rock-bolts is limited by the size of the drift or equipment (Li, 2017b). The price of rock-bolts is another important factor, these cannot be disclosed due to competition concerns.

2.5.1 Mechanical anchored rock bolt

Mechanical anchored rock bolts are bolts that are tensioned immediately after installation. The rock must be hard enough so that the anchor at the end of the bolt has enough grip, if this is the case the bolt can be tensioned to its maximum load-bearing capacity. They are installed by drilling a tight borehole and pre-tensioning of the bolt is done with a torque wrench. The main disadvantage of mechanically anchored bolts is that they can slip over time due to vibrations. The bolt can be grouted if needed, this prevents corrosion of the bolt and if the anchor fails the bolt will still retain some capacity (Hoek, 2000). The bolts consist normally of an expansion shell (4), bolt shaft (3), plate (2) and a nut (1) (DSI, 2016).

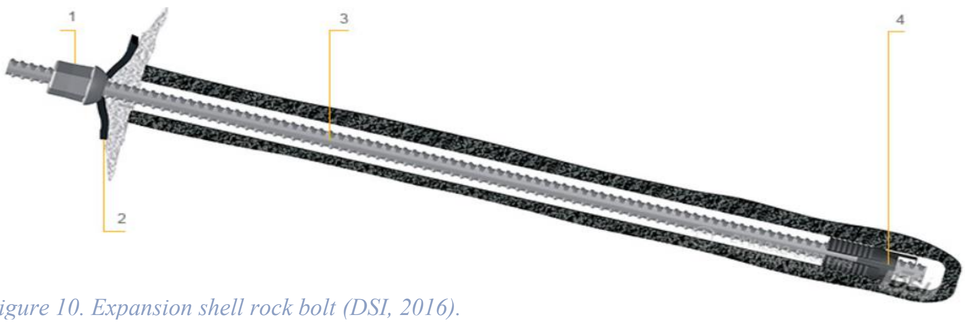

Figure 10. Expansion shell rock bolt (DSI, 2016).

2.5.2 Grouted rock bolts

Grouted rock bolts are bolts that are encapsulated by resin or cement. The bolts normally consist of a threaded rebar. The resin or cement can be injected into the hole before or after inserting the bolt. These bolts don't have immediate load capacity, they are usually not pre-tensioned. Cement grouted rock bolts rely on the displacement of the rock to activate their load capacity. These bolts can thus be installed close to the working face, they don't lose their load capacity due to blasting vibrations. Fully grouted bolts are preferred over point anchored bolts because the resulting tensile load from the deformation is transmitted to the rock mass (Hoek, 2000).

- Resin cartridges

Resin encapsulated bolts are installed by inserting resin cartridges into the borehole before inserting the bolt. The bolt breaks the cartridges and spinning of the bolt results in the mixing of the two resin components. A downside of the resin grouted bolt is the fact that is the resin is expensive and the use of cartridges limits the filling of cracks and voids. A combination of fast and slow setting resin can be used, this allows for tensioning of the bolt after the fast resin has set. Resin can be used in wet boreholes as the resin won't mix with water (Barret, 2006). The optimum annulus thickness is between 3-4 mm wide, the annulus is the space between the rock mass and the bolt. An optimal annulus space results in the strongest bond between the resin, bolt and rock interface (Ulrich, 1989).

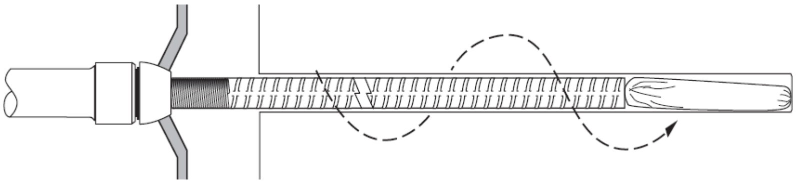

Figure 11. Resin cartridge bolt installation (Barret, 2006).

- Cement grouted

Cement grouted bolts have a longer curing time than resin grouted bolts and cannot be used in boreholes with running water. They can be installed by inserting cement cartridges or pumpable cement into the drilled hole. Pumpable cement is the cheapest option of the grouting methods but has as downside that it is made in batches. The system needs to be cleaned after each shift, this has a negative impact on the productivity. Pumpable cement has the ability to fill cracks and voids this improves the installation quality, the space between the bolt and drill hole wall is always filled (Hoek, 2000).

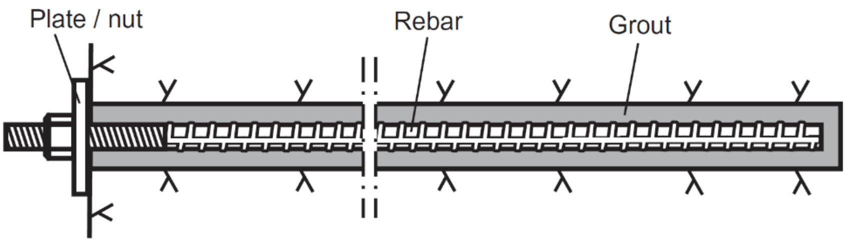

Figure 12. Cement grouted rock bolt (Li, 2017b).

2.5.3 Combined rock bolt (CT-bolt)

For some applications it is necessary to tension the bolt immediately and fully grout it, the grouting prevents corrosion. This can be done with a combination bolt, this is a fully grouted bolt with a direct load capacity. The bolt consists of an expansion shell, grouting head and tube mounted on the bolt. The bolt is installed as a normal mechanical anchored bolt, the grout is pumped through the head afterwards (DSI, 2018).

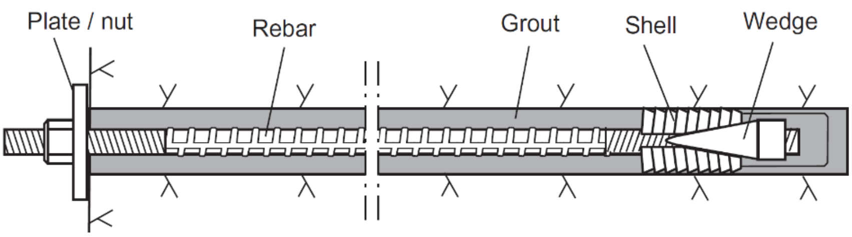

Figure 13. Cement grouted and expansion shell bolt combined (Li, 2017b).

2.5.4 Cable rock bolt.

Cable bolts are used when the required length to reinforcement the rock mass is too large for stiff bolts. They consist of a steel cable that is inserted in the borehole, the hole is filled with cement afterwards. The advantages of cable bolts are their long reinforcement length and high load-bearing capacity. Cable bolts are less stiff than rebar rock bolts and are more sensitive to corrosion due to the smaller diameter. The cables may have anchors attached to them or be bulged to increase the load-bearing capacity (Hoek, 2000; Li, 2017b).

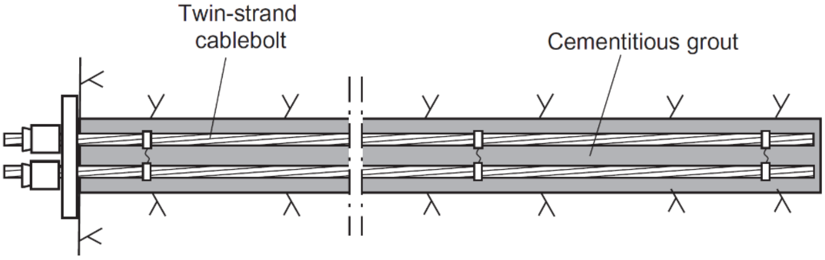

Figure 14. Cement grouted cable bolts, double strand (Li, 2017b).

2.5.5 Frictional rock bolt

Frictional bolts are bolts which give immediate support to the rock mass. The anchor mechanism is based on the frictional resistance between the bolt and the borehole. Frictional bolts are sensitive to corrosion because there is no protecting layer around the rock bolts. There are more expensive friction bolts that have a protective coating (AtlasCopco, 2016; Li, 2015; Ma, 2018).

The Split-set bolt is made out of a slotted steel tube that is slightly larger than the drilled hole. The diameter of the bolt decreases slightly when the bolt is hammered into the hole, causing outward pressure that reinforces the rock mass (Rollforms, 2010).

The Swellex bolt is another frictional bolt, this bolt is expanded inside the hole by using high-pressure water. The bolt was designed by Atlas Copco around 1980, it has been copied by other manufactures since. The bolt is made of a steel tube folded into an omega shape. The bolt is inserted into the hole and expanded by injecting high pressure water into the bolt. This results in the mechanical interlocking of the bolt. After expansion, the internal pressure is released and the deformed bolt provides support to the rock mass. Modern Swellex bolts have a protective coating and are therefore more corrosive resistance (AtlasCopco, 2016; Hoek, 1987).

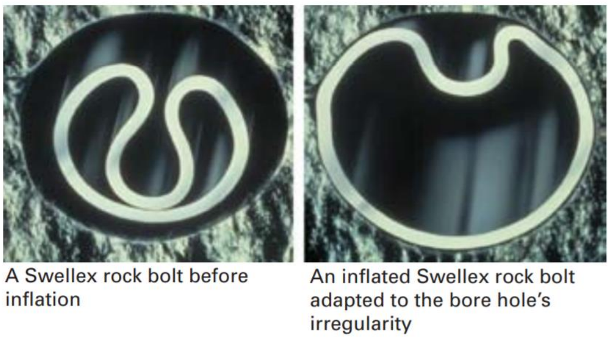

Figure 15. Section of the Swellex rock bolt (AtlasCopco, 2016).

2.5.6 *Energy absorbing yield rock bolt*

Energy absorbing rock bolts are designed to withstand much greater deformation such as rock bursts which happen more often in high stress environments. They consist in general of a steel bolt with a part of high ductile steel that can deform. They can be both point anchored and fully encapsulated, the ductile steel part is smooth so there is less friction when deforming. The bolt absorbs the deformation of the rock mass by taking advantage of the deformation capacity of high quality steel (Cai, 2013; Li, 2017b).

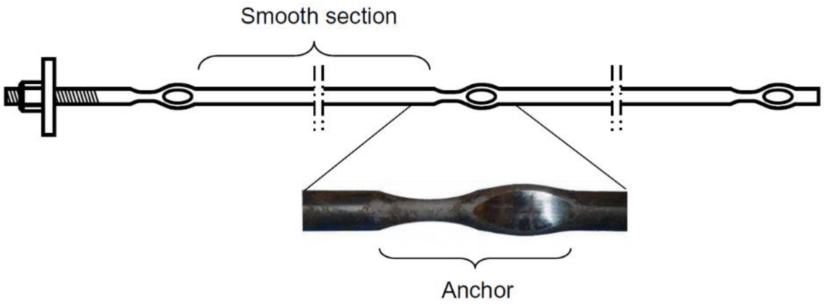

Figure 16. Dynamic rock bolt (Li, 2017b).

2.5.7 *Self-drilling rock bolt*

Self-drilling bolts consist of a hollow rock bolt with a disposable drill bit on top of it. This allows for the grout to be pumped through the bolt. In this way, the bolt can be left in place after it is drilled and there is no possibility of the drill-hole collapsing. This is called the 1-step method because the drilling and bolt inserting is done at the same time. The drill bit can only be used once, this makes these rock bolts more expensive. This is still a hurdle for wider acceptance (Duin, 2012). These bolts are mainly used in unstable soils or heavily fractured rock which tend to be obstructed after drilling (Minova, 2017b). The price of the drill-bit increases with the rock strength it needs to be able to drill, strong competent rocks have less need for self-drilling bolts. There is less need for self-drilling bolts in strong rock because there is less chance that the hole will collapse after drilling.

2.5.8 *Plates, nuts & washers*

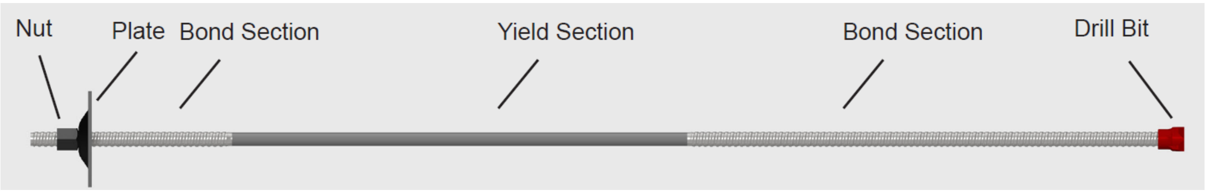

Figure 17. Self-drilling bolt with a yield section (Minova, 2017e).

Plates help to transfer the load from the rock bolt to the rock surface. They are also used to connect rock support like mesh, straps and shotcrete. The most common plate used is a square plate with a hole, this is the cheapest form. There are also dome shape plates which are better in withstanding displacement. The load-bearing capacity of the plate should be higher than the strength of the bolt. Nuts are used to connect the plate to the rock bolt, they must also have a higher bearing capacity as the bolt. To prevent the nut punching through the plate washers have been developed. These are spherical cones made to redistribute the load of the nut equally over the plate (Li, 2017b). From a safety point, it is preferable that the bolt is the weakest link and not the nut or plate.

2.6 Installation methods

Installing roof support is a time-consuming process that doesn't add production but is necessary for safety (Archibald, 2000). The installation methods for rock bolting have been greatly improved over the past. This improvement has mainly been in terms of operator safety and easiness of handling the materials. It started with the manual drilling and installation of bolts, here the operator was close to the unsupported work face. This has been modernized by mechanized drilling and bolt installation, the operator is further away from the face protected in a cabin (Gustafson, 2013).

2.6.1 Manual bolt installation

The oldest method of setting a rock bolt, a hole is drilled with a handheld pneumatic or hydraulic drill. After this the bolt is inserted by hand and if needed tensioned, this limits the ability to fully grout and pre-tension rock bolts. The bolt installation is done with hand-held equipment, close to the unsupported working area. Working close to the unsupported working with handheld equipment has negative effects on the long term health of operators.

This method is mostly applied in small scale mines with narrow veins where large equipment can't easily reach the working area (Kendall, 2015; Menasce, 2006). In Figure 18, the drilling part of the manual installation of a rock bolt is shown.

Figure 18. Handheld hydraulic rock drilling (AtlasCopco, 2014).

2.6.2 Semi mechanical bolt installation

Semi mechanical bolt installation is done with the support of a drilling jumbo. A drilling jumbo is used to drill the hole and the bolt is afterwards installed with a service platform, this is shown in Figure 19. This removes people from the unsupported face while disturbing the rock mass while drilling. There are employees working near the unsupported face while installing the bolts, this is the reason why this method is being replaced by fully mechanical bolt installation (Kendall, 2015; Marek, 2012).

Figure 19. Semi mechanized bolt installation (Kendall, 2015).

2.6.3 Fully mechanical installation

Fully mechanized bolting rigs consist usually of an underground drilling rig equipped with hydraulic rock drills and a bolt magazine, additional features consist of a control system for positioning and a grout injection system. The bolt is inserted into the hole directly after it is drilled, this minimizes the possibility of the drill hole collapsing. The operator sits in a cabin protected by fall on protection, so the operator is not working directly under the unsupported roof (Li, 2017b). Figure 20 shows a fully mechanized rock bolter of Atlas Copco.

Figure 20. Fully mechanized bolt installation with the Boltec S (AtlasCopco, 2013).

2.7 State of the art

The state of the art rock bolting methods and equipment are nowadays mostly used in the civil engineering industry. This is because in civil engineering projects the need for fast installation of support is greater; every step in the blast cycle should be finished as soon as possible. When constructing a tunnel there is only one working face, the minimization of the blast cycle duration has the highest priority. The required lifetime of civil engineering projects is in general greater than that of mining projects, this increases the need for higher quality materials.

2.7.1 Rock bolts

Rock bolts are chosen for their specific application in the mine depending on the needed deformation allowance, required strength and other factors. This is why there is not a single rock bolt which is better than other ones. Although considering installation speed, self-drilling bolts are top of the line. Rock bolts tend to get more complicated and try to combine direct support with the ability to be fully grouted. Due to higher stresses that come with deeper mines, dynamic energy absorbing bolts are in higher demand than in the past (DSI, 2016; Minova, 2017b). Self-drilling bolts enable the installation of rock bolts to go faster and with fewer steps, it combines the drilling and bolt inserting into one step. The resin capsule is incorporated into the bolt or a pumpable resin is pumped through the hollow bolt. This installation method is called the 1-step bolting, this method is to the researchers' knowledge currently being developed by three companies; DSI-underground, Jennmar and Minova (DSI-Underground, 2015; Fiscor, 2017; Minova, 2018). Rock bolts with smart-sensors to check the integrity of the bolts are being developed. This is currently done with the pull-out test; a destructive method. With this test bolts are pulled out hydraulically while the displacement is measured, this is done until the bolts fail. These sensors can monitor the axial load, grout quality and corrosion without destroying the bolt. These data could be sent real time to a control program which would alert the rock mechanics if something is wrong (Song, 2017).

2.7.2 Installation methods

State of the art mines as observed in the Nordics use fully mechanical bolting equipment. This is the safest method for the operator and does not require a lot of physical strength. Getting operators away from unsafe working areas is one of the highest priorities for mining companies. With fully mechanical installation there is no need for the operator to be close to the unsupported face. The bolts are normally installed in a predefined pattern designed by the rock mechanics engineer. Bolting patterns leave less room for errors and decrease the chance off rock-falls (NewBoliden, 2018). The 1-step method looks very promising in terms of automation possibilities, fewer process steps result in fewer errors and therefore the need for human intervention. With the 1-step bolting the delivery of bolts to the carousel is still done manually. This limits the maximum number of possible installed bolts to that of the carousel. Bolt delivery systems are being developed but they are still in the research state (Duin, 2012; Epiroc, 2018).

3. Mechanical bolt installation methods and work processes

This chapter will describe the fully mechanical installation methods of rock bolting. At first, two current bolting methods are explained in detail, the newly developed methods will be explained after this. In order to compare the methods, machines from Epiroc will be compared with each other. After comparing the machines typical installation rounds will be explained, this will be done at the hand of field observations.

3.1 Typical design of a mechanical rock bolter

Most fully mechanical rock bolters have more or less the same design: they consist of a self-propelling vehicle. A rock bolter is between 10 and 16 meters long, around 2.5 meters wide and between 1.3 and 3.1 meters high. These dimensions are all specific for the application the rock bolter is used for, they are constrained by the size of drifts. The size of the rock bolter dictates the maximum length of the bolts that can be installed. The drift size required by mechanical rock bolters is around 3 by 3 meters, larger drifts will improve the operational handling of the rock bolter. Special rock bolters for low seam mines can work in headings as low as 1.8 meters (Epiroc, 2018).

Figure 21. Boltec E (Epiroc, 2018b).

The operator cabin is in the middle of the vehicle and on the front there are 2 booms; one for mesh handling and one for drilling, grouting and inserting bolts. In Figure 21 a typical mechanical rock bolter is shown, the yellow boom is used for the bolting operation. The drilling and installation of the bolts are done with hydraulics, powered by electricity. This means that the bolter needs to be connected to power and water during the installation of bolts. On the drilling boom there are at least 3 elements; one for the drilling, one for the grouting and one for the inserting of the bolt. The drilling is done with a hydraulic rock drill, this tool is connected to a high-grade drill steel with an easily replaceable drill-bit. The drilling is normally flushed with water or air, depending on the work environment. The grouting tool consists of a pump and a set of tubes, the grout is inserted into the drilled hole through these tubes. These tubes normally have to be inserted into the drilled hole for a certain length, this is to ensure that the bolt is fully grouted. The bolt inserting tool consists of a bolt carrousel that can hold multiple bolts. This carousel can rotate to keep supplying bolts to the arm that inserts the bolts into the hole. The carousel has to be refilled manually, a typical carousel holds 8 to 16 bolts. A carousel filled with bolts is shown in Figure 20 on the left side. These tools are designed in such a way that the boom does not have to be adjusted, they should be aligned. The correct alignment of the tools is important to ensure the fastest possible installation of bolts. On the front or back of the rock-bolter there is space for a rack that holds up to 150 bolts, these and other options are normally installed according to specifications from the mining company (Epiroc, 2018; Sandvik, 2018).
Three different grouting techniques are described in more detail; cement, resin cartridges and pumpable resin. These systems and installation methods will be described from personal

observations. These observations are done in Swedish mines and add up to over a hundred hours of underground observations. The workflow for the cement grouted and resin cartridge bolts has been observed in the Kristineberg mine of Boliden. The workflow for the 'High Performance' 1-step method has been observed at Malmberget a mine of LKAB, the 2-step method is deducted from these observations in Malmberget and Kristineberg. These workflows may differ from mine to mine depending on logistics and work orders.
Kristineberg is a mine of Boliden, it mainly produces zinc, copper and lead. The mine uses the overhand cut-and-fill method, this is a small scale mining method. The deepest level that is being mined at the moment is at 1320 meters below surface (NewBoliden, 2018).
Malmberget is an iron ore mine of LKAB, they use sub-level caving to extract the ore. This is a massive scale mining method, the current haulage level is at 1250 meters below surface (LKAB, 2018). The 1-step 'High Performance' method uses hollow self-drilling bolts, the resin is pumped through the bolt. There is only 1 inserting step hence the name. The 2-step 'High Performance' Method uses hollow bolts. But the hole is drilled with a drilling-steel that is used multiple times. There are 2 inserting steps resulting in the 2-step 'High Performance' method.

The following rock-bolt systems can be installed on mechanical rock-bolters without major adjustments to the overall layout. For each of the three setups the pumps and storage units need to be replaced.

3.1.1 Mechanical cement rock-bolter

Cement bolters have a dry cement storage and the cement mixing unit next to the engine. The cement storage can hold up to 800kg of dry cement, the mixer can mix 150kg of wet cement at the time. From here the mixed cement is pumped through tubes to the front of the bolter where it is injected into the hole.

3.1.2 Mechanical resin cartridge rock-bolter

Resin cartridge bolters have a large compartment next to the engine, at the same place as the cement mixer. These cartridges are transported to the boom via a series of tubes, this is done by air pressure. The cartridge holder needs to be refilled by hand, it holds up to 150 cartridges. These cartridges can have different settling times, these are colour coded if used.

3.1.3 Mechanical 'High Performance' rock-bolter

Bolters that use pumpable resin have two resin tanks instead of a cement storage, the cement mixer is replaced by a pumping system. The two tanks can each hold 150 litres of the resin component, the mixing rate is 1:1 so both tanks will empty at the same rate. The 2-component resin is pumped separately towards the injection piece where it is mixed. After each bolt installation biodegradable grease is pumped through the mixing unit to clear it from resin. A schematic overview of the system is shown in Figure 22, the resin is mixed just before it enters the bolt.

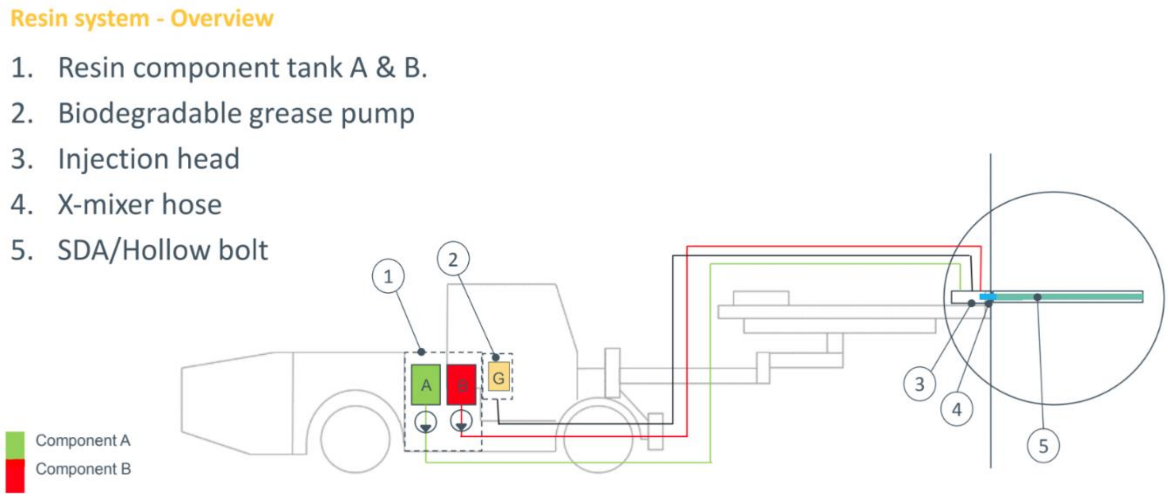

Figure 22. Schematic resin system - Boltec 'High Performance (Epiroc, 2018).

3.2 Work process of cement grouted rebar-bolts

The mechanized installation method of cement grouted bolts is done in an order of steps, this is called the bolt installation cycle. This installation cycle is discussed below and these steps can be seen in Figure 23. The green arrows show the order of steps if there are no interruptions. The minutes stated below the actions are averages measured during the observations.

Upon arrival at the face the machine and working area are checked for their overall condition. If these are both in good condition then the operator starts the cement mixing, this is done at first because this process takes the longest. A maximum of 150 kilograms of cement grout is being mixed at the time, this is normally enough for 20 bolts. While the cement is being mixed the operator starts loading bolts into the bolt-carrousel. Depending on the operator, the boom is lubricated with oil to prevent the cement from sticking on it. When the cement is ready the operator starts drilling the first hole, when this is finished the cement hose is inserted. The hole is filled with cement, this can be done automatically or in case of cracks and voids manually. After the hole is grouted a steel rebar bolt is inserted into the hole, the last 45 centimetres of the bolt is bent to prevent the bolt from falling out. After the correct installation of the bolt, the operator can reposition the boom to the next location (NewBoliden, 2018).
This process is continued until the operator has installed 10 bolts then the carousel is empty. The operator has to refill the carrousel with bolts, this moment is also used to mix more cement if needed. If more cement has to be mixed then the operator has to wait until this is ready. The operator cannot install more bolts while the cement is being mixed. Cement that is not properly mixed can obstruct the hoses. Mixing the cement can take up to 5 minutes each time.

Certain errors can occur during the processes described above, below the most common errors:

- The alignment between drill-hole, cement tube or rock bolt is wrong this results in the tube or bolt not entering the hole. The operator has to make manual adjustments to the boom position to fix this. Equipment and materials can be damaged due to hitting the face and operating time is lost when making these adjustments.
- If there are cracks/voids in the rock and the operator does not fill the hole manually, the bolt is not completely grouted. This results in the incorrect installation of the bolt. Experienced operators will visually check if a bolt is fully grouted by pulling the bolt partially out of the hole.
- If the bolt is not bent sharply enough or if an operator forgets this, there is a possibility of the bolt falling out until the cement is hardened. This means that the working area is not secure for another 4 to 8 hours.
- If the cement is not mixed properly lumps can get stuck in the hoses, the operator has to dismantle hoses manually. If it is stuck close to the dismantle point then the operator can remove it with a piece of iron wire.

The cycle above is repeated until the work is done or when the operator has to leave the machine. If the machine is left alone for more than half an hour the operator has to flush the cement system and clean the boom. During a normal shift this happens twice; before lunch/dinner and before the end of the shift. If the machine is moved to another face it also has to be cleaned. Cleaning of the machine takes on average 25 minutes, depending on the level of cleanness required by the operator. During observations it has been noticed that operators do not find it useful to start working 60 minutes before lunch or shift change. The mixing of the cement and cleaning the system takes too long to productively work. If the machine runs out of cement or rock-bolts, new supplies need to be collected from the storage. Operators try to restock on bolts and other supplies in-between tasks; they often drive close to the storage when changing work locations.

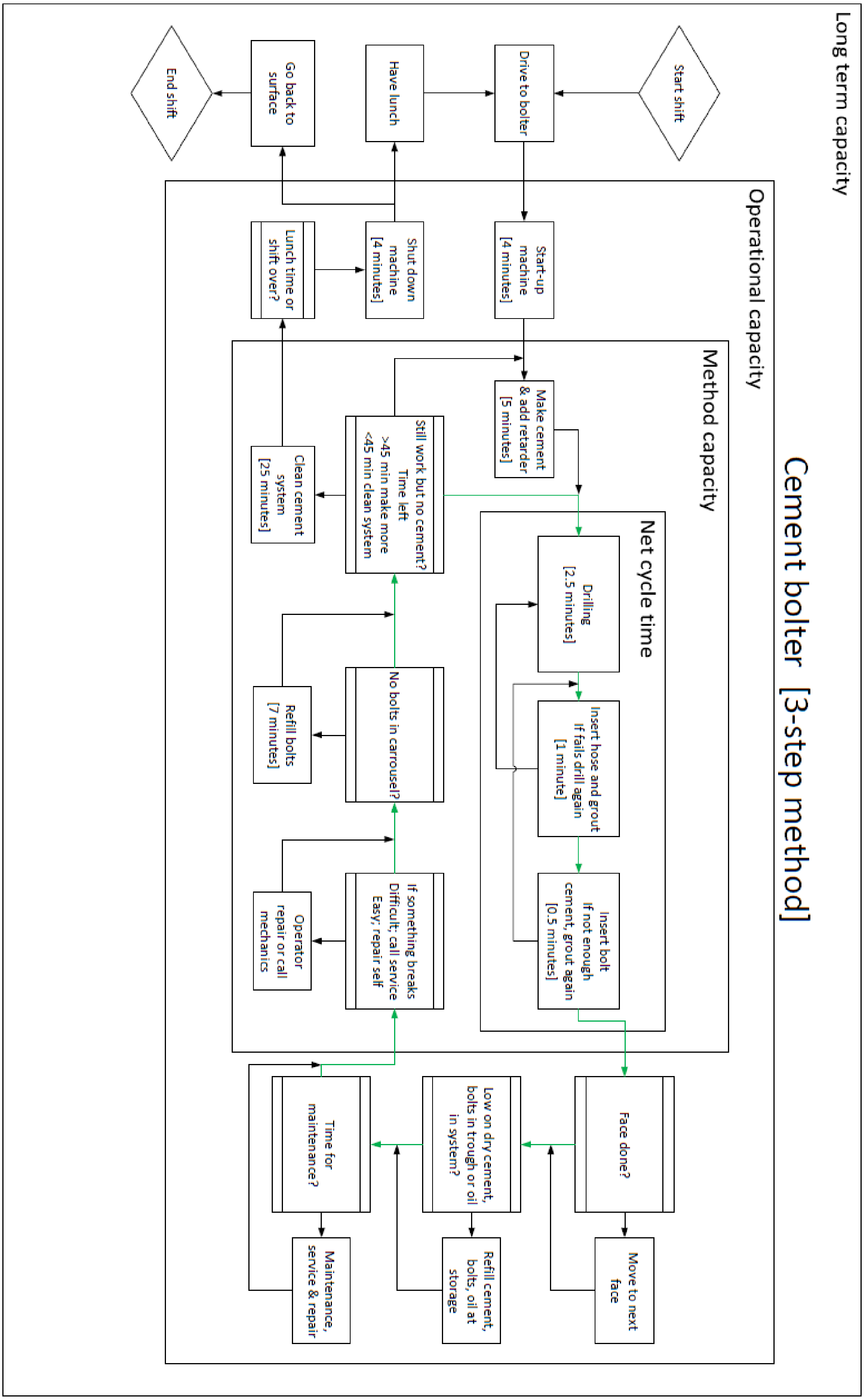

Figure 23. Observed workflow of the cement method.

3.3 Work process of resin cartridge rebar-bolts

The installation cycle of the resin cartridge system is similar to that of the cement grouted method. The biggest difference is that there is no need to make and clean cement instead the cartridges have to be refilled.

Upon arrival at the face the machine and working area are checked for their condition. If these are both in good condition then the operator starts filling the cartridge magazine and the bolt carrousel. The filling of the cartridge magazine and bolt carrousel is consuming more time than the cement mixing and filling of the bolt carrousel. If these steps are finished then the operator starts drilling the hole, after this is finished the cartridge hose is inserted. A certain number of cartridges is inserted into the hole; this number depends on the size, number of cracks/voids and the operator's experience. Multiple cartridges can be loaded into the inserting unit at once but it is slower than inserting cement. After the cartridges are inserted a steel rebar is inserted into the hole, this is done while the bar is being rotated to mix the resin. When the bar is fully inserted it must be held in place for another 30 seconds to let the resin harden. The nut can be tightened after the resin is hardened to pretension the bolt. After the correct installation of the bolt, the operator can reposition the boom to the next location. This process is continued until the operator has installed 10 bolts, then the carousel is empty. The operator has to refill the carrousel with bolts. This moment is also used to refill the cartridge magazine if needed.

Certain errors can occur during the processes described above, below the most common errors:

- The alignment between drill-hole, cartridge tube and rock bolt is wrong. This results in the tube/bolt not entering the hole. The operator has to make manual adjustments to the boom position to fix this. Equipment is damaged due to hitting the face and operating time is lost when making these adjustments.
- The rock mass is fractured and a piece of rock blocks the cartridge inserting tube from fully entering the hole. The operator has to insert the drill-steel again to remove the loose rocks from the drill-hole.
- If there are cracks/voids in the rock and the operator does not insert enough cartridges, the bolt is not completely grouted. This results in the incorrect installation of the bolt.
- The bolt is not being rotated according to the standard operating procedure, this results in a poor mixing of the resin. Which may result in the incorrect installation of the bolt.

The cycle above is repeated until the work is done or when the operator has to leave the machine. If the machine runs out of cartridges or rock-bolts, new supplies need to be collected from the storage. Figure 24 shows this cycle with possible interruptions that are likely to happen during the bolting cycle.

Refilling and inserting the cartridges make the process slower than the cement grouted method. Resin cartridge grouting is more expensive than grouting with cement. But not losing time on making and cleaning the cement is seen as an advantage over the other method. Another advantage is that resin cartridges can be used in boreholes with water (NewBoliden, 2018).

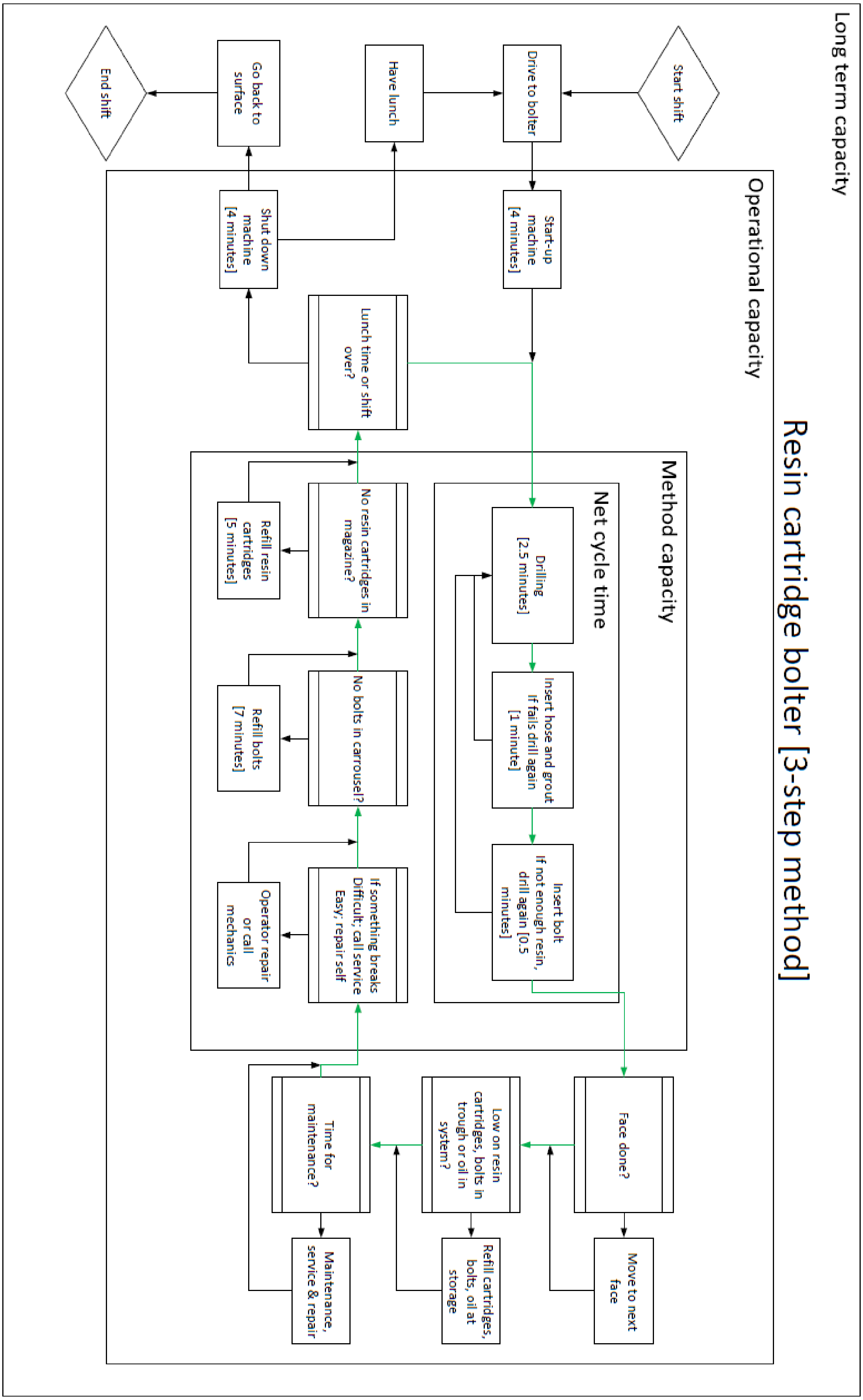

Figure 24. Observed workflow of the resin cartridge method.

3.4 Work process of 'High Performance' method with hollow bolts

The workflow that can be seen in Figure 25 is a proposed workflow for the 2-step bolting method, this workflow has been adapted from the 1-step bolting workflow. Upon arrival at the face the machine and face are checked for their condition. If these are both in good condition then the operator starts loading bolts into the bolt carrousel. When the operator has finished this task, the drilling can start. The drilling is done with a drill-steel, after the hole is drilled the hollow bolt is inserted. The resin injector is coupled to the bolt and the resin is pumped into the bolt filling up the hole from the back. The mixing of the resin is done just before it enters the bolt, this is done by a static X-mixer. When the resin appears at the plate the pumping is stopped and the X-mixer is automatically flushed with biodegradable grease. This is done to prevent the resin from hardening in the X-mixer. The bolt has to be kept in place for another 20 seconds until the resin is hardened. After the correct installation of the bolt, the operator repositions the boom to the next location.
This process is continued until the operator has installed 10 bolts, the carousel is empty. The operator has to refill the carrousel with bolts.

Certain errors can occur during the processes described above, below the most common errors:

- The alignment between the drill-hole and the rock bolt is incorrect, this results in the bolt not entering the hole. The operator has to make manual adjustments to the boom position to fix this. The equipment and bolt can be damaged in this process and operating time is lost when making these adjustments.
- If there are cracks/voids in the rock and the operator cannot visually check if the bolt is fully encapsulated, another bolt has to be installed next to the incorrect installed bolt.

The misalignment problem between the bolt and resin injector is taken away by locking the bolt in the claw. The cycle above is repeated until the work is done or when the operator has to leave the machine. If the machine runs out of resin or rock-bolts, new supplies need to be collected from the storage.

If the hoses or pumps containing the resin components need to be replaced, the system needs to be emptied of resin. This can be done by flushing the system with a fuel oil, the resin mixture and fuel oil should be deposited in chemical waste containers.

This method is faster than the previous two methods because there is no time wasted on cement cleaning or on refilling the cartridges. The grouting hose is replaced by the hollow-bolt, this removes a process step, streamlining the operation. It has to be taken into account that the hollow bolts are more expensive than ordinary rebar bolts.

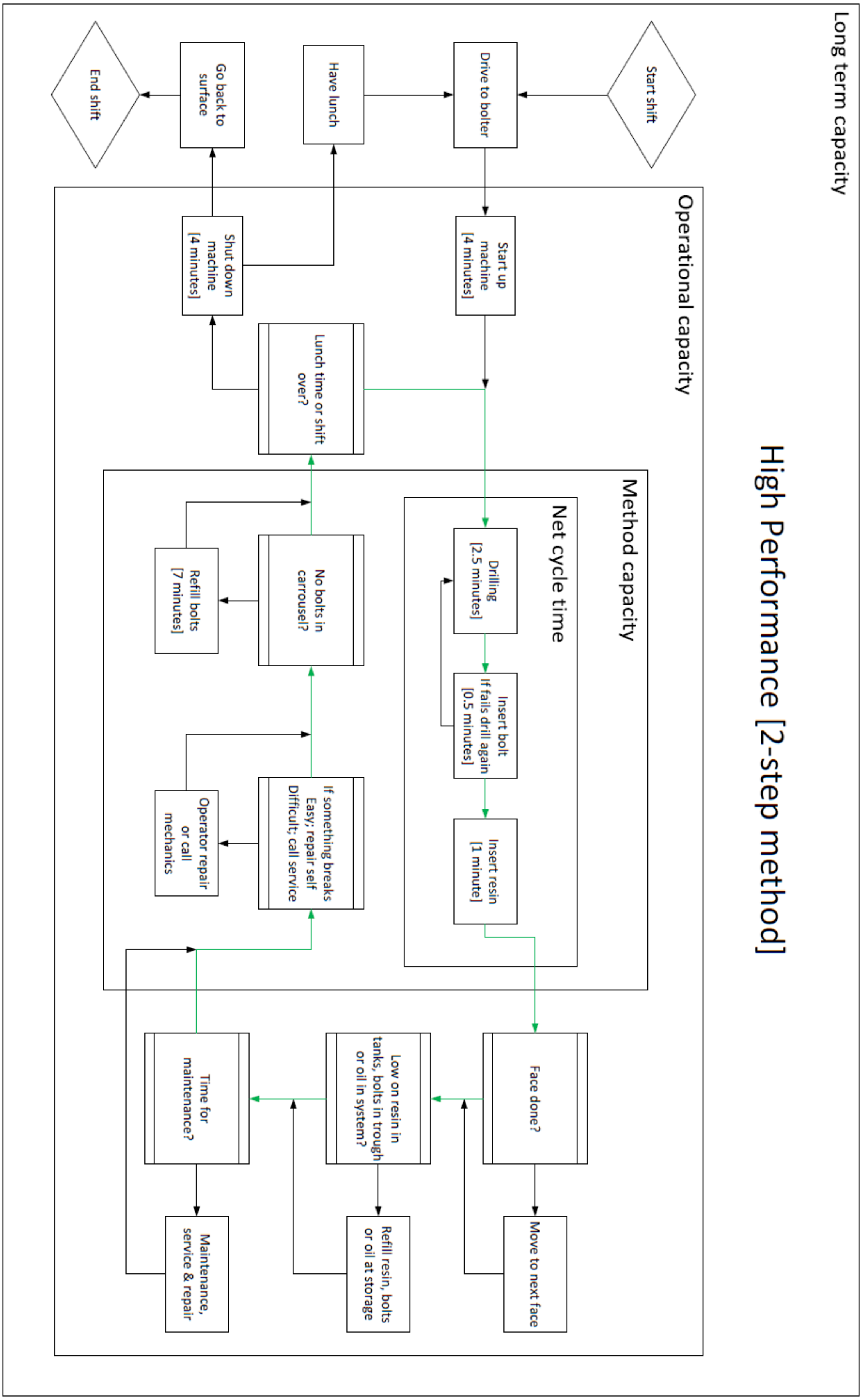

Figure 25. Proposed workflow of the 'High Performance' method with hollow bolt.

3.5 Work process of 'High Performance' method with self-drilling bolts

The installation of a pumpable resin self-drilling rock-bolt is the most streamlined installation of all the installation methods that have been addressed.

The workflow of the 'High Performance' method with self-drilling bolts (SD-bolt) can be seen in Figure 26. When this workflow is compared with the cement grouted method it is clear that there are fewer process steps. Upon arrival at the face, the machine and face are checked for their condition. If these are both in good condition then the operator starts loading bolts into the bolt carrousel. When the carousel is loaded then the operator can start drilling with self-drilling bolts. After the hole is drilled, the bolt is locked by the claw and remains in the hole. The resin injector is coupled to the hollow self-drilling bolt. Pumps start automatically and the resin is mixed by an X-mixer just before it enters the bolt. The resin will start filling up the hole from the back, if it appears at the plate the pumping is stopped. Due to the thixotropic behaviour of the mixed resin, it will stop flowing when pressure is removed. The X-mixer is automatically flushed with biodegradable grease to prevent the resin from hardening in the mixer. The bolt is kept in place for another 20 seconds until the resin is hardened. After the correct installation of the bolt, the operator can reposition the boom to the next location.
This process is continued until the operator has installed 10 bolts, the carousel is empty. The operator has to refill the carrousel with bolts.

Certain errors can occur during the processes described above, below the most common errors:

- If there are cracks/voids in the rock and the operator cannot visually check if the bar is fully encapsulated, another bolt has to be installed next to the incorrect installed bolt.

The misalignment problem between the bolt and resin injector is taken away by locking the bolt in the claw. The cycle above is repeated until the work is done or when the operator has to leave the machine. If the machine runs out of resin or rock-bolts, new supplies need to be collected from the storage.
If the hoses or pumps containing the resin need to be replaced the system needs to be empty of resin. This can be done by flushing the system with a fuel oil, the resin mixture and fuel oil can be deposited in chemical waste containers.

This method is the fastest and most streamlined of all the methods mentioned. The bolt is also used for drilling and grouting the hole. As with the 2-step method, no time is wasted on cement or on resin cartridges. Self-drilling bolts have another advantage, always drilling a predefined length; in this case the bolt length. This and leaving the bolt in the rock results in the perfect drilling length. Over and under-drilling are not an issue anymore, less resin is wasted and the bolt is always tensioned as planned. Over-drilling may result in insufficient tensioning of the bolt and excess grout is needed to fill the hole. Under-drilling may result in either over- or under-tensioning of the bolt. This depends on how the nut is being fastened. Using hollow bolts with a sacrificial drill-bit makes this the most expensive option of the methods discussed (Barret, 2006; Maepa, 2017).

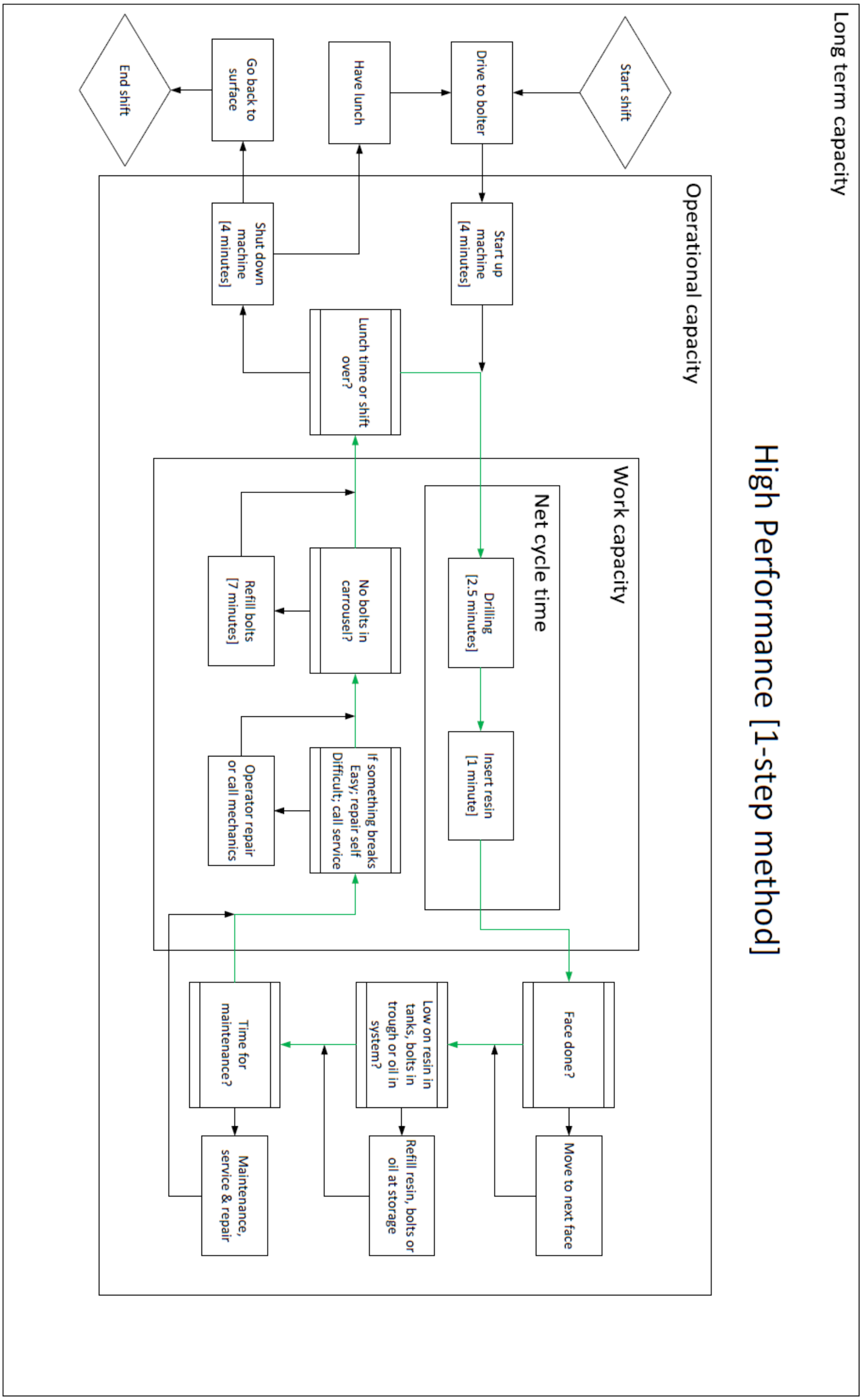

Figure 26. Observed workflow of the 'High Performance' method - self drilling.

4. Health, safety and environmental aspects

In this chapter the health, safety and environmental aspects of the pumpable resin, cement and resin cartridges are discussed. All the health and safety data summarized in this chapter has been taken from the safety data sheets provided by the manufacturers of the components (Minova, 2017d). Additional safety procedures have been added according to the standard operating procedures of Boliden. There is no standard operating procedure for working with the pumpable resin at Boliden, this has to be developed before the 'High Performance' method is implemented.

4.1 Pumpable resin properties – CarboThix 150710

The newly developed resin by Minova is a two-component silicate resin, which is developed for the sealing of rock-bolts. Component A is a special sodium silicate with additives and component B which is a modified poly-isocyanate. It is an instantly thickening and fast curing resin. If the product is used correctly then a hard plastic composite is formed in which the hazards associated with the product before use are minimal after use. After mixing the two components, the resin achieves a greasy-like viscosity so that the mix stops flowing and requires pressure for displacement. The mix hardens to form a hard resin within 30 seconds. The final product has a relatively low modulus of elasticity with high strength. This results in a uniform transfer of local rock stresses over the whole length of the bolt rod. The compressive strength of the mixture is above 20 MPa after 30 minutes and the shore hardness reaches D60 after 4 hours, this is as hard as a golf ball (Minova, 2017f; Redwoodplastics, 2010).

The mixing can be done with static mixers, just before it enters the hollow bolt. The mixed resin fills the annulus space and adjacent large cracks, due to the high thixotropy of the mixed resin this is done without leakage. The mixed resin will not mix water or be diluted in wet holes, it forms a non-porous grout that covers the bolt. These properties ensure full encapsulation of the rock bolt. The recommended processing temperature is between 10° and 20° C. The shelf life of the resin is at least 12 months after production in a dry and frost free storage. If the components cool to below zero degrees it is advised to transport the components to the work site at least 36 hours before processing so that they can adapt to the temperature. The lower the temperature of the resin, the slower the chemical reaction (Minova, 2017a).

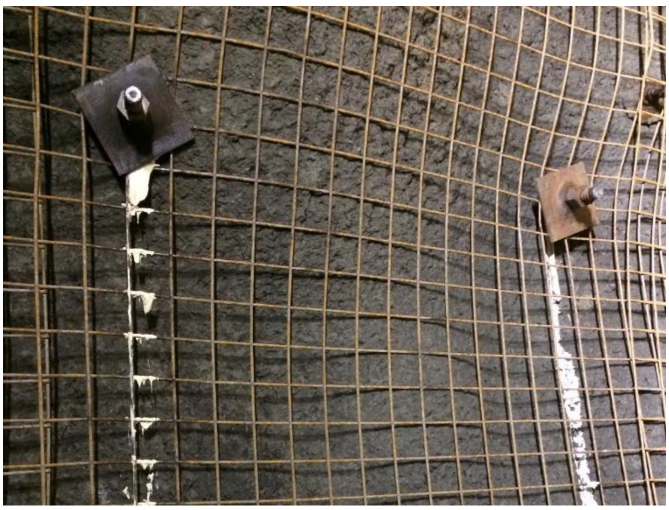

Figure 27. Self-drilling bolts installed with pumpable resin as seen in Malmberget.

Both components are dangerous chemicals to work with, in the section below the hazards and protective measures are discussed. This will be done for the A and B component, all the data used are from the safety data sheets of Minova. Component B is the more dangerous component of the two, it contains isocyanates. These are toxic and may cause cancer, it is therefore necessary to avoid inhalation and skin contact. The hazard identifications for component A and B are from the safety data sheets of Minova, the hazard identifications can be seen in Table 3 and Table 4 (Minova, 2017d). These hazard identifications are according to the European regulation on the classification, labelling and packaging of substances known as the CLP regulation (ECHA, 2018). All the pictograms used are according to European CLP regulation, the pictograms are retrieved from (REACH, 2018).

Table 3. Hazard identifications for Carbothix component A.

Hazard identifications for component A			
GHS05 *Corrosion*		*GHS07* *Danger*	
Skin Corrosion 1A, causes severe skin burns and eye damage.		*Acute Toxicity 4, harmful if swallowed.*	
Eye Damage 1, causes serious eye damage.		*Skin Sensitisation 1, may cause an allergic skin reaction.*	

Table 4. Hazard identifications for Carbothix component B.

Hazard identifications for component B			
GHS08 *Danger of systematic health hazards*		*GHS07* *Danger*	
Respiratory Sensitisation 1, may cause allergy or asthma symptoms or breathing difficulties if inhaled.		*Specific target organ toxicity (single exposure) 3, may cause respiratory irritation.*	
Carcinogenicity 2, suspected of causing cancer.		*Skin Irritation 2, causes skin irritation.*	
Specific target organ toxicity (repeated exposure) 2, may cause damage to organs through prolonged or repeated exposure.		*Skin Sensitisation 1, may cause an allergic skin reaction.*	
		Eye Irritation 2, causes serious eye irritation.	
		Acute Toxicity 4, harmful if inhaled.	

Special information
The vapour pressure of component B at 20°C is 0.00001 hPa, this means that the component does not evaporate intensely at 20°C (Halpern, 2018). The release of isocyanates is limited at temperatures below 20°C, this changes if the component is heated.

Toxicology information
Component B contains isocyanates, these are extremely harmful when inhaled or in case of skin contact. The substance is suspected of causing cancer and when exposed repeatedly it may cause damage to organs due to specific target organ toxicity (Minova, 2017d).

4.1.1 Protective measures
All the personnel working with the isocyanates should be informed about the risks and have the knowledge of how to work safely with the resin. Training is required for employees whose work may expose them to hazardous chemical products. This training shall at least inform them about all the risks involved and which protective measures to take. The training must be verified through a certificate which describes the element included in the training, this must be done at least every 5 years. The employees will undergo a medical examination offered by the employer according to the Swedish work environment authority (SWEA, 2014). The following personal protection equipment measures should be taken when working with the resin. General protective and hygienic measures should be taken into account. Protective gloves and eye protection in the form of tightly sealed goggles is advised. The gloves should be made of Nitrile rubber (NBR) or Fluorocarbon rubber (Viton). The penetration time of the glove material has to be found out by the manufacturer of the gloves and has to be observed. Respiratory protection must be available at all time in case of fire, a respiratory filter device in case of low pollution or brief exposure. In case of intensive or longer exposure, a self-contained respiratory protective device should be used. It is advised to install a self-contained respiratory device in all equipment handling component B and educate employees on how to use these (Minova, 2017d).

4.1.2 Handling requirements
When handling and storing the component the following measures should be taken:
- *Ensure good ventilation/exhaustion at the workplace*
- *Prevent the formation of aerosols and vapours*
- *When aerosols occur, always wear protective breathing equipment*
- *Provide signs that indicate hazardous chemical substances*

4.1.3 Storage requirements

- *Store in a tightly closed, dry and well-ventilated place. If component B becomes damp CO_2 is generated, the pressure increase can result in an explosion*
- *Do not store with: Acids, amines or products containing amines*

Always keep a self-contained respiratory protective device available. To prevent an accidental release of the material, it is advised to store both components in containers that are difficult to penetrate. Steel plated containers for example when using 1000 litre tanks.

When it is needed work on the resin system it is needed to empty it, this is done by flushing the system with a fuel oil. The mixture and the fuel oil should be collected in tanks which should be disposed of as hazardous waste.

If an accidental release happens the following measures are advised:

- *Ensure adequate ventilation*
- *Wear protective clothing, keep unprotected persons away*
- *Mount self-contained respiratory protective device*

Component A causes a particular danger of slipping on the leaked product.
The environmental precautions state that it is not allowed to enter sewers, surface or groundwater. Contaminated water should be collected separately and disposed of according to official regulations.

For containment and cleaning the following procedures are stated:

- *Absorb with liquid-binding material (sand, diatomite, acid binders, universal binders, sawdust).*
- *Dispose of contaminated material as waste according to official regulations.*
- *Ensure adequate ventilation.*
- *Use a neutralizing agent for component A, the chemical reaction of component A with water leads to an increased pH-value.*

4.1.4 Firefighting measures,

During heating or in case of fire poisonous gasses are created, therefore always wear breathing equipment and protective overalls. All personal trained for firefighting should be educated in the risks involved with the resin. Suitable extinguishing agents are: dry extinguishing agents, foam, carbon dioxide (CO_2) and water sprays. Contaminated extinguishing agents must be collected and disposed of separately. Cool endangered containers of component B with water. If the material overheats, there is the danger of gaseous decomposition products being released. This decomposition of component B could result in an explosion of the container. The components do not present an explosion hazard (Minova, 2017d).

4.1.5 First aid measures include the following

Symptoms of poisoning may occur after several hours, therefore medical observation is needed for at least 48 hours after the accident occurred. Remove any clothing that is soiled with the product. All the first aid measures are stated on the safety data sheets of Minova.

After inhalation, supply fresh air and if required provide artificial respiration. Keep the patient warm and call for a doctor if symptoms persist. In case of unconsciousness place the patient in a stable side position for transportation.

After skin contact, immediately wash with soap and cold water, rinse thoroughly.

After eye contact, rinse opened eye for several minutes under running water consult a doctor afterwards if symptoms persist.

After swallowing, Drink plenty of water and provide fresh air and immediately call for a doctor. Do not induce vomiting when component A is swallowed, only rinse mouth.

4.1.6 Risk analysis

The biggest risks for working with pumpable resin are analysed in Table 5. The consequence level, probability factor and risk rating can be seen in Appendix A. An uncontrolled spillage of the resin has the highest residual risk, this would affect the production and possibly require everyone cleaning up and working in air affected to wear protective breathing equipment. The following information gaps are identified: emergency clean-up plan, redesign tank coupling, water vapour extinguishing system, ventilation plans.

Table 5. Impact table – 'High Performance' resin.

Aspects	Impacts	Inherent risk			Mitigation measures	Residual risk			Comments/information gaps
		Consequence	Probability factor	Risk rating		Consequence	Probability factor	Risk rating	
Health resin									
Spillage	Small/controlled spillage at tank coupling, human contact with resin components. May cause allergic skin reaction or cancer in case of repeated exposure	Level 3	Level 5	1000	Redesign coupling system so spillage is minimazed. Ensure correct PPE and training for all personnel working with the resin.	Level 1	Level 3	10	Redesign tank coupling
	Big/uncontrolled spillage, making the workplace unaccesable without proper equipment. Loss of production, enhanced risk of achieving dangers levels of earosols	Level 3	Level 3	100	Ensure the use of adequate containers. Ensure adequate ventilation. Follow contingency plans for immediate clean-up of resin.	Level 3	Level 2	30	Emergency clean-up plans
Fire	Resin catching fire, uncontrolled release of isocyanite gasses. May cause cancer or damage to organs in case of repeated exposure	Level 5	Level 2	300	Use self-contained respiratory device. Resin storage away from areas with a high probability for fire. Ensure adequate ventilation	Level 1	Level 2	3	
	Resin in containers heating up, resulting in increase in pressure and danger of explosion	Level 4	Level 2	90	Cool endangered containers with water. Store containers in fire-proof areas.	Level 1	Level 1	1	Create vapour extinguishing system
Air pollution	Release of small amounts of isocyanite gasses when mixing resin, may cause cancer or damage to organs in case of repeated exposure	Level 3	Level 4	300	Ensure adequate ventilation. Follow standard operational procedures. Educate personnel in working with the resin.	Level 3	Level 1	10	Adequate ventilation plans
	Formation of earosols and vapours, may cause breathing difficulties and may cause cancer	Level 3	Level 4	300	Ensure adequate ventilation. Never pressurize containers. Follow standard operational procedures. Educate personnel in working with the resin.	Level 2	Level 2	9	
Safety of installation									
Installation quality	Bolt is not fully grouted, resulting in ineffective support	Level 2	Level 4	90	Install another bolt next to the failed bolt.	Level 1	Level 1	1	
Environmental									
Spillage	Big/uncontrolled spillage, resin contaminates mine water. May lead to increased pH-values.	Level 4	Level 3	300	Collect separately and dispose according to regulations. Follow contingency plans for immediate clean-up of resin. Neutralize increased pH-values.	Level 1	Level 2	3	Emergency clean-up plans

4.2 Portland cement

Portland cement is a standard ready to mix concrete with a high early-strength. It is mixed with water at a predefined water to cement ratio, the ratio influences the strength. It reaches a strength of 28 MPa after 24 hours and up to 60 MPa after 28 days (Kristjansson, 2014).

When installing cement grouted rock bolts an operator has to take in mind some health, environment and safety concerns. When cleaning the rock bolter with a high-pressure water hose, the operator has to make sure to wear proper eye protection. Cleaning the mixing equipment parts of the rock bolter is done outside of the mixer, these heavy parts should be lifted out of the mixer in a correct manner. The rock bolter should also be moved away from the unsecured face, the cement needs 4 to 8 hours to cure. When refilling the cement container, protective measures must be taken to minimize the chance of cement powder getting in your eyes and lungs (NewBoliden, 2018).Table 6 shows the following hazard identifications for Portland cement according to the safety data sheet of Hanson Cement (HansonCement, 2015).

Table 6. Hazard identifications for Portland cement.

Portland cement			
GHS05 *Corrosion*		*GHS07* *Danger*	
Skin Irritation 2, causes skin irritation.		*Skin Sensitisation 1B, may cause an allergic skin reaction.*	
Eye Damage 1, causes serious eye damage.		*Specific target organ toxicity (single exposure) 3, may cause respiratory irritation.*	

4.2.1 Protective measures

When loading dry cement in the container on top of the bolter all measures should be taken to minimize the forming of dust, it is advised to wear protective goggles and gloves. When mixing the cement the same protective equipment should be used, dust can occur when mixing the cement. Cleaning the wet cement from the bolter should be done wearing tightly sealed goggles, protective gloves and general protective equipment, the high water pressure causes the cement to be propelled in all directions. These measures are according to the standard operating procedures at Boliden.

4.2.2 Handling requirements

When handling and storing the component the following measures should be taken:

- *Ensure good ventilation/exhaustion at the workplace*
- *Prevent the formation of flue dust*

4.2.3 Storage requirements

- *Store in a tightly closed and dry place such as a container*
- *Do not use aluminium containers*

If an accidental release happens the following measures are advised:

- *Ensure adequate ventilation*
- *Wear protective clothing, keep unprotected persons away*
- *Respiratory protective device is needed in situations with high dust levels*

The environmental precautions state that it is not allowed to enter sewers, surface or groundwater. Contaminated water should be collected separately and disposed according to official regulations (HansonCement, 2015).

For containment and cleaning the following procedures are stated:

- *Use dry methods to clean-up if possible, vacuum exhaust systems that do not create dust*
- *Try to reuse the spilt cement/binding agent*
- *Avoid inhalation of dust and skin contact*

4.2.4 Firefighting measures,

No special measures are required, cement/binding agents do not pose any fire-related hazards. They are non-combustible and non-explosive, will not facilitate or sustain the combustion of other materials.

4.2.5 First aid measures include the following

No special personal protective equipment is required for first aid providers, they should avoid contact with wet cement. These measures are a combination of measures stated on the safety data sheet and standard operating procedures at Boliden.

After inhalation, dust should be removed quickly from nose and throat. Seek fresh air and call for a doctor if symptoms persist.

After skin contact, immediately wash with water and rinse thoroughly. Remove contaminated clothing and clean these thoroughly before re-using them. Seek medical treatment in all cases or irritation or burns.

After eye contact, do not rub eyes dry this may cause damage to the cornea. If applicable remove contact lenses and rinse open eye under running water for at least 20 minutes. Use isotonic eye-cleansing solution if available, consult a doctor afterwards.

After swallowing, wash out mouth and drink plenty of water. Do not induce vomiting and immediately call for a doctor.

4.3 Resin cartridges

Lokset resin cartridges are capsules with two compartments, one contains the resin the other part contains the catalyst. The resin is thixotropic and fast setting, ranging from 15 seconds to 10 minutes. Depending on the cartridge that is used, this allows for immediate tensioning of the rock bolt. The resin has a strength of 25 MPa after 2 hours and reaches a final strength of 35 MPa after 24 hours (Minova, 2016). With the installation of resin cartridges there are less health, environment and safety risks than with the pumpable resin. The biggest risk with resin capsules consist out of the resin capsules breaking, getting in contact with the resin may cause cancer and damage organs. It is mandatory to wear gloves and long sleeves when working with resin. Handling the resin capsules should be done with care. The capsules are small so the limits the amount of resin that can leak if one breaks. If the product is correctly used then a hard plastic composite is formed, in which the hazards associated with the product before use are minimal after use. All the data about the measures and requirements for working with the Lokset resin cartridges is compiled from the technical and safety data sheets of Minova. A Lokset resin cartridge has the following hazard identifications according to the safety date sheet of Minova, this can be seen in Table 7 (Minova, 2016; Minova, 2017c).

Table 7. Hazard identifications for a Lokset resin cartridge

Lokset resin cartridge			
GHS08 *Danger of systematic health hazards*		*GHS07* *Danger*	
Skin Irritation 2, causes skin irritation.		*Eye Irritation 2A, causes serious eye irritation.*	
Carcinogenicity 1A, may cause cancer.		*Specific target organ toxicity (repeated exposure) 2, may cause damage to organs through prolonged or repeated exposure.*	
		Acute aquatic toxicity 2, Toxic to aquatic life	

4.3.1 Protective measures

The following personal protection equipment measures should be taken when working with the resin. General protective and hygienic measures should be taken into account. Protective gloves and eye protection is advised. The gloves should be made of a material that is impenetrable, in case of the cartridge leaking. If there is a risk of inhalation, wear an organic vapour or particulate respirator device. Ensure adequate ventilation to the working place, the vapour is heavier than air therefore prevent the concentration of vapour in slumps (Minova, 2017c).

4.3.2 Handling requirements

When handling and storing the component the following measures should be taken;

- *Ensure good ventilation/exhaustion at the workplace*
- *Prevent the formation of aerosols and vapours*
- *Avoid skin and eye contact and breathing in vapour*
- *All open sources of ignition must be eliminated, flameproof equipment is necessary*

4.3.3 Storage requirements

- *Store in a cool, dry and well-ventilated place, keep away from sunlight*
- *Store away from sources of heat*
- *Keep containers closed when not in use*

If an accidental release happens the following measures are advised:

- *Ensure adequate ventilation*
- *Shut down all possible sources of ignition*
- *Wear protective clothing, keep unprotected persons away*
- *Mount self-contained respiratory protective device*

The environmental precautions state that it is not allowed to enter sewers, surface or groundwater. Contaminated water should be collected separately and disposed of according to official regulations.

For containment and cleaning the following procedures are stated:

- *Absorb with liquid-binding material (sand, universal binders, sawdust).*
- *Dispose of contaminated material as waste according to official regulations.*
- *Use non-sparking tools*

4.3.4 Firefighting measures

Use normal foam or dry agent as extinguishing medium. It is a combustible paste, on burning it will emit toxic fumes such as oxides of carbon. Firefighters should wear self-contained breathing apparatus and suitable protective clothing. Containers with the resin should be cooled with water sprays. Do not use heavy water streams, they may help to spread the fire.

4.3.5 First aid measures include the following

Symptoms of poisoning may occur after several hours, therefore medical observation is needed for a prolonged period after the accident occurred. Remove any clothing that is soiled with the product.

After inhalation, supply fresh air and if the person feels unwell call for a doctor. Keep at rest until fully recovered.

After skin contact, immediately wash with soap and cold water, rinse thoroughly. Obtain medical attention if irritation develops.

After eye contact, rinse opened eye for at least 15 minutes under running water consult a doctor afterwards.

After swallowing, only rinse mouth, do not induce vomiting. When natural vomiting occurs, rinse mouth and give plenty of water. Immediately call for a doctor or poison centre.

5. Quality of installation

The quality of installation of a bolt is a qualitative measure on how well the bolts are installed and encapsulated. This is highly dependent on the material used to encapsulate the bolt. The quality of installation is discussed for each of the grouts that in discussed before. The installation quality is compared for the standard operating procedures at Boliden. The main encapsulation methods nowadays are either resin or cement, both have certain advantages and disadvantages.

5.1 Cement grout

Cement grout is grout based on Portland cement, mixed with a 0.35 to 0.40 water to cement ratio. One of the biggest advantages of pumpable cement grout is the ability to fill cracks and voids, cement grouted bolts are therefore almost always fully encapsulated. Cement grout offers great protection against corrosion when fully encapsulated (Çeliker, 2012; Fishman, 2015). The mixing of the grout has to be done according to the standard operating procedure; if the mixing is done poorly lumps of cement can blockade the hose. Cement grout cannot be used in wet boreholes because the cement will flow out and not encapsulate the bolt properly. The curing time of most cement grouts is between 4 to 8 hours depending on the use of retarders. Retarders are used to minimise the chance of cement hardening in or on the bolting equipment. The long curing time means that cement grouted bolts cannot be pre-tensioned and the face is not yet secure. Cement grout is the cheapest grouting method currently available, it only uses cement and water (NewBoliden, 2018).

5.2 Resin cartridge

The main advantage of using resin cartridges over cement is the fact that resin cartridges can be used in boreholes with water inflow. These cartridges can have different hardening times from 20 seconds up to several minutes, this enables the ability to pre-tension the bolt when needed. If correctly installed it protects the bolt from corrosion and the resin is unaffected by vibrations (Maepa, 2017). One of the disadvantages of resin cartridges is that it is harder to encapsulate the whole bolt correctly. This can happen due to incorrect mixing durations or if the plastic from the cartridge wraps around the bolt. It is not possible to check if the resin is correctly mixed without destroying the bolt (Bharti, 2014). The annulus size is important for the correct mixing of the resin, the optimal thickness is between 3-4mm wide (Ulrich, 1989). Another disadvantage of using cartridges is the fact that the operator has to estimate how big the cracks/voids in the hole are. Underestimation results in poor encapsulation of the bolt and overestimation results in wasting material and leaking of unmixed resin which is dangerous. Resin cartridges are more expensive than cement grout when installing a bolt (NewBoliden, 2018).

5.3 Pumpable resin

The main advantage of pumpable resin is that it has the ability to fill cracks and voids, if there are voids the operator just pumps more resin. Full encapsulation can visually be checked by the operator by looking if resin is visible at the bolt plate. The resin will always be mixed correctly with the use of a static mixer before the resin enters the bolt, the resin can be used in boreholes with water. Another advantage of pumpable resin is the curing time of the resin this is around 20 seconds. This ensures as with resin cartridges that the working area is safe after installation of the bolts. The bolts can be pre-tensioned directly after installation if this is needed. 1-step bolting is more beneficial if it is used in poor rock conditions or in combination with wire mesh. Self-drilling bolts are left in the rock, so in poor rock conditions the hole cannot collapse. Wire mesh needs to be installed overlapping, making it more difficult to find the drilled hole when using the cement grout and resin cartridge methods. Self-drilling bolts do not have this issue.

The 2-step method has a higher potential to be used in good rock conditions as this method is less expensive than the 1-step method. The main disadvantage of the pumpable resin is the fact that it is more expensive than cement and requires hollow bolts for installation. When using self-drilling bolts the optimal annulus size can be guaranteed every time because the drill-bits and bolts are configured by the manufacturer. Pumpable resin is more expensive than cement grout but expected to be cheaper than resin cartridges, there is no need for packaging. The price per bolt will still increase due to the fact that hollow bolts are needed. If self-drilling bolts are used the price of a sacrificial drill-bit has to be included (Epiroc, 2018; Minova, 2018).

6. Potential for automation of the installation process.

This chapter will describe the potential for automation in the rock bolting process. Automation in rock bolting has been a bit slow in catching on, this process is one of the most complicated in the mining sequence. With the elimination of process steps, fewer errors can occur and less human interference is needed. The first step in automation in the rock bolting process is the automated installation of one rock bolt. This is already achieved with the 1-step 'High Performance' method. After this the movement of the boom to the next position has to be automated. Moving the boom to the next position can be compared with fan drilling on production rigs. Automatic drilling is already being performed on production drill rigs, this system could be implemented onto rock bolters (Morton, 2018). Rock bolters would need a device to scan the work face and would need to have a predefined bolt installation layout.

This could result in a rock bolter that would work autonomously during the breaks and shift changes. This would be the most effective with the self-drilling bolts, these are the least sensitive to problems. If the alignment of the bolting tools is correct then the 2-step method could also be automated. The productivity gain will depend on the conditions of the mine operation, bad rock conditions can result in the incorrect installation of bolts. Automatic reloading of the bolt carrousel is a more difficult step to automate, this currently limits the automation capacity. Bolt delivery systems are being developed but they are still in research state (Duin, 2012; Epiroc, 2018). The overall effectiveness of the system would depend on the reliability of the system. The number of bolts installed without operator interference dictates the productivity gain. Rock conditions will have a big impact on this number, it is therefore hard if not impossible to give an estimate of the percentage of bolts that can be installed correctly. This has to be studied for each mine individually, since rock conditions will be different everywhere.

7. Rock bolting productivity

In this chapter definitions and methods to compare rock bolting productivity are described. As last different rock bolting methods are compared for methods common in Nordic countries.

The bolting process consists of a number of activities, the most time-consuming ones are logged for this study. All these events were divided into a number of categories to make it easier to calculate the productivity of the different methods. These categories were based on previous bolting productivity studies by Boliden, they have been adjusted to better suit the purpose of this study. These categories consist out of the following:

- Cycle time is defined as the time it takes to drill a hole, grout the hole, install a bolt and manoeuvre the boom to the next position.
- Method time is defined as the time all support activities at the face take such as painting the boreholes, filling the bolt carousel, repositioning and start-up/shut down procedures.
- Operator repair time is defined as the time it takes the operator to repair something on the bolter, for example replacing a hydraulic hose.
- Cement related time is defined as the time that is lost on making and cleaning the cement. The cleaning is done before every pause in bolting activity larger than 30 minutes, to prevent the cement from hardening on and in the machine. This also includes unproductive time due to cement, this is defined as time spent at the face not working because it is seen as useless to make a new batch of cement and clean the bolter afterwards. This happens when the bolter arrives at a new working face 60 minutes before the break or shift change.
- Restocking supplies is defined at the time it takes to travel to the bolt and cement storage and refill the bolter with bolts, cement and other supplies.
- Diesel-time is defined as the time it takes to drive from a working face to another working face or as the time it takes to drive from the storage to another face.
- Lunch & dinner breaks are defined as the time it takes to drive to the canteen, have lunch and drive back to the bolter.
- Maintenance & service is defined as the time the bolter is scheduled for planned maintenance, this also includes washing before maintenance.
- Operator delay time is defined as the time spent by the operators to move from above ground to the machines and vice versa, this is also called the ‘logistic delay’.
- Stand-by time is defined as the time spent not working because there was no new work order or the bolter is waiting for maintenance.

7.1 Comparison of methods

The productivity of rock bolting can be stated in different ways; the fleet utilization can be maximized or the face utilization can be maximized. When the fleet utilization is maximized the goal is to have the bolters operating at all time, this is only possible if there is no shortage of work faces. When the face utilization is maximized the bolting process is seen as part of the blast cycle and each step in that cycle must be performed as fast as possible (Gustafson, 2016). In the mining industry multiple faces can be open at the same time, the productivity is therefore measured in the utilization of the fleet. As shown in Figure 28 the productivity can be measured including different categories.

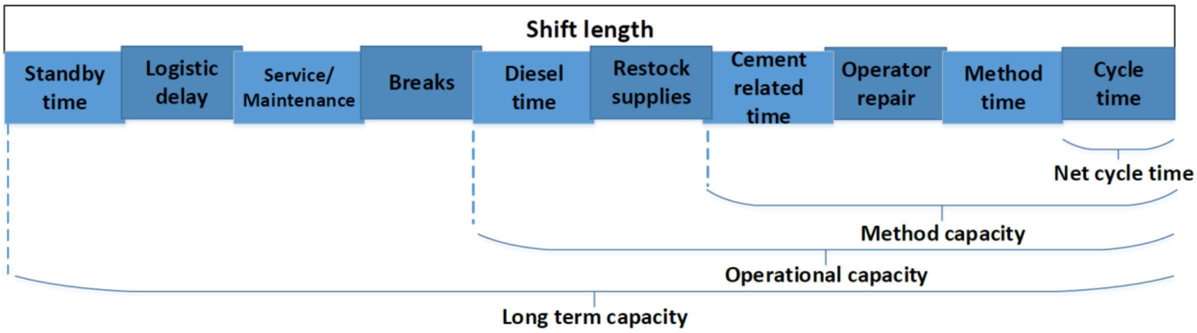

Figure 28. Rock bolting capacity definitions, adapted from (Gustafson 2016).

The net cycle time is the time it takes to install a bolt, this includes drilling, grouting and inserting the bolt. This can be best used to compare rock conditions and installation requirements. The method capacity is defined as the time spent working at the face. This is the net cycle time, method time, operators repair and the cement related time these are all the operating hours at the face. Comparing this still leaves room for deviations in some mine specific characteristics such as; operator skill, rock conditions and installation requirements. But the method capacity eliminates differences in working schedules, driving distances and resupplying the rock bolter, it focusses on the productivity when the rock bolter is in use and at the face. The operational capacity is defined as the productivity the bolter can reach when we exclude the standby-time, logistic delay, maintenance and dinner/lunch breaks. In the operational capacity all operations directly supporting the bolting are included. The operational capacity can be used to estimate the productivity during the possible working hours of a shift. The long-term capacity is the capacity that the bolter can reach during shift hours. The long-term capacity should only be used as a rough guideline to compare productivity between mines because too many factors influence this productivity. Comparing rock bolting equipment is best done when comparing the net cycle time and the method capacity, these leave most of the mine specific factors out of the calculation.

7.2 Rock bolting productivity in Nordic countries

A typical mechanized bolting operation in a mine in Scandinavia would have a long-term capacity between 4 and 6 bolts per hour, depending on the installation method and mine specific factors. The method capacity for bolting is between 8 and 19 bolts per hour (Gustafson, 2016). There are mine specific factors that make it difficult comparing the capacities between mines in a fair way. When comparing these capacities the rock conditions, installation requirements and operator skill should be taken into account. The numbers in Table 8 are from internal Boliden documents, these numbers are believed to be accurate for Nordic mines.

Table 8. Compiled from internal Boliden documents from Taavoniku & Karlsson and Gustafson, Schunnesson & Bejgarn.

	Expanding friction [Swellex]	Resin cartridge [Robolt]	Resin cartridge [Boltec]	Cement grout [Boltec]
Method capacity (bolts/hour)	13-19	9.7	8.76	10.99
Long-term capacity (bolts/hour)	5.69	5.86	4.47	5.75

There are a lot of factors influencing these bolting capacities but from field observations of the resin cartridges and cement method the following possible explanation can be given. From the data it can be seen that installing bolts with resin cartridges is the slowest, this is due to the refilling of the cartridges. Grouting with cement is a bit faster, time is lost on cement related activities but in between a high productivity can be reached. The installation of friction bolts is the fastest this is probably due to the fact that no resin or grout has to be used (Rocbolt, 2014). The long-term capacity shows that all the methods can reach between 4 and 6 bolts per hour, these numbers are a lot closer together because of differences in work schedules and operational priorities.

7.3 'High Performance' method

The productivity of a new bolting method can be estimated in different ways, this has to be done for the 'High Performance' method. Running field tests with equipment in the mine is the most expensive and time-consuming way of finding the productivity. It is therefore better to compare it with a method that looks like it and change the steps that are going to be different. Theoretical calculations should always be adapted to the specific mine conditions, therefore it is best to look at method specific steps that change. In order to estimate this for the 'High Performance' method a detailed time study has been conducted on cement rock bolters. This time study and calculation methods will be explained in the case study, the goal of the case study was to benchmark the new method. The initial goal of the 'High Performance' project was to install bolts twice as fast as the existing Kiruna bolt installation process. The Kiruna bolt is a dynamic rock support system as seen in chapter *2.5.6*, the installation was in this specific case done with wire mesh (Epiroc, 2018).

That the 1-step is expected to save around 30 seconds on not having to retract and insert the bolt but the drilling is expected to be slower due to the sacrificial drill-bits. These drill-bits are of lesser quality than drill-bits that can be used multiple times.

8. Summary of the methods

In this chapter a summary of the four rock bolting methods is given. The 'High Performance' method is a promising rock bolting method, it has quite a few advantages over the current methods. It removes the installation quality issues of resin cartridge and has a higher installation speed. When comparing it to cement grout the biggest advantage is the fact that there is no need to clean the system, the method also gives immediate support. The main disadvantage of the 'High Performance' methods are the costs of the resin and hollow bolts. It has to be observed if these prices drop when the method becomes mainstream. The residual health risks of the poly-isocyanates in the resin are another concern that has to be studied to make it as low as reasonably possible.

Table 9. Summary of the four methods.

	Cement grout 3-step	Resin cartridges 3-step	Pumpable resin 2-step	Pumpable resin 1-step
Curing time	4-6 hours	30 seconds	20 seconds	20 seconds
Sensitive to water	Yes	No	No	No
Price	Cheap	Moderate	Expensive	Expensive
Encapsulation checkable?	Visual	No	Visual	Visual
Mixing grade	Can form lumps	Can be incorrect	Always correct	Always correct
Cleaning needed	Yes	No	No	No
UCS/Strength?	28 MPa @ 24 hours	25 MPa @ 2 hours	20 MPa @ 30 minutes	20 MPa @ 30 minutes
Installation speed	11 bolts/hour	9 bolts/hour	[unknown]	12 bolts/hour*
Residual HSE risks	Medium	Medium	High	High

** The installation speed of the 1-step pumpable resin includes the installation of wire mesh and was measured during a trial, it is therefore lower than the expected final value.*

Residual HSE risks

Cement grout, the medium residual risk rating for cement grout arises from the unsecured bolts and from cleaning the rock bolter.

Resin cartridges, the medium residual risk rating for resin cartridges arises from the health concerns of the resin.

Pumpable resin, the high residual risk rating for pumpable resin arises from the health concerns of the resin. This is classified as high because the volumes are larger than when working with cartridges.

Part II - Case study – Rock bolting productivity at Kristineberg

The second part of the study is a case study about rock bolting productivity in Kristineberg. The rock bolting productivity will be linked to a possible production increase in the mine, at last the financial impact of this method is discussed.

9. Introduction

The installation of rock bolts at Boliden's Kristineberg mine is the bottleneck of their operation. The Kristineberg mine is an underground mine in the Skelleftea field, located around 150 km to the west of Skelleftea. The mine produces between 600-700 thousand tonnes of ore per year. The mine mainly uses the overhand cut and fill method, this is a small scale mining method that has a low productivity but a high selectivity. These rooms are backfilled after the ore is mined out, the backfill consists of waste rock and hydraulic tailings. The deepest level that is currently being mined in Kristineberg is at 1320 meters below surface (NewBoliden, 2018). Kristineberg uses five Atlas Copco rock bolting rigs at the moment, of which three use cement as grout and two use resin capsules as grouting. These cement bolters are going to be replaced in the coming years. The rock-bolters are expected to be the bottleneck of the operation that is why this mine site was chosen for the study. The aim of this part of this study is to analyse if this bottleneck can be resolved by implementing the 'High Performance' rock-bolting method. This is focussed on replacing the 3 rock-bolters that use cement as grout with the 'High Performance' bolters. In order to compare the cement bolters with the 'High Performance' bolters both machines have been observed underground.

These observations were used to estimate the productivity and calculate the possible impact on the mining production. The last chapter of the thesis will be a financial analysis of this method compared to the current method. For this study both the current and 'High Performance' method were followed underground. During this study the cycle times and with this the productivity of the methods was determined.

10. Methodology

This chapter describes the methods that are used to gather and process data about the rock bolting productivity. It also lists some assumptions and limits of these methods.

The methodology used for this thesis is based on multiple techniques. The combination of these techniques is set out to give a clear and complete picture of the rock bolting productivity. The rock-bolting processes would be best compared with each other if only the bolting method would be the changing variable. This is not feasible and realistic in an ongoing mining process, implementing this new rock-bolting method would carry huge capital costs and possible downtime of production (MOSIMTEC, 2013). Therefore calculations and simulation are used to estimate the changes on the production process.

10.1 Field observations

Field observations were done for the existing rock-bolting process as well as for the new to-be rock-bolting process. These field observations were done by the writer; during these observations the duration of processes was gathered. Breakdowns and unexpected events were also recorded. This to ensure that the model would represent the actual situation. These data were recorded for every step of the bolting procedure on minute scale.
For drilling the hole, grouting and inserting the bolt the time was recorded on a 5-second scale. These steps generally take less than a minute, to get a good overview of the rock bolting productivity more precise data were necessary. This way the productivity of the rock bolting methods could be compared more accurately.

10.2 Interviews

Interviews were held with operators, dispatchers and production planners to gain insight into the rock-bolting processes. All the operators were asked to record their start and end moments of the cement cleaning process and not the duration. Asking operators to record and report the duration could result in encouraging operators to speed up their cleaning procedure. This could have influenced the research. The cleaning times were recorded to get a more accurate average of this specific process. This process was chosen because it will be unnecessary when using the 'High Performance' method. Interviews were held to gather information about unplanned downtime, breakdowns and manoeuvrability of the rock bolter. This was done for the existing process as well as for the 'High Performance' process; this was done by conducting semi-structured interviews. This style was chosen to be able to go into detail why certain events happen and how often they happen (Zorn, 2005).

10.3 Dispatch system

Dispatch system data were analysed, these data were continuously gathered by the dispatch system 'Gantt'. This system tracks the tasks of the machines but the duration and moment are not detailed enough. Operators reported when they started and ended a work order, this lacks detail because of reliability concerns. Breakdowns were also recorded, these data were reported by the operators to a central dispatcher. The operators also reported how many bolts were installed each shift. These data were used to get an overview of what was happening during a shift but it was not detailed enough to base calculations on. It lacked detail because operators sometimes forgot to report the exact time and number of bolts installed (NewBoliden, 2018).

10.4 Telematics solution system

Production data were also gathered by a telematics solution system 'Certiq'. This system allowed to gather equipment information data on the machines real time. This system showed in detail the moments and durations of events. Everything that was logged was machine-system related, common downtimes due to external factors were not recorded. Events that were logged were for example: drilling time, water-pumping time, transmission and engine status. This system provided a detailed overview of what was done if there were no disturbances, disturbances were not recorded in the system.

10.5 Real-time location monitoring system

Real-time location monitoring was used in the Kristineberg mine, this system was mainly in place in case of emergency situations. This system was analysed to complement the data from Gantt and Certiq. The main benefit of using location monitoring was to know if an operator was driving to another working face or to the refilling storage. This could not be seen from the other systems.

10.6 Numerical analysis

All the numerical methods used to calculate the bolting productivity and the overall production were based on the time measurements. They consist in the general form of the principle that time saved with the 'High Performance' method was spent on activities directly related to the rock bolting operation. The calculation methods were a mixture of already existing methods and logical reasoning. They have been confirmed by experts at Boliden, together with them the probability of the solutions were discussed. These time measurement calculations were conform industry standards, they were adapted for the specific equipment and project requirements.

10.7 Limits of the data

There were some expected limitations on the accuracy of the data that were gathered. The field observations were the most precise but time-consuming to gather. Due to the time-consuming style of these data, the amount of data gathered with this method were limited. Smaller batches of data are more prone to outliers. The dispatch, telematics solution and real-time location system data are gathered more rapidly and in a higher volume. This increases the amount of data gathered and analysed, increasing the accuracy of the data. The accuracy of the data is increased because the increased amount of data decreases the impact outliers have on the data. There is a downside regarding the data gathered by the systems, there might be some misclassification between processes. It is believed that the combined data of the dispatch, telematics solution and real-time location system is accurate.

10.8 Possible bottlenecks and assumptions

The mine production increase may be limited due to other bottlenecks in the whole operation. For calculation purposes some assumptions have been made. The most likely bottlenecks and assumptions are listed below, including possible solutions.

- Rock bolting productivity is a bottleneck, this might be solved by using the 'High Performance' method
- Number of free work faces available is a possible bottleneck, this can be solved by creating more work faces. This would increase difficulties in planning and scheduling.
- Amount of available skilled personnel is a bottleneck for mines in the Nordics and can't be solved in the short term. Automation might be a solution but is not immediately available.
- For calculation purposes the 2-step 'High Performance' method is believed to have the same cycle and method capacity as the grouted cement method, the productivity gain is realised by the savings on the cement time.
- The hoisting limit is not a possible bottleneck because ore can be transported to the surface by trucks via the ramp.

11. Data collection

This chapter describes the how the data were collected and categorized to be able to compare it. This has been done for the field observations and for the data gathered from the equipments' onboard system.

11.1 Observations - Cement grout method

The shifts at Kristineberg started at 05:30 and at 15:00 with a production meeting above ground. After the meeting operators drove to their machines to arrive there around one hour later. The operators started the rock bolter and visually check the machine and working face for their conditions. The cement mixing would be started, after this the operator started refilling the carousel with bolts. After this the operator would install rock-bolts until +-30 minutes before lunchtime when the operator would start to clean the machine. The Lunch break took on average 1 hour including driving to the canteen and vice versa. The operator would continue installing bolts until +-90 minutes before the end of the shift, at this time he would start to clean the equipment again. They would leave the rock bolter +-60 minutes before the end of the shift. During the data collection in the field, the morning shift had been followed to get an understanding of their daily routine.
The morning shift had been followed because this was easier with planning and practical matters. It was explained to the operators that the goal of this study was to get a baseline for the bolting performance and that all the data were anonymous, this was done in order to make sure that the operation would be representative. All reasonable actions have been taken into account to ensure that the data collection process did not influence the daily operation.

The data gathered from field observations and the data that were logged by the described systems was entered into Excel for further processing. All the data gathered were from a machine utilization viewpoint, meaning that if the operator did a task not connected to the productivity of the machine it would be entered as unproductive work time. It was chosen to work from a machine utilization point of view because the machines are being evaluated. For the field observations the data were collected and entered into excel per shift, these data have the highest reliability. A typical shift would consist of over 150 data points. During a shift the start and end times of the following events would be gathered: shift start, arrival at the machine, making cement, drilling, grouting, refilling the carousel and cleaning of the cement. During the shift the number of bolts installed and common stoppages were also recorded.
All these events were divided into a number of categories to make it easier to calculate the productivity of the current method and compare this with the new method.

These categories consist out of the following;

- Cycle time is defined as the time it takes to drill a hole, grout the hole, install a bolt and manoeuvre the boom to the next position.
- Method time is defined as the time all support activities at the face take such as painting the boreholes, filling the bolt carousel, repositioning and start-up/shut down procedures.
- Restocking supplies is defined at the time it takes to travel to the bolt & cement storage and refill the bolter with bolts, cement and other supplies.
- Making cement is defined as the time that is lost when waiting for the grout to be properly mixed.
- Cleaning time is the defined as the time it takes to clean the bolter from cement. This needs to be done before every pause in bolting activity longer than 60 minutes, to prevent the cement from hardening on and in the machine. This is done according to the standard operating procedure of Boliden.

- Unproductive time due to cement is defined as time spent at the face not working because it is not seen as useful to make a new batch of cement and clean the bolter afterwards. This happens for example when the bolter arrives at a new work face an hour before the break or shift change.
- Operator repair time is defined as the time it takes the operator to replace a hydraulic hose or repair minor breakdowns on the bolter.
- Diesel-time is defined as the time it takes to drive from a working face to another working face or as the time it takes to drive from the bolt-storage to a new work face.
- Lunch & dinner breaks are defined as the time it takes to drive to the canteen, have lunch/dinner and drive back to the bolter.
- Maintenance & service is defined as the time the bolter is in planned maintenance or is reserved for maintenance.
- Logistic delay time is defined as the time spent by the operators to move from above ground to the machines and vice versa, this is also called the 'logistic delay'.
- Stand-by time is defined as the time spent not working because there was no new work order.

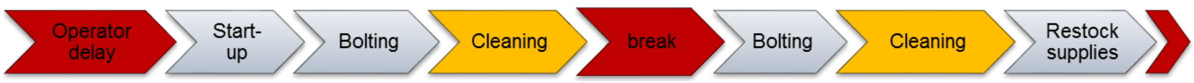

Figure 29. Example of typical cement bolting operations during a day.

In Figure 29, the typical operations during a day of bolting are shown, the lengths of the blocks do not represent the time spent on the tasks. The bolting operation includes cycle and method time.

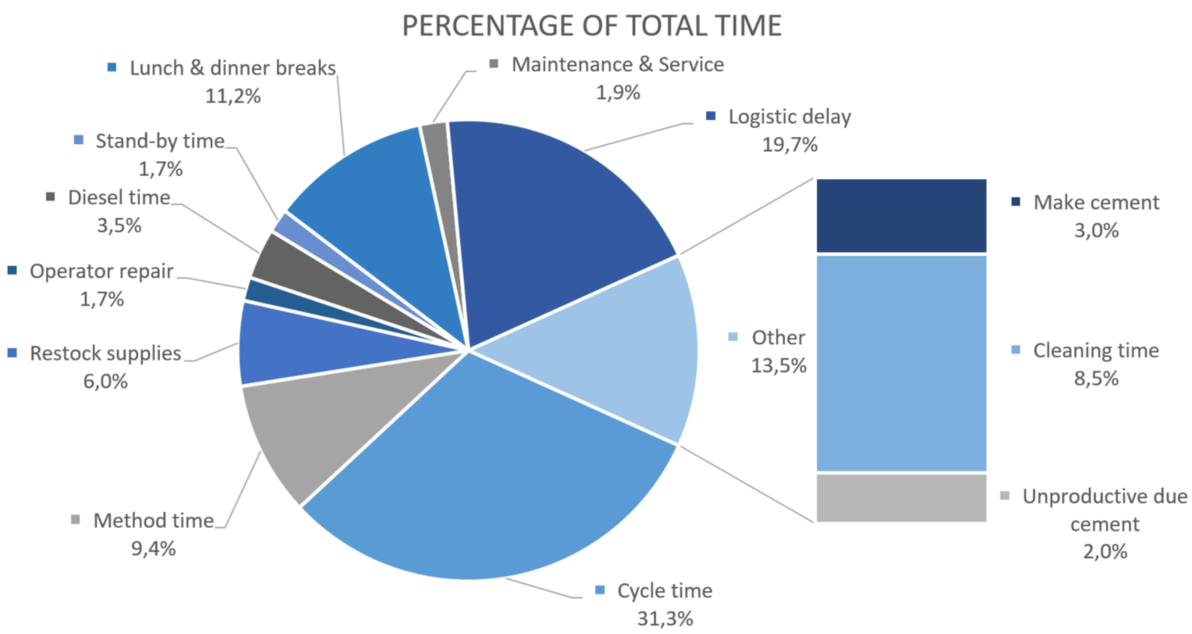

Figure 30. Division of time spent on bolting activities.

All the data were added together to get a better overview of an average shift. In total 94.6 hours were spent observing the cement bolters, while installing 519 bolts. During these shifts two different machines were followed with multiple operators. In Figure 30 an overview of the time spent on activities can be seen. The cement related time has been added together because this is likely to change with the 'High Performance' method.

During a part these observations the drilling, grouting and bolt inserting times have been logged on 5-second scale. This has been done for 55 bolts on multiple shifts to get a clear picture of the length of different steps in the cycle time. These observations are added together to get a total installation time per bolt, this cycle time has been compared with the cycle time we measured on a minute scale. There is a 9% difference in cycle time, this is most likely the result of differences in operator skill and rock conditions.

The categories mentioned above are used to calculate four different bolting productivity rates. Where the net cycle time consists of the time it takes to manoeuvre the boom, drill a hole, grout the hole and insert a bolt. The method capacity is the productivity that can be reached while working at the face. The operational capacity is the rate that the machine can reach while including all the operations necessary for bolting. The long-term capacity is the rate that the equipment can reach including all the operational steps. See Figure 31 for a detailed division of the operations and capacities.

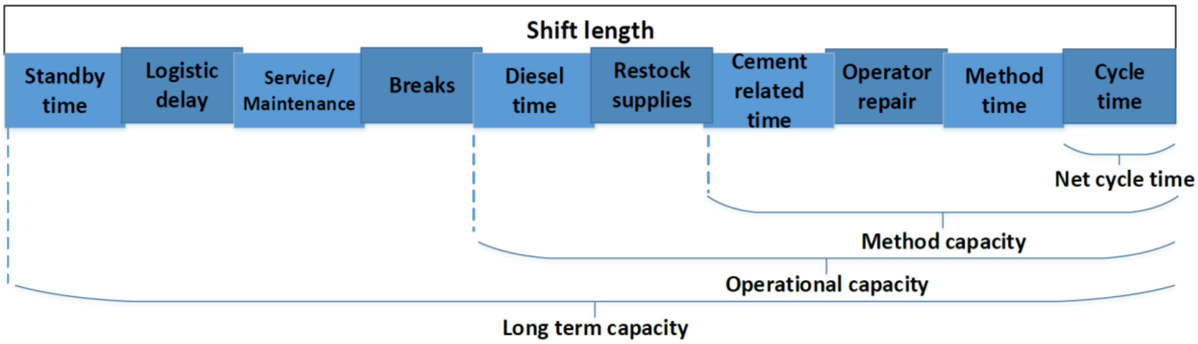

Figure 31. Rock bolting capacity definitions, adapted from (Gustafson, 2016).

The operators were asked to record the start and end times of the cement cleaning for the duration of a month. With the start and end times, the duration of each cleaning moment has been calculated. These durations can be used to estimate the productivity gain by not having to clean anymore, 118 data points were collected this way. The durations have been verified with personal observations and are believed to be accurate, there is an 8% deviation. The durations reported by the operators are shorter, they reported an average of 23.6 minutes. During the observations an average of 25.5 minutes was recorded, for the calculations the times reported by the operators will be used this results in a more conservative estimate.

11.2 System data - Cement grouted method

For the data gathered from Certiq and Gantt the same categories were used, except for the making cement category it was not feasible to estimate the time lost on this operation. During the mixing of the cement operators normally start working on other tasks so including this would lead to an overestimation of the possible productivity gain. The data of 2 machines were collected, the third machine was not connected to the Certiq system and could therefore not be analysed. The data gathered were read out of the Certiq web application here the diesel engine, tramming, pump and drilling activities are shown. In Figure 32, a screenshot from the utilization calendar is shown. Each row represents 1 day, when hovering over an event the exact start & end times and total duration are shown.

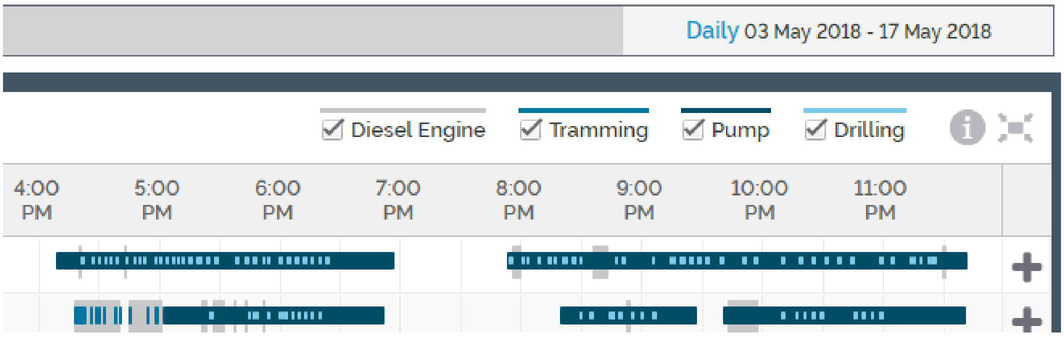

Figure 32. Screenshot of Certiq utilization calendar.

The data from the production scheduling in Gantt was analysed to get a better understanding of tasks performed by the bolters. These data were used to estimate the length and reason of repairs and stoppages. Data from Gantt also showed the working location and could therefore be used to distinguish between diesel-time and restocking supplies time. In Figure 33 one day is shown, purple activities are bolting, light grey is parking, red is unplanned reparations and dark grey are common stoppages these also include repairs by the operators.

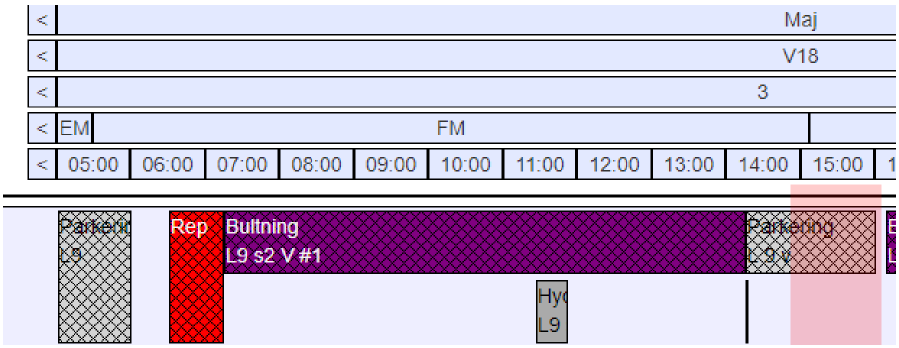

Figure 33. Screenshot of GanttScheduler web application.

The number of bolts installed and unplanned interruptions are reported to the dispatch centre, this information is shown when selecting a bar.

The data are gathered over a period of a month, both the morning and afternoon shifts are included to maximize the number of operators. Operator skill and efficiency have a big influence on the bolting productivity, this has been observed. Therefore it is needed to include as many different operators as possible to get a correct average.

In total 571 hours of working time were categorized, in this time approximately 2629 bolts were installed. This is the number of bolts reported by the operators, it is expected that there are errors in this data. The reported number of bolts by the operators over the period of a year has been compared with the number of drilling durations above 55 seconds recorded by Certiq. It was chosen to use 55 seconds as a minimum duration because some holes need to be re-drilled or the drilling function is used to loosen the drill-bit if it needs to be replaced. From the observed drilling durations it can be concluded that the minimum time to drill a borehole is around 80 seconds. The difference between the reported bolts and the number of drilled holes over the course of a year is 0.7%, therefore it is believed that the number of bolts reported is accurate.

11.2.1 Work start moments

The data reported by the operators to the dispatch centre was also used for two other purposes. These data are also stored in an online database which can be accessed and transferred to excel, this allows for analysing bigger quantities of data. These times that were analysed were still reported by the operators so there are errors in the data. There have been no changes in the work schedule or methods used in the last year.

From the Gantt data the current start time of bolting activities were analysed, this was done in order to estimate when operators would not start working on a new face. It can be seen that there are 2 peaks at the beginning of the shifts, it decreases until the lunch/dinner break is over. After this employees continue to start working until half an hour before they normally head up. From these observations it is concluded that there is resistance against starting new tasks when there is limited time left.

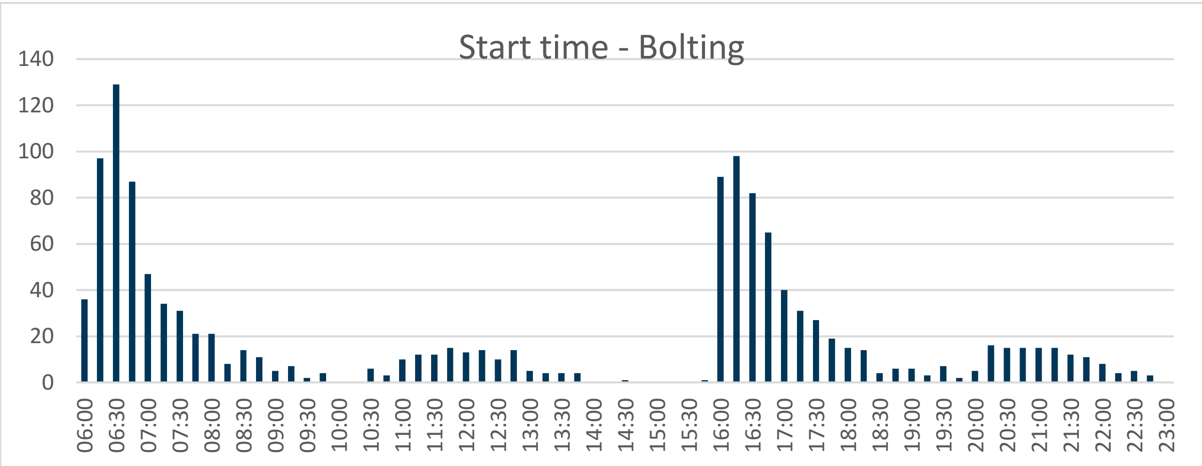

Figure 34. Reported bolting start times from 01/2018 until 06/2018.

11.2.2 Simulation input

For the simulation model the activity duration of the mining cycle steps were analysed, from this the mean, 10th and 90th percentile were of interest. The simulation works with a minimum, maximum and mean value for the time distributions, this time distribution is based on a triangular distribution. A triangular distribution was used because there was only a limited amount of data available and the data were so skewed that using a normal distribution would give a worse result (Petty, 2013). The mean, 10th and 90th percentiles gave the best representation of this triangular distribution. Using these percentiles was decided by iteratively comparing the average activity durations results of SimMine with the actual durations. This is the same method as used for another verified simulation model made by Boliden. The errors in these data were mostly filtered out by removing unrealistic outliers, these outliers were discussed with the mine planners. These outliers consisted mainly of moments where people forgot to report the end time or where people forgot to report they had started a task. The data analysed were from 06/2017 until 06/2018, the data were verified with the data from 03/2018 until 06/2018. The data of the last year were used in order to get an unbiased average and remove seasonal fluctuations.

11.3 Observations – High-Performance method

The new method was being tested by LKAB in their Malmberget mine, this is the second biggest underground iron ore mine in the world (Danielsson, 2016). When collecting data at a different mine there are certain process steps that change; it is therefore important to have an idea of the steps that stay the same. When LKAB was testing the 'High Performance' method, they were installing self-drilling bolts with mesh. This means that the cycle time, mesh handling time and the method time had to be measured separately. While doing the observations, the rock bolter stayed in the same place, the bolts and resin were delivered to the bolter. This means that no time was lost on getting supplies or on diesel-time. Due to the fact that the 'High Performance' method is a new method, some start-up issues occurred. This resulted in an inflated time spent on operator repairs. This meant that including the operator repair time would not reflect the situation as if the machine would run full production. For comparing the methods the percentage of time spent on operator repair of the current method was taken, as the design of the bolter is similar. Due to all these changes in the work process the observations were focussed on the cycle, method time and the time saved on cement related activities. The time saved on cement related activities would show up in a decrease in start-up and shut down time. As stated in chapter 8, the main difference between the methods is the need for cleaning and therefore the ability to be highly productive even when working for a short time.

Figure 35. Example of the 'High Performance' bolting operation.

The cycle and method time were recorded but as the rock conditions in Malmberget differ from the rock conditions in Kristineberg these values can only be used as a guideline. The observed installation rates have to be compared with the current rate at Kristineberg.

12. Data analysis

This chapter will describe how the data gathered were analysed. This will be done separately for the observed data and for the data from Certiq and Gantt. This is done because the confidence level is different for both data sets. The data gathered from Certiq and Gantt is less accurate, this is because small interruptions in the process cannot be categorized correctly. These data are however more reliable this is due to the amount of data collected this way. Together with the experts at Boliden it was decided that full shifts of planned maintenance would be left out of the data collection. During planned maintenance a backup machine is being used, keeping maintenance time in would distort the productivity calculation. The machines productivity during working hours would be affected and this is not the goal of this study.

12.1 Shift time

Shift time is defined as the whole shift, it starts when the operators arrive at the meeting room above ground and it ends ten hours later when they meet there again. It was decided to analyse the operators shift and not a whole day because changing the working schedule was not part of this study.

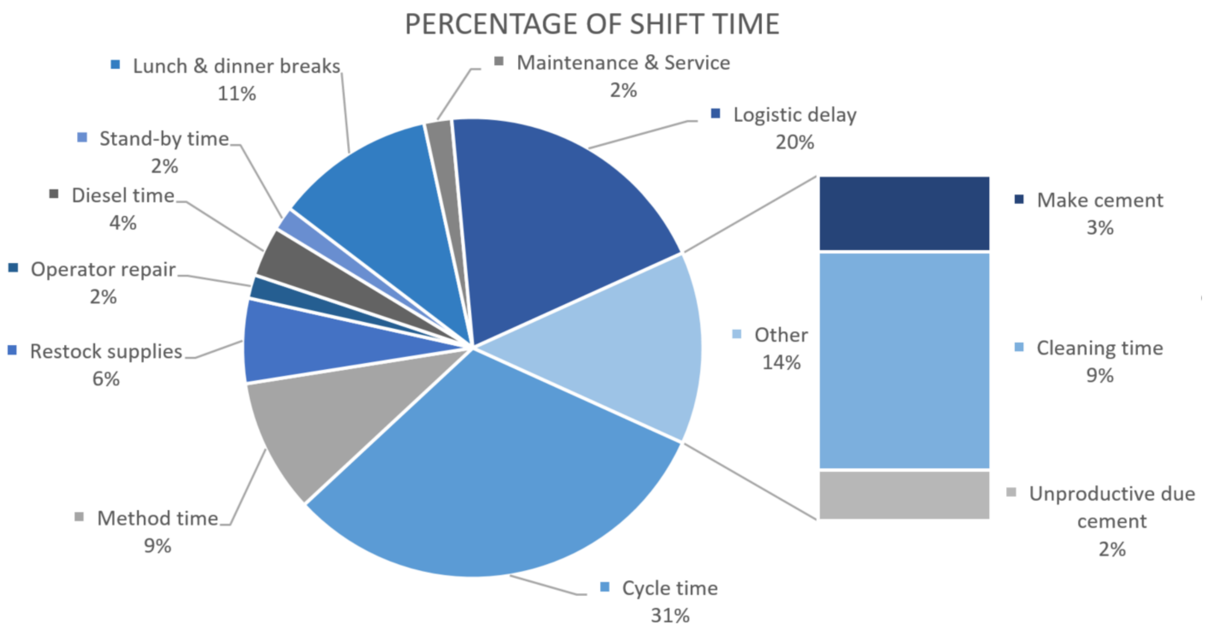

Figure 36. Division of time spent on bolting activities – Observations.

During the in-field observation 519 bolts were installed in 94.6 hours, this results in a long-term capacity of 5.5 bolts per hour. In Figure 36 the breakdown of activity durations are shown, cement related activities are grouped under ‘other’ to have a clear overview of these activities. The cycle time takes up only 31% of the shift time, this means that only 31% of the time is actually being spent installing bolts, 9% is spent on support activities at the face. The rest of the time is spent on other auxiliary tasks to enable the bolting process. Of the shift time 14% is spent on events that are cement related of which 9% is cleaning the machine.

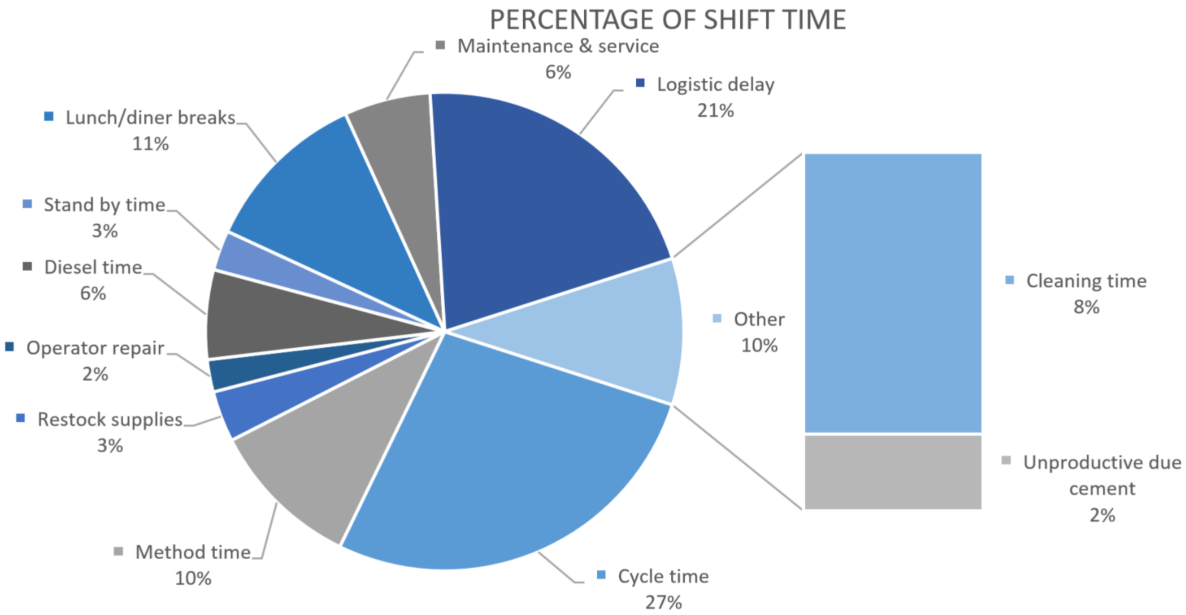

Figure 37. Division of time spent on bolting activities - System data.

During the data gathered via Certiq and Gantt 2629 bolts were installed in 571 hours, resulting in a long-term capacity of 4.6 bolts per hour. This is a bit lower than the observed data, it is believed that this is due to an increase in auxiliary operations.

Installing bolts takes 27% (vs 31%) of their working day, another 10% (vs 9%) is spent on support activities at the face. Lunch & dinner breaks and logistic delay are the same percentages as the observed data (11% vs 11%) and (20% vs 21%) respectively. The time spent on cement related activities decreased from 14% to 10%, this can be contributed to the fact that it is hard to estimate the time spent on making the cement (0% vs 3%). This all can be seen when Figure 36 and Figure 37 are compared.

The overall picture when comparing the total work time is that the data from Certiq and Gantt is believed to give an accurate representation of the reality. There are only minor differences in percentages, these can be contributed to multiple factors such as: operator efficiency, data interpretation inaccuracy and differences in work orders.

12.2 Operational time

The operational time has also been compared for the observations and the system data, this is done because there are fewer factors influencing the operational time. The operational time is defined as the time that the operator actually could have been working. This is the shift time excluding the lunch-, dinner-breaks, maintenance, logistic delay and standby time. These operations are not going to change when using a different bolting method, they would therefore just add noise. It is expected that the differences become percentage-wise larger but that the productivity is closer to each other, as there are fewer operations that influence it.

12.2.1 Observations

In Figure 38 it can be seen that 48% of the operational time is spent installing bolts and 14% on support activities at the face, a total of 62% is spent on bolting or direct support activities. The time spent on cement related activities has increased to 21% of which 13% is spent on cleaning the machine.

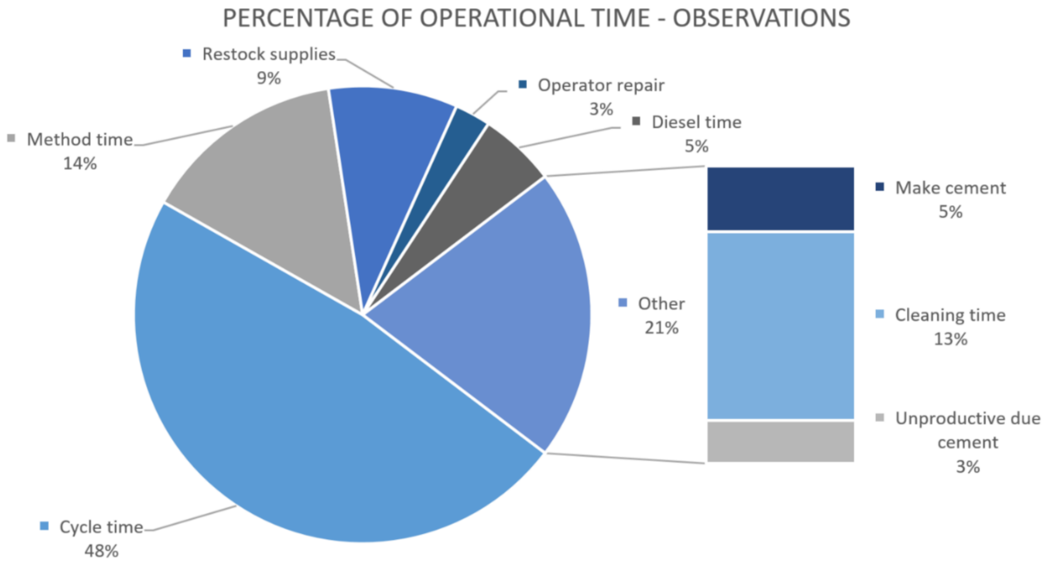

Figure 38. Division of time spent on bolting activities – Observations.

12.2.2 System data

The time installing bolts increases to 46% together with the method time of 17% a total of 63% of their operational time is spent on bolting or direct support activities. Cement related activities take up 17% of the operational time, 13% cleaning the cement and 4% due to not being able to begin work on a new face. The total breakup of the operational time is shown in Figure 39.

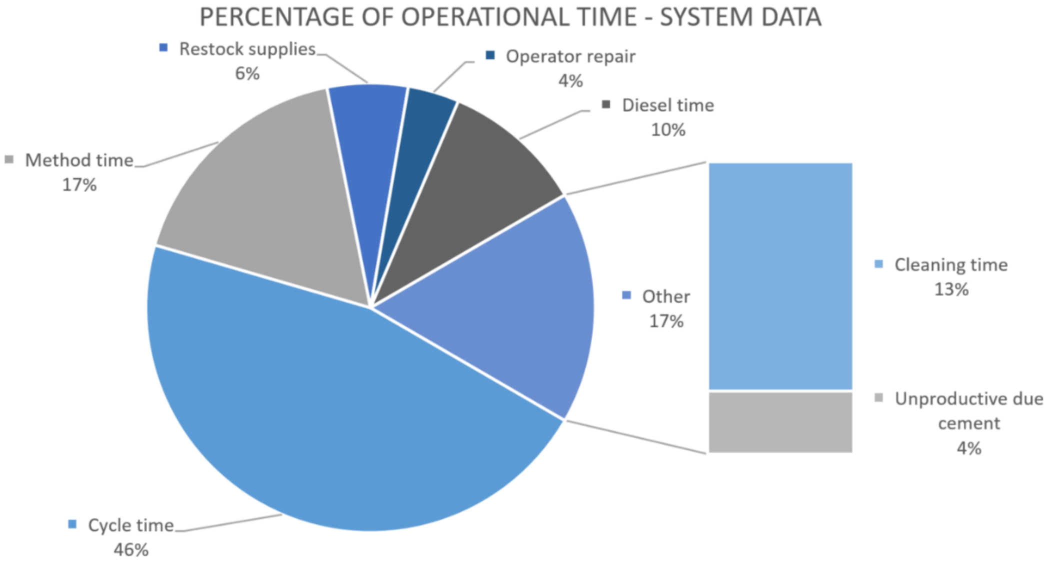

Figure 39. Division of time spent on bolting activities - System data.

When comparing the percentages of operational time spent for the observations and system data. The cycle time is close to each other, this is probably because this operation is well defined and easy to measure in Certiq. The biggest unexpected difference is in the diesel-time, this is probably because there is some miss-classification between the diesel-time and restock supplies time. The making cement time which is not included in the system data, is the cause for the lower percentage of cement related activities.

When comparing the bolting rate during the operational time we see that the observed rate is 8.4 bolts per hour and the system data has a rate of 7.8 bolts per hour. This difference is believed to be small enough to represent an accurate value, previous studies conducted in Kristineberg have found similar values (NewBoliden, 2018).

12.3 'High Performance' method - Observation at Malmberget

When comparing the observations between different mines it is needed to keep in mind that due to the differences in work organization, rock conditions and installation requirements it is not possible to compare the methods directly. Diesel and restocking time could for example not be recorded due to differences in work setup. During the observations the resin and rock bolts were delivered to the bolter and the bolter was scheduled to work at the same location for multiple shifts. It is evident that the time spent on repairs (34%) is too high for a realistic comparison between the methods; this is so high due to unexpected start-up issues with the new method. The bolting productivity during the cycle and method time is the best metric to compare the methods, it needs to be noted that rock conditions are different. The installation time of seven bolts has been observed on a second scale. This included the drilling and resin pumping time. The average drilling time was 141 seconds and the average resin pumping time was 44 seconds, resulting in 185 seconds per bolt. Compared to Kristineberg where the drilling took 104 seconds, cement filling took 47 seconds and bolt inserting took 38 seconds. Giving a total bolt installation duration of 189 seconds per bolt. It is known from previous projects that the productivity of new equipment will increase with operators getting more experience on the machine. It can take up to more than a year to fully capitalize on this, there are standard operating procedures but each operator tweaks this to her/his preference (NewBoliden, 2018). During the observations the 'High Performance' method reached 11.3 bolts per hour, this includes installing a bolt, refilling the carousel and other support activities at the face.
The final results of the test in Malmberget showed that the bolting productivity went up to 12 bolts per hour. Before the 'High Performance' method the productivity at Malmberget was around 6 bolts per hour. It is believed that the 'High Performance' method can reach 15 bolts per hour with a fully trained operator (Epiroc, 2018).

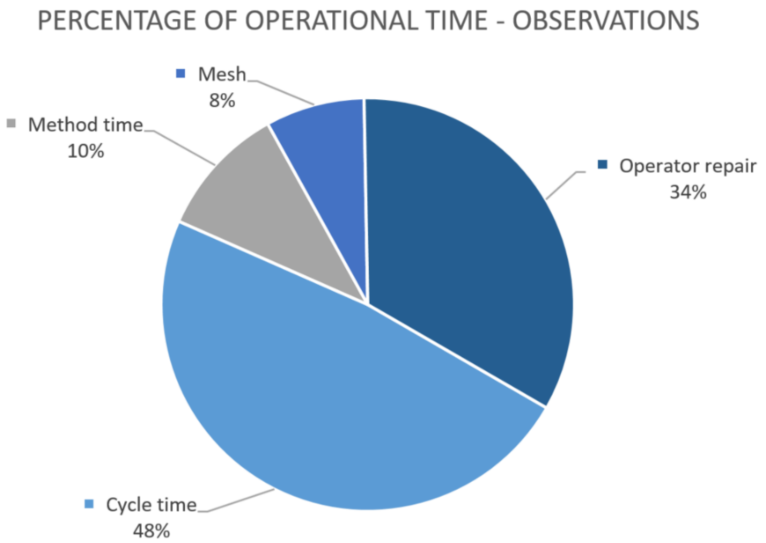

Figure 40. Division of time spent on bolting activities – Observations.

13. Results

In this chapter the results of the current rock bolting method are discussed, this is done for both the observations and for the system data. The 'High Performance' bolting productivity is also estimated. With the 'High Performance' productivity the possible increase in ore production is calculated, this is done with multiple methods.

13.1 Bolting productivity

In order to be able to compare rock bolting productivities it is needed to remove as many changing factors as possible. The only factor that should be different is the rock bolting method. The productivity of the time spent at the face would be easiest to compare with a different mining operation. As shifts schedules, breaks and logistics differ from mine to mine. If these productivities are compared it is necessary to keep in mind that rock conditions and installation requirements may differ and influence the productivity.

13.1.1 Current bolting productivity

The current productivity of the bolting method can be calculated with many different methods. For this study it was decided to use the number of bolts installed per time unit, specifically minutes per bolt and bolts per hour.

The calculations are done separately for the observed and system data, the observed data were used as a reference for the correctness of the system data. For the current bolting productivity the operational capacity is used. This rate is used because the lunch/dinner breaks, maintenance, stand-by and logistic delay times are not going to change by implementing the 'High Performance' method.

If the time spent on cement related activities could be used for bolting activities the bolting rate will increase. Currently the following activities are needed to have a functioning bolting operation; diesel-time, restocking supplies, cement related time, operator repair, method time and cycle time. This is defined as the operational capacity of the bolting method, as shown in Figure 41.

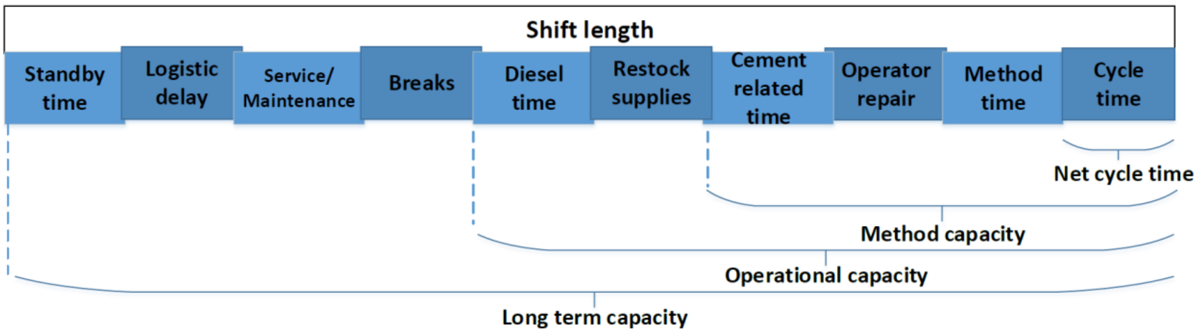

Figure 41. Rock bolting capacity definitions.

These capacities are calculated by adding the time spent on the activities included and dividing the number of bolts set by this time. The amount of bolts installed is the same for each capacity but the number and therefore time spent on activities changes. An overview of these capacities is given in Table 10, if fewer activities are included then the differences between the measurements get smaller.

Table 10. Measured rock bolting capacities.

	Observed data	System data	Difference
Net cycle time (seconds per bolt)	206	213	+3.4%
Method capacity (bolts/hour)	9.8	9.3	-5.1%
Operational capacity (bolts/hour)	8.4	7.8	-7.1%
Long term capacity (bolts/hour)	5.5	4.6	-16.4%

The 'High Performance' method is not included because the confidence level of that data is not in in the same order as the data from Kristineberg.

13.1.2 Future bolting productivity

To get an estimate of the operational capacity for the 'High Performance' method the operational time minus the time spent on cement related activities have been added together. These are the following activities; cycle time, method time, operator repair, restocking supplies and diesel-time. The number of bolts set has been divided by this time, the same method is used for the current productivity. The percentage of time spent on these activities will increase with the new rock bolting method. The machine will perform more bolting cycles in the same time span. This possible division can be seen in Figure 42. This gives a possible future rate of 10.6 bolts per hour for the observed data and 9.4 bolts per hour for the system data. These rates were multiplied with the time spent on cement related activities to get the number of bolts that could have been installed extra. A summary of the observed and system data is given in Table 11.

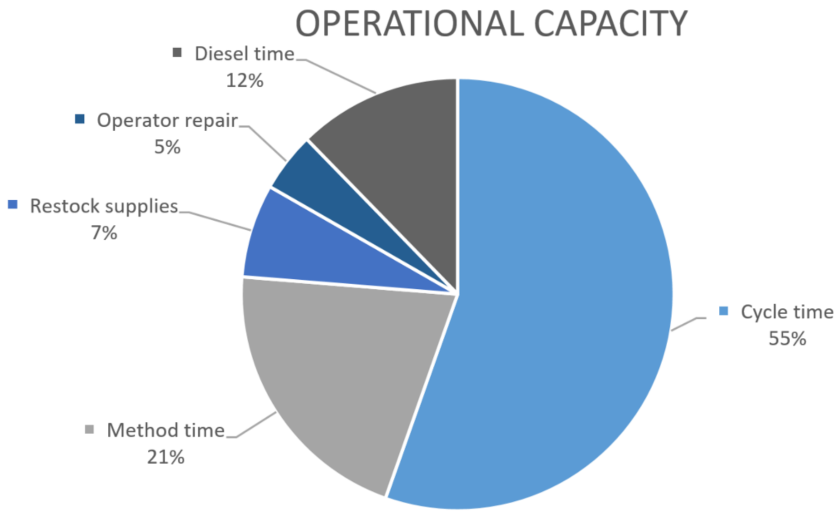

Figure 42. Possible 'High Performance' division of time spent on bolting activities.

Table 11. Possible operational capacity of 'High Performance' method.

	Observed data	System data
Current bolts installed	519	2629
Possible extra bolts based on cement time	135	528
Possible bolting productivity increase	26%	20%
Future operational capacity (bolts/hour)	10.6	9.4

The future operational capacity of the 'High Performance' method is not known for Kristineberg, it was decided that the operational capacity from above would be used as an estimation. For calculation purposes the productivity from the system data are used, these data are more conservative and is believed to be more accurate.

The installation of the bolt will be faster because there are fewer installation steps but the drilling time will increase, because of the increase in diameter of the new bolt. The new bolt is hollow, to retain the same properties the diameter has to be bigger. The cycle time, method time, operator repair, restocking supplies and diesel-time will percentage-wise increase due to the fact that the new method has a higher productivity.

13.1.3 Bolting duration of a face

The bolting capacity per hour is used to calculate the average bolting duration of a work face. In an average work face 58.2 bolts are installed, these data are reported by the operators. 207 data points were analysed, this was done for May 2018. The current method can bolt a work face in 7.70 hours, the 2-step resin method is expected to do this in 6.42 hours. This would result in a time reduction of 17%, this includes the time to get supplies and drive from face to face. It is important to include these auxiliary operations otherwise the improvement gets overestimated.

Table 12. Current and possible future face duration.

Operation including restock & diesel-time	Current method	2-step resin method
Operational capacity (bolts/hour)	7.78	9.35 (+20%)
Hours per face	7.70	6.42 (-17%)

The 20% in operation capacity will most likely not be fully utilized, we therefore cannot say that this is directly translatable to an increase in production. This method does not take into account any other possible bottlenecks but the results can be used in future calculations.

The same method has been applied the time purely spent at the face, so excluding the diesel and restock times. The mean reported time spent bolting at the face was 6.76 hours, the reported average working duration is 7.10 hours; these are from 1718 reported work faces. Both these durations can include lunch/dinner breaks and are reported by the operators so they are subjected to errors.

The calculated average working duration of a face is 6.47 hours, it is believed that this is accurate if we incorporate that lunch/dinner breaks are not included. With the 'High Performance' method the time spent at the face could decrease to 5.18 hours.

13.2 Mine production

The 'High Performance' bolting rate will be used to calculate the possible increase in ore production of the whole mine. This is important because an increase in production will lead to a financial benefit which could set off the extra costs of the new bolting method. The production increase can be calculated in different ways, these will be explained for each method.
There is a chance that it will not be possible to fully use the calculated increases in production due to several reasons. The most likely are the following: the increase is larger than the gap to the next bottleneck, inefficiency caused by operators not fully adapting to the new method and the loss of efficiency due to lack of available work faces. The different methods will be used to find the most likely case and verify each other. These different methods will be discussed with a panel of experts at Boliden.

In order to estimate the production increase we followed multiple calculation methods, these methods are chosen so we approach the problem from multiple sides. The ore production in a mine depends on a complex system, a productivity gain in one process might not lead to an increase in production. The process which is the bottleneck will constrain and dictate the output of the mine (Mathu, 2014), according to Boliden this is the rock bolting operation at Kristineberg. It is not known what or how big the gap is to the next bottleneck, it is therefore not known what the maximum production increase can be. To get an idea of how big the gap to the next bottleneck is, methods are used that incorporate some of these bottlenecks in the calculations. The limitations and benefits of each method will be explained at the corresponding method.

In all the calculations the bolting capacity includes getting supplies and moving from work face to another work face. The new method will work faster, therefore need more supplies and drive to new works more often. These are or incorporated into the bolting productivity or added as a fixed duration to each task that is performed. The mine production is calculated on the base of implementing 3 'High Performance' rock bolters and 2 currently used rock bolters.

13.2.1 Improvement probability

The second method focusses on the probability that the 'High Performance' method would lead to an actual improvement in productivity. This is done because not all the time spent on cement related activities can be used in an effective way to increase the productivity. This is done by calculating the probability that the equipment was cleaned while it could have continued working with the new method. And by calculating the probability that equipment did not start working because there was too little time to mix and clean the cement.

Figure 43. Example of a cement bolting cycle during a day.

To get an idea of these probabilities Certiq and Gantt data were analysed for the duration of a month. The number of cleaning moments when the equipment still had worked on the same face afterwards were counted and divided over the number of shifts checked. This percentage gives the probability that the 'High Performance' method is actually useful. The same was done for the unproductive time and moments the possible automation function could be used. The automation function will be discussed in chapter 13.4 as this is not the main goal of this study. These data were gathered for 108 shifts when the machines were operating, there were 171 moments it was cleaned unnecessary and 20 moments the time was seen as too short to start working again. This results in a 158% chance that the operators spent 23.6 minutes cleaning each shift, there is a 19% chance the operators could work for 50 minutes extra due to unproductive work time. The time spent cleaning is based on the average time reported by the operators, the unproductive work time is based on personal observations. The possible bolts installed per shift are based on a bolting rate of 9.4 bolts per hour, calculated in chapter 13.1.2. This number of bolts per calculation method can be seen in Table 13.

Table 13. Summary of the probability calculation.

	Chance	Time (minutes)	Bolts per shift extra
Cleaning	158%	23.6	5.8
Unproductive time	19%	50	1.4
Total			7.2

Currently 50.6 bolts are installed on an average shift, this has been calculated by multiplying the current bolting productivity by the average shift length. The 'High Performance' method would add another 7.2 bolts per shift this would result in a total of 57.8 (+14.4%). The new operational capacity would be 8.9 bolts per hour versus the 7.8 bolts per hour currently.

This increase would result in an 8.6% increase in the overall number of bolts installed. This is translatable into a production increase of 8.6%. This method does not take into account any other possible bottlenecks, it is just a more realistic approach to the productivity increase. Bottlenecks that could influence this increase are could include: the number of available faces, other mining operations and scheduling difficulties.

In Figure 44 is shown how the new process could look like, with the current method operators probably would not start the last bolting activity because of the limited amount of time left. Being able to bolt productively for a short time span also motivates the operators. During the observations it has been noticed that there is a big difference in productivity if an operator knows that high productivity is required, for example when a work face can be completed just before the shift change.

Figure 44. Example of a 'High Performance' bolting cycle.

13.2.2 *Blast cycle method*

One of the main concerns regarding bottlenecks at Kristineberg is the number of free work faces that are available (NewBoliden, 2018). This bottleneck can be incorporated into the calculation if the blast cycle as a whole is analysed. When the blast cycle as a whole operation analysed then it is clear that the bolting operation takes the longest, 6.47 hours. The whole cycle duration is 22.8 hours, this means in theory that it would take 22.8 hours to complete a cycle. In practice this takes longer because there is some delay between the operations, the machine utilization is more important than the face utilization. The average duration of each activity has been taken from +-1500 data points over the past year, these durations were reported by the operators.

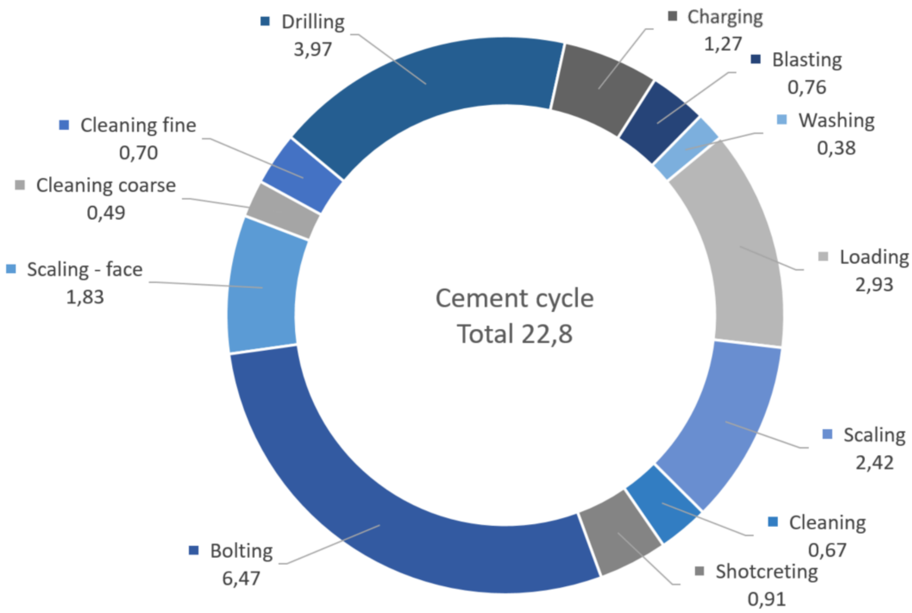

Figure 45. Current division of the blast cycle duration at the Kristineberg mine.

With the ‘High Performance’ method the bolting operation would take 5.18 hours, calculated in chapter 13.1. With this improvement the new total cycle time would decrease to 21.5 hours. This would result in an increase of 5.7% in blast cycles per ‘High Performance’ bolter. These divisions are shown in Figure 45 for the cement cycle and in Figure 46 for the ‘High Performance’ cycle. This increase in blast cycles means that a drift can be mined 5.7% faster, the number of available faces does not influence this. The total mine production could increase with 3.4% if 3 bolters were changed. The downside of this calculation method is that it does not reflect the full potential of the new bolting productivity. It neither shows which operation might be the next bottleneck in the blast cycle. This would result in a 3.4% increase in total mine production. The difference between the 20% bolting productivity and the 3.4% increase in production shows that the bolting operation has more time for support activities. Such as getting supplies, drive to the next working face, etc. this would make planning easier and the whole operation more reliable as tasks would start on their scheduled moments.

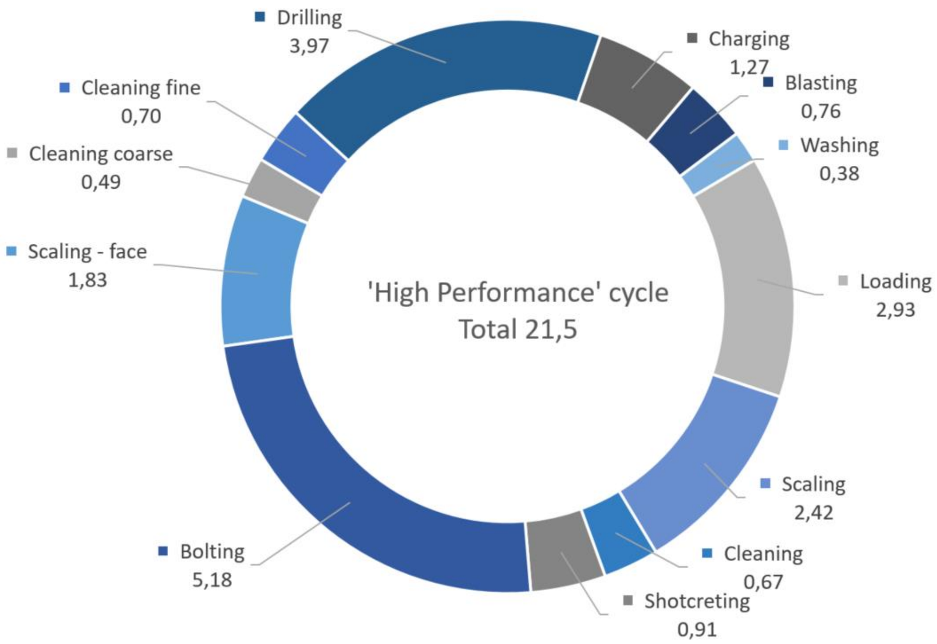

Figure 46. ‘High Performance’ method division of the blast cycle duration at the Kristineberg mine.

13.2.3 Scheduling optimization

In order to have an idea what the next machine bottleneck could be, the maximum possible number of faces per shift has been calculated. This is based on the duration of the activity including transport time, this gives a number of faces each machine can complete in a shift. Operators have been scheduled in the most optimal way to get an idea of the maximum possible production per shift. This is based on the current working time of 6.5 hours per shift, this is based on personal observations. The number of faces per week have been calculated to make comparing them the current productivity easier. Activities with the same colour are carried out by the same machines, these are grouped because switching between these tasks is easier. The same average activity durations are used as in chapter 13.2.2, these are retrieved from the dispatch centre.

In Table 14 the optimal shift schedule is shown for the current and 'High Performance' method.

Table 14. Optimized shift schedule current method vs 'High Performance' method.

	Current set-up			High Performance' set-up		
Activity	**Number of operators**	**Faces per shift**	**Faces per week**	**Number of operators**	**Faces per shift**	**Faces per week**
Scaling - face	1,20	3,47	48,6	1,20	3,47	48,6
Cleaning - coarse	0,50	3,58	50,2	0,50	3,58	50,2
Cleaning - fines	0,60	3,49	48,9	0,60	3,49	48,9
Drilling	2,20	3,26	45,6	2,30	3,41	47,7
Charging	0,90	3,47	48,6	0,90	3,47	48,6
Washing	0,50	4,08	57,1	0,50	4,08	57,1
Loading	1,70	3,30	46,2	1,80	3,50	48,9
Scaling	1,50	3,44	48,1	1,50	3,44	48,1
Cleaning	0,60	3,59	50,2	0,60	3,59	50,2
Shotcreting	0,70	3,43	48,0	0,70	3,43	48,0
Bolting	3,60	3,04	42,5	3,40	3,45	48,2
Maximum production			42,5			47,7
Total FTE	14,00			14,00		
Increase in production						12,2%

The colours in the columns are scaled for the columns separately, dark red specifies the possible bottleneck. The traffic-lights show the high/lows of the columns combined, red still gives the possible bottleneck. With the new method there are no red traffic lights, there is less stress on the other operations in terms of available operators.

The current method could theoretically reach 42.5 blasts per week, at the moment this is not being realised due to efficiency losses. It would be realistic to assume that these efficiency losses continue to exist. With the shorter bolting time the production could go up to 47.7 blasts per week, an increase of 12.2%. This is based on implementing 5 'High Performance' bolters, in case of using 3 'High Performance' bolters the production could increase with 8.2%.

The current production is around 36 blasts per week, if the possible increase is added then this could go up to 39 blasts per week. The bolting productivity includes getting supplies and diesel-time, this is done because this is a big part of the operational time spent by bolting equipment. The number of operators has been limited to 14 operators per shift, this is the average that is working each shift. For the other operations a transport time of 25 minutes is chosen as an average, this has been verified by experts at Boliden.

This method shows that drilling and loading are the possible next bottlenecks, the number of operators on these tasks is increased. The number of operators per shift does not have to be an integer because it is common for operators to change between equipment during a shift. This leads to an efficiency loss but if it is planned around shift breaks this shouldn't impact the production too much. This method shows which operation is the possible next bottleneck, the production increase only works if there are enough faces available. The 8.2% increase in production versus the 20% increase in bolting productivity shows that the bottleneck shifts to another operation before the 20% is reached.

13.3 Comparison of results

The results from the different methods are all theoretical, these were discussed with a group of experts within Boliden. A summary of the results is shown in Table 15.

Table 15. Summary of the results.

	Future bolting productivity	Improvement probability	Blast cycle method	Scheduling optimization
Production increase	+20%	+8.6%	+3.4%	+8.2%
Bottlenecks included	None	None	Available faces but not machines	Machines but not available faces

Productivity gain – total cement time

Increase of 20% in the bolts set per hour, based on the time spent cleaning. Not all the time spent on cement will result in installing more bolts. This method is overestimating the productivity gain but can be used to estimate the new average hours spent working on a face.

Production gain - cement time including chance

Increase of 8.6% in the bolts set per hour, takes into account the time spent on cement related activities and the probability that the operator could install more bolts with the new method. This method does not take the other bottlenecks in the operation in consideration, it also requires that there is always work available for the bolters. This can be solved by opening up more active working faces but this makes planning more difficult and is more expensive.

Production gain - blast cycle

The lowest production gain of all methods, only a 3.4% increase in production. This method gives the speed that a drift can be mined faster, which could be translated in a production increase. It does not take into account other bottlenecks but there is an overcapacity in all the other machines, if another machine is the bottleneck rescheduling operators could solve this. The bolters would also have more time preparing for a work task, this would increase the reliability of the bolters and make planning easier. In this blast cycle no time is taken into account for the curing of the cement after shotcreting and bolting, taking this into account would increase the total cycle time.

Production gain – optimized shift

Comparing the optimal current shift schedule with the future one gives an increase of 8.2% in production. This method considers other machine operations and personnel bottlenecks. But it works with the prerequisite that there is always work available for the machines, this can be resolved by opening up more active faces.

13.4 Automation potential

Epiroc is planning to automate the installation of 10 rock bolts, the number of bolts currently in the carousel. This could improve the productivity if the rock bolter is left alone at the face during lunch/dinner breaks and shift changes, this method is also used in chapter 13.2.1.

The potential for this automation is calculated by multiplying the possible number of bolts installed times the probability that automation could increase production. This probability is calculated by counting the moments the bolter was at the face while there was a break or shift change and dividing these moments by the number of shifts.

Figure 47. Example of a 'High Performance' bolting cycle.

During the breaks and shift changes the automatic function could install up to 10 bolts, the current maximum in the bolt carrousel. This would require increased planning from the operator because the carousel would need to be refilled before each break. The installation of a self-drilling bolt takes +-180 seconds another 60 seconds should be added for manoeuvring the boom, results in a total installation time of 4 minutes. For the automated installation of 10 bolts a break of 40 minutes would be the minimum.

Figure 48. Example of an automated bolting cycle.

The automation function could potentially be used 126 times in 108 shifts, this results in a 117% chance. This means that during 108 shifts there were 126 moments when the rock bolter was at the face with work left during a break or shift change. It was estimated that with the current rock conditions 75% of the self-drilling bolts could be installed correctly. This leads to 8.75 extra bolts installed per shift, bringing the total number of bolts installed per shift to 66.6. This is a 31.6% increase from the current bolting productivity and a 15.1% increase from using the 'High Performance' method. It is unknown if the percentage of bolts installed correctly is correct, this can only be measured during field trials.

13.5 Delivery of resin and bolts

Delivering the resin and bolts to the rock bolter as done in Malmberget is an option for the 'High Performance' method. With the cement bolter this is less viable because of need for a dry cement pump on the delivery truck. The truck delivering the resin could consist of a big pick-up truck with two 1000 litre tanks. This option could eliminate between 6% and 9% of their operational time being lost on these actions. The 6% is what is seen from the system data and the 9% is from observations. It is estimated that the 6% is on the low side because it is not always clear from the system data when equipment is busy restocking supplies or driving there. Having a refilling truck would mean that someone would be driving this truck, the shift boss already visits all the bolters each shift so maybe this could be combined.

14. Simulation - SimMine

This chapter describes the simulation software that is used and reviews the results.

The simulation software that will be used is SimMine, this is a discrete event simulation software package developed for the mining industry (Sjodin, 2015). SimMine is used for optimization of underground resource planning, scheduling and equipment selection (SimMine, 2013a). This program uses the actual mine layout, equipment characteristics and cycle times for all the operations in the mining cycle. Cycle times are distributed according to a triangular distribution, to model the variation in task lengths. Maintenance is split up in preventive maintenance and repairs, these are based on the mean time to repair, mean time between failure and the number of operating hours of a machine. This together gives an availability of the equipment, the availability has been validated by experts at Boliden. Cycle times can be changed to fit the current machine productivity, all the cycle times for the machines are manually gathered from data reported to the dispatch system. The improvement of the new method is therefore based on the calculated productivity gain from chapter 13.1.2, the average time spent at the face decreased from 6.4 hours to 5.2 hours.

Multiple scenarios will be made and evaluated on basis of their productivity and machine utilization. The results used from SimMine were the number of rounds completed, operating hours, machine utilization and average work duration. The number of rounds completed was used because this is easy to compare with the current situation. Comparing the tonnages would decrease the accuracy due to differences in dimension and density factors. To minimize the uncertainty it was decided to work with percentages and not with absolute values. The percentages are given as an increase/decrease from the base case, this way the results are more reliable when comparing them. The difference in operating hours for the rock bolters was recorded in order to make sure the work was completed in more or less the same time span. The machine utilization is used to check if the bolting operation is still the main bottleneck of the model. The operation with the highest utilization and lowest idle time is most likely the bottleneck of the operation (SimMine, 2013b). Utilization is defined as the time a machine is working divided by the total time a machine is scheduled to work. Idle time is defined as the time the machine is scheduled for work but hasn't found any work. The average work duration at the face was used to calibrate and validate the model. In Figure 49 part of the vehicle summary is shown, the average hours per face should represent the real situation.

Vehicle summary

Vehicle	Travelled distance (km)	Work (h)	Travel time (h)	Utilization (%)	Dev m	Rounds	Setups	Avg h/face
MAB67 Charger	1984	1377	199,1	33			907	1,31
MAB68 Charger	859	588	86,3	14			373	1,31
MBR 21 Boomer	1476	2204	295,6	63	2323	532	532	3,67
MBR 22 Boomer	1211	1880	242,6	52	2081	423	423	3,66
MBR 23 Boomer	1028	1563	205,8	41	1813	326	326	3,71
MBS27 Shotcrete	2067	1053	259	25			921	0,83
MBS28 Betongbil	2691	1491	67,6	35				

Figure 49. SimMine – Screenshot of the vehicle summary overview.

There is always an uncertainty factor when working with a simulation like this because it omits a lot of factors that influence the production. The model does for example not take the delivery of the cement for the shotcreter and the maximum amount of employees working at the same time into account. If any of these are the next bottlenecks this won't show-up in the simulation results. It was also not possible to add the cement related time as a unique event to the rock bolters, this had to be included in the cycle time.

14.1 Simulation scenarios

This simulation is run for 4 different setups, the base case; 3 cement bolters and 2 resin cartridge bolters. Looking into replacing the 3 cement bolters by 3 'High Performance' bolters, replacing all 5 bolters by 'High Performance' bolters and scaling down from 5 bolters to 4 'High Performance' bolters. For all these cases the number of rounds done, machine utilization and work hours are compared. To be able to analyse the scenarios in depth all the fleet data have been saved, this allows for comparing the average face time and utilization of each machine. Each of the scenarios was simulated 15 times to average out outliers which are created by the random values used in the distributions. All the simulations run from 1 January 2016 until 1 January 2017, this is a bit outdated but it allows for the use of the mine layout. The simulation is set to maximise the number of development meters per week.

14.2 Simulation results

The results received from the simulation are in line with the calculated production gains. The results are believed to be correct and have been discussed with a team of experts at Boliden. Some possible bottlenecks have not been incorporated into the simulation, these have to be investigated in the future.

14.2.1 Base case simulation - 3 'High Performance' bolters & 2 resin cartridge bolters

This setup is the most likely if the mine chooses for the 'High Performance' bolters, this is because three of the current cement bolters are up for replacement. Using the new set-up resulted in a production increase of 10.7% and a decrease of 0.5% in operational hours. Rock bolting still was the bottleneck in the new operation, this could be concluded from the idle times of the machines. These idle times increased from 0.9% to 1.1%.

14.2.2 Maximum production simulation - 5 'High Performance' bolters

When we replace all the current rock-bolters with 'High Performance' bolters this could look like the future set-up when all the current rock bolters are replaced. This set-up resulted in an increase of 18.3% in production together with a 0.2% decrease in operational hours. This set-up was also used in order to check if the bottleneck would shift to another operation. As we can see in Figure 50 that the idle time in light-blue is still the smallest at the bolters, this means that they are still the bottleneck, the average idle time increased from 0.9% to 1.3%.

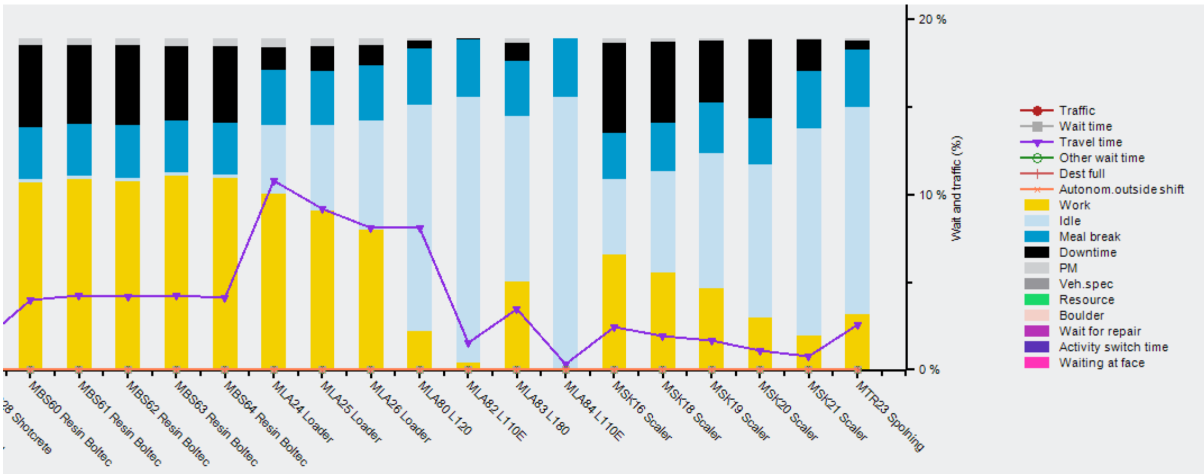

Figure 50. SimMine – Screenshot of the machine utilization overview, 5 rock bolters on the left.

14.2.3 Maintain production simulation - 4 ‘High Performance’ bolters

In order to check if the mine would be able to maintain its current production with 4 ‘High Performance’ bolters instead of 5, this scenario was also analysed. This was of interest because an increase in production might not be feasible due to other bottlenecks but doing the same amount of work with less equipment and people might result in a financially interesting case. When doing the work with 4 ‘High Performance’ bolters the production dropped with 4.0%, the operational hours dropped with 19.9%. The drop of almost 20% in operational hours was expected because there is one machine less to operate. If this drop in production can be minimalized by changing work priorities or maintenance schedules this is an interesting option. It has to be said though that a production increase is always more beneficial in the mining industry due to the massive amount of money already invested in the mine. The savings of one machine will not have a big impact on the overall finances of the operation.

15. Financial analysis

In this chapter the financial costs and possible gains are analysed. This is done in order to get an idea if the 'High Performance' method can be implemented at Boliden's Kristineberg mine. The most common method to evaluate expansion projects in the mining industry is with the discounted cash flow (DCF) method. This method gives the net present value (NPV) and the internal rate of return (IRR) for the project, it happens that projects with a low NPV still get started because of strategic reasons (Stojanović, 2013). This method is used because the real value of having a higher production is getting the ore earlier out of the ground, this results in having the benefit earlier. In a mining environment with high metal prices the DCF tends to overestimate the value of expansion projects. This is partial because the capital expenditure for expansion projects is small compared to the revenue of the production increase. It is therefore advised to include a cost per tonne measure, this gives an indication if the project is viable when metal prices are lower. The NPV of a project can be positive while the cost per tonne increases, this might make it a bad investment. Using the cost per tonne should be in comparison with industry peers, it is a measure on how competitive the operation is. A lower cost per tonne of ore increases amount of the ore that can be mined at a profit, resulting in an increase in ore reserves. All the price s stated are in Swedish crowns (kr), the conversion factor used is the average of the last 6 months (1 EUR = 10.45 kr from (XE, 2018)).

The costs of cement grouted bolts in the mining industry mainly consist out of consumables, maintenance, labour, depreciation, drill-steel & bits and fuel. These are the direct costs, indirect costs such as overhead are not included. In Figure 51, a typical division of the direct bolting costs for a mine in the Nordics is shown.

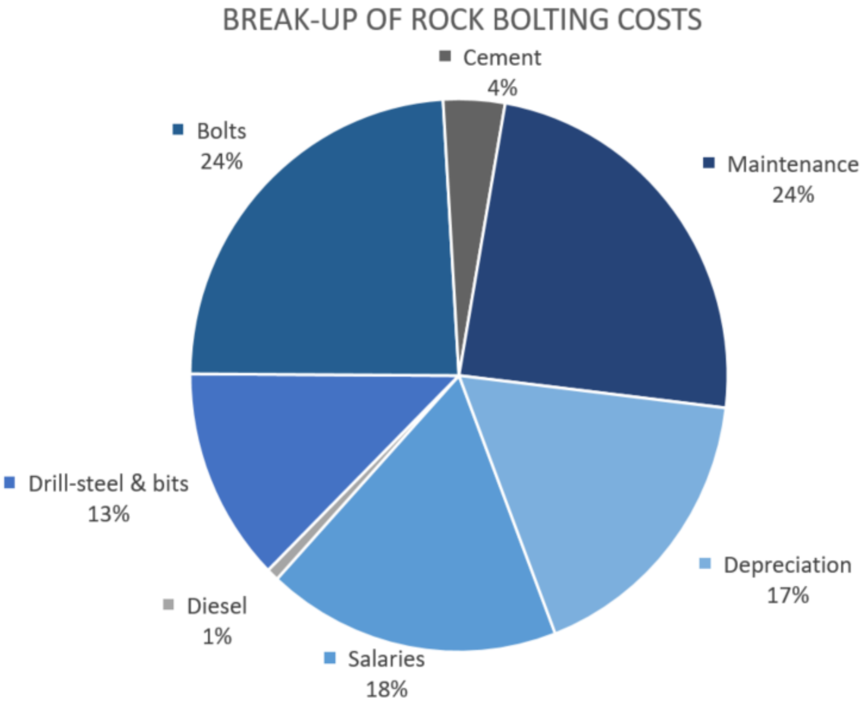

Figure 51. Break-up of direct rock bolting costs in a Nordic mine (NewBoliden, 2018).

The bolting material accounts for 28% of the costs of installing a bolt, the 'High Performance' method would increase the material cost. The labour and maintenance costs would decrease due to the ability to work faster and it is expected that there is less wear because no cement is used.

15.1 Costs

The current material cost per installed rock bolt is set to 1.0 per bolt. The actual prices are confidential.
The hollow bolt would need an extra manufacturing step, this would approximately add between 50% and 200% to the price. The current plate could be used so this price would not be affected. The costs for the resin could be the same or even a bit lower as the cartridge price as there is no need for packaging and there is less spillage of the product in the mine. An overview of current bolting material costs and possible increases is shown in Table 16. These prices has been scaled to an arbitrary price factor due to confidentiality concerns. The biggest variable is the increase in bolt price, this impact will be estimated with the help of a sensitivity analysis.

Table 16. Cost items per bolt and incremental cost.

Method	Price factor	Increase
Cement	1.00	-
Resin cartridge	1.65	.65
HP-method (+50%)	2.04	1.04
HP-method (+100%)	2.41	1.41
HP-method (+150%)	2.80	1.8
HP-method (+200%)	3.18	2.18
Offer from Minova	4.20	3.2

The offer from Minova, prices for a small batch specially made for testing the new method is used as a maximum price. The offer is four times as expensive as the current bolting costs, part of these costs will be set-off by the improved installation speed. This increase in installation speed will potentially lead to more production. The cost of the resin and hollow bolts are not yet available as this is site-specific. Each mine has different requirements for the bolts. These requirements and the actual price linked to these have to be discussed by the rock mechanic engineers and the purchasing department.

In Figure 52 the needed production increase is shown for the incremental costs per bolt. If the price of the bolts would double, the '+100%' case then a production increase between 5 and 6 percent is needed. The arrows represent the cases stated in Table 16, starting with the +50% case and ending with the offer from Minova.
The sensitivity analysis shows that changes in the estimated production increase result in the biggest change in NPV. The difference in NPV of the base case has been set to 1 and the rest of the change has been scaled to this number. The base case is based on an increase in capital expenditure, costs per bolt and production. The operational costs are based on a bolt price that would double from the current price. The operational and capital expenditure costs have more

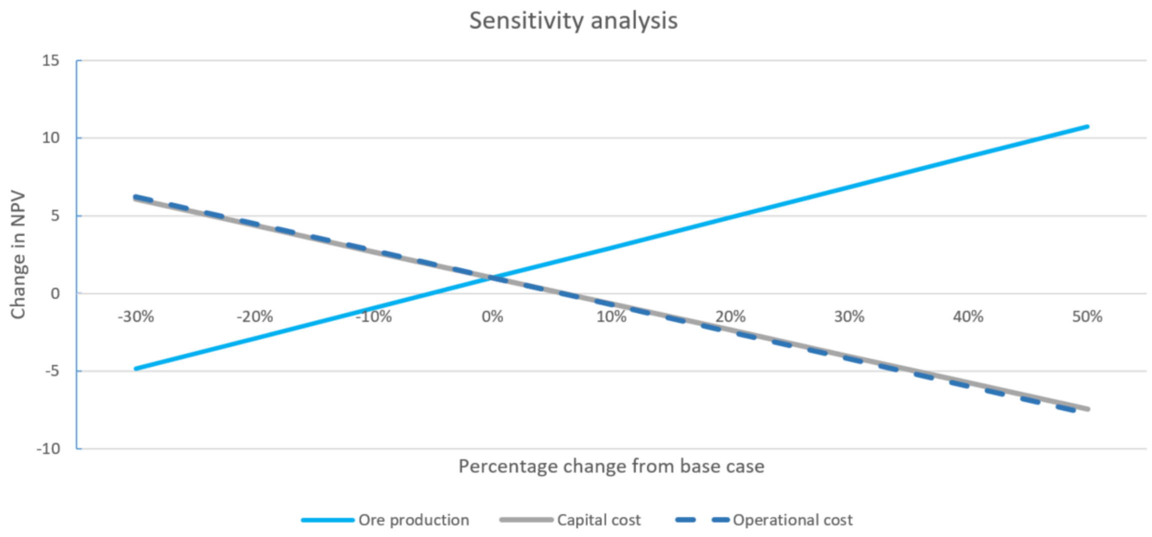

Figure 53. Sensitivity analysis for the 'High Performance' method

or less the same impact on the NPV, this is the result of using an incremental addition to the existing costs. The production increase is the most important factor and one of the hardest to estimate. The capital expenditure is less likely to deviate from the base case than the operational cost, therefore more attention should be given to the operational cost than to the capital cost.

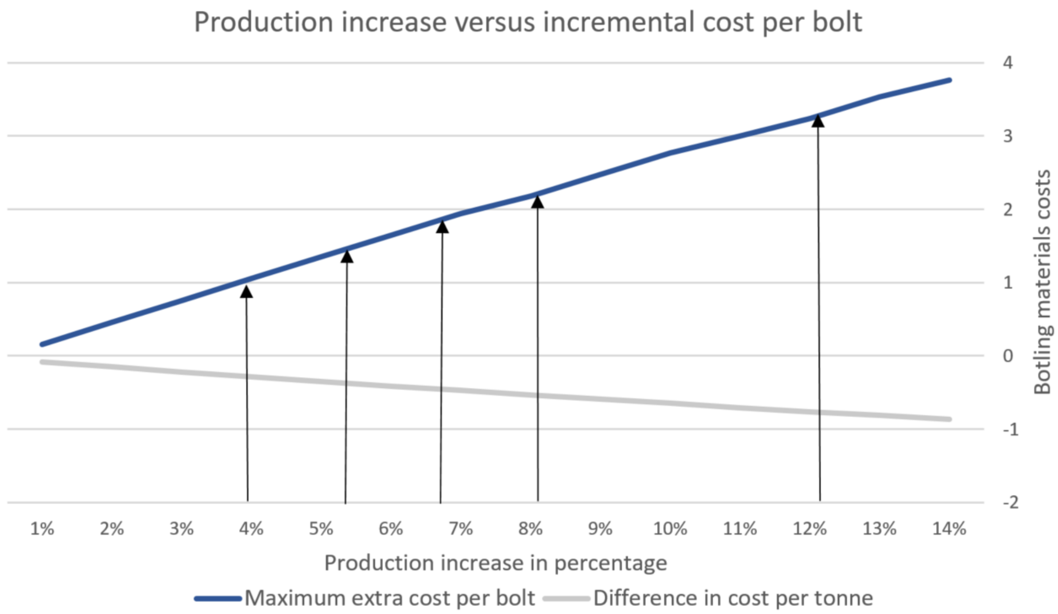

Figure 52. Needed production increase versus incremental costs.

16. Discussion

In this chapter the results and their implications will be discussed. This will be presented in the same order as the thesis.

16.1 HSE and quality of installation

The 'High Performance' method has some health and safety concerns compared to using cement or resin cartridges as grout. These concerns arise from the resin components, one of these contains isocyanates. Under normal working conditions this should not pose any danger, the accumulation of isocyanate gas is limited in a cool and well-ventilated working area. The pumpable resin combines the advantages of cement grouted bolting with those of resin cartridge bolting. It can be used if there is water present, it is always perfectly mixed and has a short curing time. The pumpable resin has a compressive strength of 20MPa after 30 minutes, this is sufficient for the mines operated by Boliden. The installation speed of bolts with pumpable resin is the fastest as there is no need for making and cleaning the cement or manually refilling the cartridges. Operators prefer working with the epoxy resin as there is no need for extensive cleaning of the machine after each shift. The 1-step bolting method is more beneficial if it is used in poor rock conditions or in combination with wire mesh. The 2-step bolting method has a higher potential to be used in good rock conditions as this method is less expensive than the 1-step method. It has not been researched if it is possible to use resins which do not contain isocyanates, this would resolve the health and safety concerns.

16.2 Mechanical bolt installation and automation

The installation of rock bolts using the 'High Performance' method is similar to the current installation method. The hole is drilled with a separate drill-steel or in case of the self-drilling bolts with the bolt. Grouting is applied through the bolt instead of by a separate tube, removing an installation step. Resulting in 2-step bolting for the hollow bolts with a separate drill-steel or in 1-step bolting if self-drilling bolts are used. The 1-step bolting method has the highest potential to be fully automated in the near future. This is due to the fact that it has the least consecutive process steps, automated installation of a bolt-carousel should be possible within a year. Refilling the carousel or developing another method to supply bolts will take longer. The automated installation of a carousel could already provide a productivity benefit as the equipment could work during the breaks and shift changes.

16.3 Bolting productivity and mine production

Fewer process steps and the fact that the 'High performance' method is faster could result in a production increase. The bolting productivity could increase with 20% for the case in Kristineberg. This could result in a production increase ranging from 3.4% to 8.6%, depending on which bottlenecks were included. The lowest increase is the result of shortening the blast cycle, this is the most conservative case. When optimizing the schedule an 8.2% increase is expected, it is believed that this is a realistic scenario. The probability of these outcomes has been discussed with experts at Boliden. Comparing the bolting productivity with the mine productions shows that there is an efficiency loss caused by planning difficulties and other bottlenecks. The difference between the increase in productivity and the increase in production will result in an increase in equipment availability. As there is more time to maintain and prepare the equipment. It has to be noted that the bolting productivity increase is based on the savings in cleaning time. Possible other gains such as the installation being faster and improvements in time spent on operator repairs are not included.

16.4 Simulation

There are many external factors influencing the production in the mine, it is impossible to incorporate all of them into the calculations and simulations. These are therefore simplified versions of reality. Each of the scenarios was simulated several times to average out outliers. These outliers are created by the random values used in the distributions. SimMine includes the mine layout, equipment characteristics and cycle time distributions in the model. This results in a fairly reliable estimate of the production increase. It has to be noted that the maximum number of employees is not included in this model. From the three scenarios that were modelled, the most interesting is the base case. An average increase of 10.7% in production is realised when replacing 3 rock bolters for 'High Performance' bolters. Rock bolting still was the bottleneck in this case, the idle time percentages were the lowest of all operations. Replacing all 5 rock bolters resulted in a production increase of 18.3%, this might be interesting for when the other bolters need to be replaced.

16.5 Financial

The downside of the 'High Performance' method is that it requires hollow bolts and resin; these are more expensive than regular bolts. When using self-drilling bolts the price increases even further. The production increase can offset a lot of the extra costs of the 'High Performance' method. With the current bolting method, material accounts for less than a third of the total bolting cost. As long as the bolting costs stay below the level dictated by the expected production increase then investing in the new method is advised. The cost per tonne of ore will decrease with the new method due to the fact that the production increase is higher than the cost increase. This is due to the fact that bolting only accounts for a small part of the mining costs. The sensitivity analyses showed that the ore production has the biggest influence on the NPV. The influence of the capital and operation costs of the new method are similar to each other. It has to be noted that it is more likely that the operation cost changes more than the capital cost.

17. Conclusion

The isocyanates in the epoxy resin are a cause of concern, site-specific research should prove that the health-related risks can stay within regulatory limits. This is to the researchers' knowledge possible for the Kristineberg mine. When using cement grouted rock bolts a lot of time is wasted on cement related activities. The 'High Performance' method can utilize this lost time and achieve a 20% increase in bolting productivity. This increase in productivity can result in an increase in mine production. It is believed that an 8.2% increase in production should be possible with the new method. The simulation showed an increase of 10.7%, further suggesting that the calculated increase could be correct. It is at this moment not possible to give an advice to Boliden if they should buy the 'High Performance' bolters. This is caused by the uncertainty in production increase and by the lack of price data for the bolting materials. If the 'High Performance' method is feasible heavily depends on the price of these materials. If the costs of the hollow-bolts and resin can be limited, not exceed the level of the benefit gained by the production increase, then investing in this method is advised. The installation process of the new method requires fewer installation steps, this makes potential automation more likely. Automated installation of a carousel is planned for next year, fully autonomous bolting might take a few more years after this. Being an early adopter can provide a good base for testing the future automation potential.

18. Further research

This thesis focussed on the productivity and economic aspects of the ‘High Performance’ method, no other methods have been investigated. It could be interesting for Boliden to look into other methods to improve the productivity.
While researching methods to calculate the rock bolting productivity it became clear that there is no defined method in the industry to calculate this. It could be interesting to create a method for calculating the productivity of equipment which is accepted industry wide. This could help Boliden to compare and evaluate the productivity of equipment in their mines. There is to the writers’ knowledge no research done on comparing the estimated production gain with the realised production gain. This could be done as part of an in-depth comparison of calculation methods to estimate the productivity and the impact of this on the overall production. Such a study would help future projects because the results would be more reliable. In order to minimize the health and safety concerns of the resin it is advised to conduct tests on the release of isocyanates in working conditions. Researching if the resin can be replaced with a component without isocyanates is another question that should be answered.
The impact of the automation function on the production in the mine has been studied minimally in this thesis. Automation is seen as the way forward in the industry so this should be studied once the function is in a further stage. Being involved in the development of new methods and being able to test them in the mine should provide useful data. It also gives Boliden the ability to steer the direction of the development.

Implementing the ‘High Performance’ 1-step method in a mining environment where mesh is needed or the rock mass is in bad condition might prove more beneficial. This should be studied as the productivity improvements might be higher.

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- Source of data.

Newboliden. (2018).

- Numerous conversations, skype meetings and e-mail contact (March 2018 – September 2018). Discussing all aspects of research related to the thesis.
- Internal documents about the standard operating procedures at NewBoliden.
- Source of data.

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Appendix A

Table 18. Consequence table

Consequence or severity			
Consequence	**Potential loss in money**	**Health and safety**	**Environment**
Level 1	€ <10,000	No medical treatment required	No direct impact on environment
Level 2	€ 10,000-100,000	Objective but reversible disability requiring medical attention	Limited damage to minimal area of low significance
Level 3	€ 100,000-500,000	Moderate irreversible effects to one or more persons	Minor effects on biological or physical environment
Level 4	€ 500,000-1M	Single falality or severe irreversible effects to one or more persons	Moderate effects but not affecting ecosystem functions
Level 5	€ 1M-5M	Multiple fatalities or severe irreversible effects to >50 persons	Serious medium term environmental effects

Table 17. Probability table

Probability of the event		
Likelihood	**Description**	**Frequency examples**
Level 1	Conceivable, but only in extreme circumstances	1 event per 5 to 10 years
Level 2	Hasn't happened yet but could	1 event per 1 to 5 years
Level 3	Could happen and has occurred here or elsewhere	More than 1 event per year
Level 4	Could easily happen	More than 1 event per 6 months
Level 5	Happens often	More than 1 event per month

Table 19. Consequence - Probability matrix

		Consequence				
		1	2	3	4	5
Probability	1	1	3	10	30	100
	2	3	9	30	90	300
	3	10	30	100	300	1000
	4	30	90	300	900	3000
	5	100	300	1000	3000	10000