# Adapting Methodologies from the Forestry Industry to Measure the Productivity of Underground Hard Rock Mining Equipment

by

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# Abstract

The purpose of this dissertation is to develop and apply a framework to characterize the ground support installation component of the mining development cycle in underground hard rock mines for the purposes of comparing equipment. A secondary goal is to identify opportunities to improve the productivity of the ground support installation process.

It was found that the forestry industry faces similar challenges as the mining industry when measuring equipment output in a variable environment where equipment productivity is affected by a range of external conditions. Despite this challenge, forestry researchers successfully developed and applied a standardized methodology and nomenclature to measure the productivity of equipment for the purposes of equipment and process comparison in variable external conditions.

The methodology used in the forestry industry was modified to measure mechanized and semi-mechanized ground support installation productivity in three Canadian underground hard rock mines. Furthermore, opportunities to improve the ground support installation process were identified. This framework can be modified to measure and compare other types of mining equipment. By using a standardized methodology to measure, compare and improve mining processes, development and production rates can be increased in underground hard rock mines.

In summary, a framework was adapted from the forestry industry to measure and compare the productivity of the ground support installation cycle in three Canadian hard rock mines, and opportunities to improve the process were found.

# Acknowledgments

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# Chapter 1

# Introduction

## 1.1 Overview and Thesis Structure

The purpose of this thesis is to develop a methodology to measure and analyze the productivity of underground mining equipment and processes by adapting methodologies used in other industries (primarily the forestry industry) to measure equipment, and apply these methodologies to measure and compare processes in the mining industry. The specific process studied is the installation of ground support.

The purpose of this thesis is to measure the ground support installation component of the mining development cycle by adapting methodologies used in the forestry industry used to measure the productivity of equipment, and apply these methodologies to the mining industry. The thesis is structured as follows:

- A high level review of the history and current status of how mines measure their equipment productivity, and demonstrate why measuring the ground support installation process is critical in mining, and how mining relates to other industries (Chapter 1),
- A general review of the ground support installation process to become familiar with the equipment and processes (Chapter 2),
- Identify and evaluate tools and methodologies for the characterization of the productivity of processes (Chapter 3),

- Development of a methodology for measuring the ground support installation process and other mining processes which combines tools and methodologies identified in the above section (Chapter 4),
- Apply the proposed methodology to a real world case study to compare mechanized and semi-mechanized ground support installation (Chapter 5),
- Analysis of the results of the case study (Chapter 6), and
- Summarize the findings of the thesis and recommendations for future work about the ground support installation productivity and the effectiveness of the methodology developed in the thesis (Chapter 7).

This study will contribute to the mining industry by providing a methodology to measure the output mining processes, and identify ways in which these processes can be improved.

## 1.2 Introduction

To access deep underground hard rock ore deposits for bulk mining, underground drifts are developed through the completion of a series of discrete tasks. For Canadian mines to remain profitable with increasing global competition and costs, these mining tasks must be accomplished as rapidly as possible to maximize the net present value (NPV) of mining operations. To improve health and safety of workers, mines have invested in increasingly sophisticated mechanized equipment over the past 60 years with the hopes of realising higher equipment productivity and drift development rate.

Despite improvements in technology, mine development is often the bottleneck for production in many Canadian mines which can decrease the ability for mines to maximize their profitability (Skawina et al., 2014).

## 1.3 Mining Development Rate at Depth

The mining development cycle generally consists of the following activities (Figure 1.1):

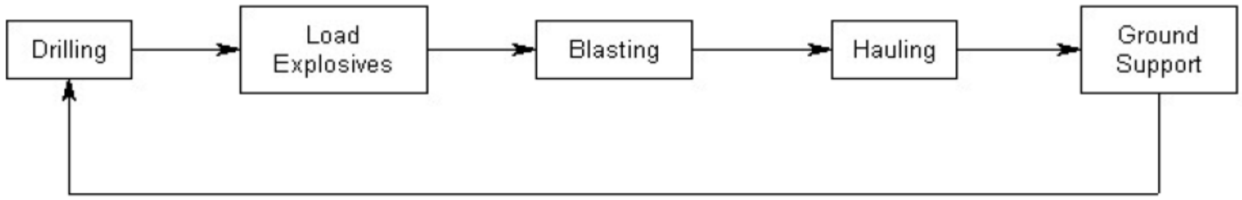


Figure 1.1 Typical mine development cycle in Canadian mines (Yuriy & Vayenas, 2008)

Despite advances in technology, development rates in the underground hard rock mining industry in Canada has been steadily dropping since the 1960s from greater than 12 m per day to 3-4 m per day as shown in Figure 1.2 to the point that the profitability of some underground mining projects can be in jeopardy (Kenzap, 2006).

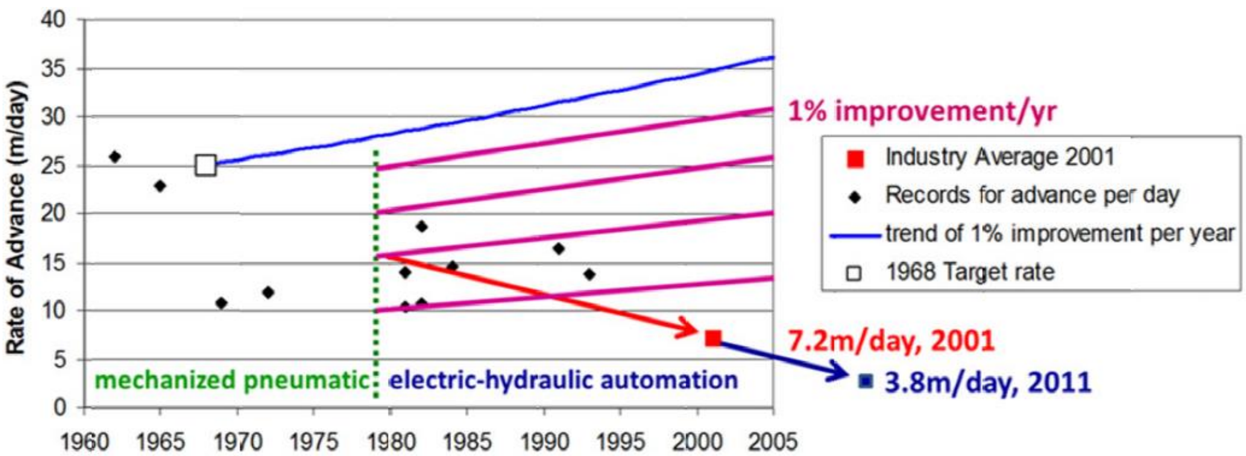


Figure 1.2 Historical trends in development rates in Canada, illustrating the decline in advancement rates over time (Morrison et al., 2014)

Principal reasons for the decline in mine development rate at depth include:

- Easily accessible high quality ore deposits are depleted, and equipment is operating in deeper and more challenging mining conditions,

- Work practices used to achieve high development rates in the past are no longer acceptable (Morrison et al., 2014; Graham & Morrison, 2003),
- Due to ground stability issues encountered in deep and high stress mines, and the larger size of excavations there is an increase in the amount of ground support installed to stabilize excavations (Morrison et al., 2014; Darling, 2011; Kenzap, 2006),
- More time is required to transport people and equipment in deep mines (Suorineni et al., 2008),
- The increase in heat due to the geothermal gradient and autocompression at depth decreases worker productivity (Krige & Barnard, 1981).

## 1.4 Mechanization in Underground Mines

There have been few studies on the implementation of mechanization in mines, however it is generally agreed upon in literature that extracting the maximum value through updating technology is challenging in the mining industry for many reasons, for example:

- Corporate culture along with an aging workforce which resists innovation in an industry that is simultaneously dependent on technology and technology-adverse which could lead to failure to succeed when adopting new technology (Bamber & Scoble, 2005),
- Failure to sustain R&D initiatives which results in many mechanization initiatives to fail (Bamber & Scoble, 2005),
- The introduction of mechanization in mines has contributed to a de-skilling of the mining workforce (Russell, 1999; Burns et al., 1983; Clement, 1981),

- Usage of powerful and more complex equipment that requires increased maintenance support combined with non-optimized maintenance practices (Kenzap, 2006; Lumley, 2013),
- Lack of ability to sustain gains achieved through implementation of mechanization,
- Excavations have increased in size to accommodate larger equipment which decreases cycle time (Morrison et al., 2014),

> *"Paradoxically, headings have become larger as a result of using larger equipment which in turn is supposed to improve performance but appears to have degraded it"* – Ross, 2014

All of the above contributes to low overall equipment effectiveness[1] (OEE) as shown in Figure 1.3. With an increase in the number of deep mines and mines operating in challenging conditions (both geologically and technologically), it is essential that mines operate in an efficient way to remain profitable by maximizing their OEE which would result in an increase in development rate.

[1] There are multiple definitions of OEE, but in the context of mining, it is usually defined as OEE = Availability * Utilization Rate * Production (or Process) Efficiency (Paraszczak, 2005). This measure is defined in more detail in Section 3.2.1.

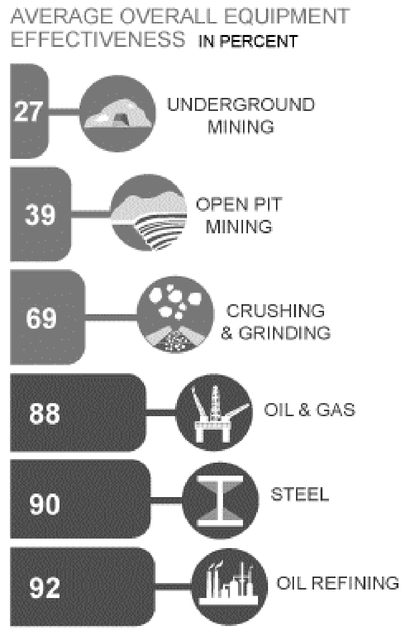


Figure 1.3 OEE in underground mining is the lowest of any industry (McKinsey, 2015)

## 1.5 Assessing the Cause of Low Development Rates in Underground Mines

In order to make objective decisions about production, mines must be able to repeatedly measure the output of their mining processes. It is commonly stated - *"You can't manage what you don't measure".*

The cause of low development rates and failure to see improvements despite increased mechanization is often difficult to assess since many mining companies fail to capture or effectively utilize machine and maintenance data (see: Figure 1.4).

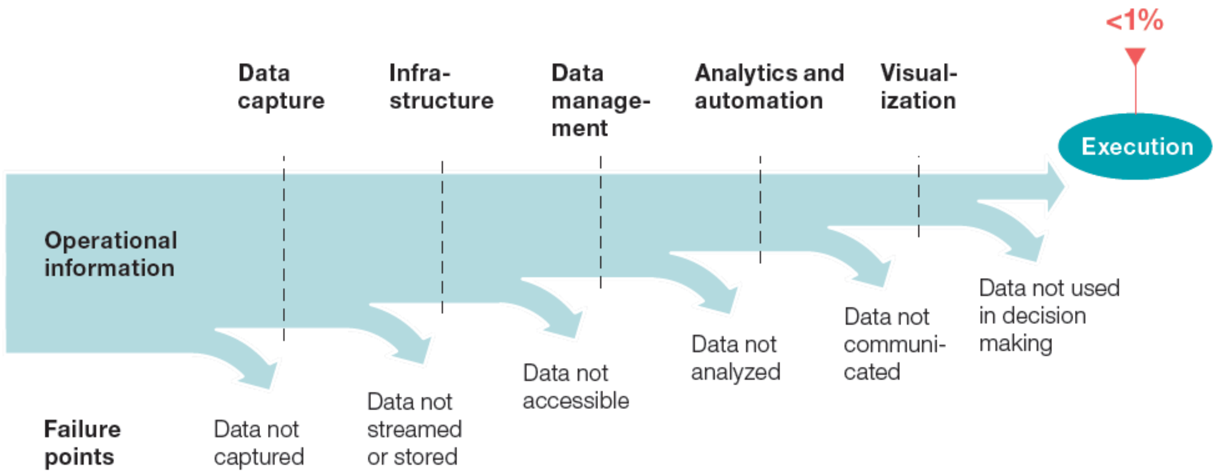


Figure 1.4 Mining companies use a fraction of their data (McKinsey, 2015)

Mining equipment output can be improved through the implementation of lean manufacturing principles[2] and practices ("lean mining"). Lean mining is the application of lean manufacturing tools (which vary based on work site requirements) in mines for the purposes of increasing operational efficiency and effectiveness of a company's processes by mapping, analyzing and continuously improving process output through various human-centered techniques. To implement lean standards, mining processes must be measured, resulting in higher throughput and less waste (Cavender, 2000).

Historically, process measurement methods in mining have typically been modified from the automotive manufacturing industry, however adapting the techniques used in those industries to mining is challenging due to differences in the working environment (Table 1.1).

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[2] Lean manufacturing is a philosophy where principles are translated into practices to eliminate waste, and achieve production targets (Lööw, 2015)

Table 1.1 The mining environment is both more hostile and variable than the manufacturing environment (Dunstan et al., 2006)

| **Resource and minerals business** | **Automotive business** |
|---|---|
| A smelter or refinery cannot be stopped so there is inherent production push in the process | An automotive assembly line can be stopped so there is the ability to create pull systems |
| Production is in continuous units and around the clock | Production is in discrete units and often on less than one day cycles |
| Generates considerable dust | Little dust |
| Physically challenging environment | Ambient conditions |
| Inherently variable environment | Stable work environment |
| Remote locations | Large centres |
| Impact of weather | Indoor environment |
| Inherently variable raw materials | Controlled raw materials |
| Geographically spread output teams | Compact plants |
| Molten metal has a short shelf life before it solidifies | Long-life components suitable for supermarket-style storage |

There are more factors which could be compared; Table 1.1 could be considered to be incomplete. The magnitude of variability difference between mining and manufacturing can also differ greatly among different operations. To the author's knowledge, there is no widely used standardized methodology to measure the productivity of mining equipment and identify opportunities to increase process output and improve process quality. This is substantiated by recent publications in the mining industry (for example: Mohammadi, 2015; Lanke, 2016).

## 1.6 Process Measurement in Other Industries

Operations Research (OR) is a broad discipline in industrial engineering in which various frameworks are used to assess the effectiveness of equipment and maintenance (Darling, 2011). Within these frameworks are methods for measuring and comparing equipment performance, and improving equipment productivity. Many of these frameworks are sporadically used in mining, and the objectives of the assessment frameworks are the same – identification of ways in which operations can be improved to increase the productivity of processes and equipment. These frameworks have been systematically and successfully applied by researchers in the forestry and manufacturing industries to remain profitable in the face of increasing capital costs and growing competition. The mining industry can benefit from applying OR methods to improve the effectiveness of materials handling, logistics, maintenance, communication and equipment in a challenging work environment. Despite the need for OR in the mining industry, little work has been reported in the public domain to standardize and apply these methods in underground mines.

## 1.7 Selection of a Process to be Studied

A breakdown of time that contributes to the development cycle rate in a mine is shown in Figure 1.5. Process reduction factors that affect many mining processes such as road conditions could be assessed, improved, and the positive effects of changes can be quantified. A mine can improve its development rate by iteratively measuring, analyzing and eliminating process reduction factors through work study.

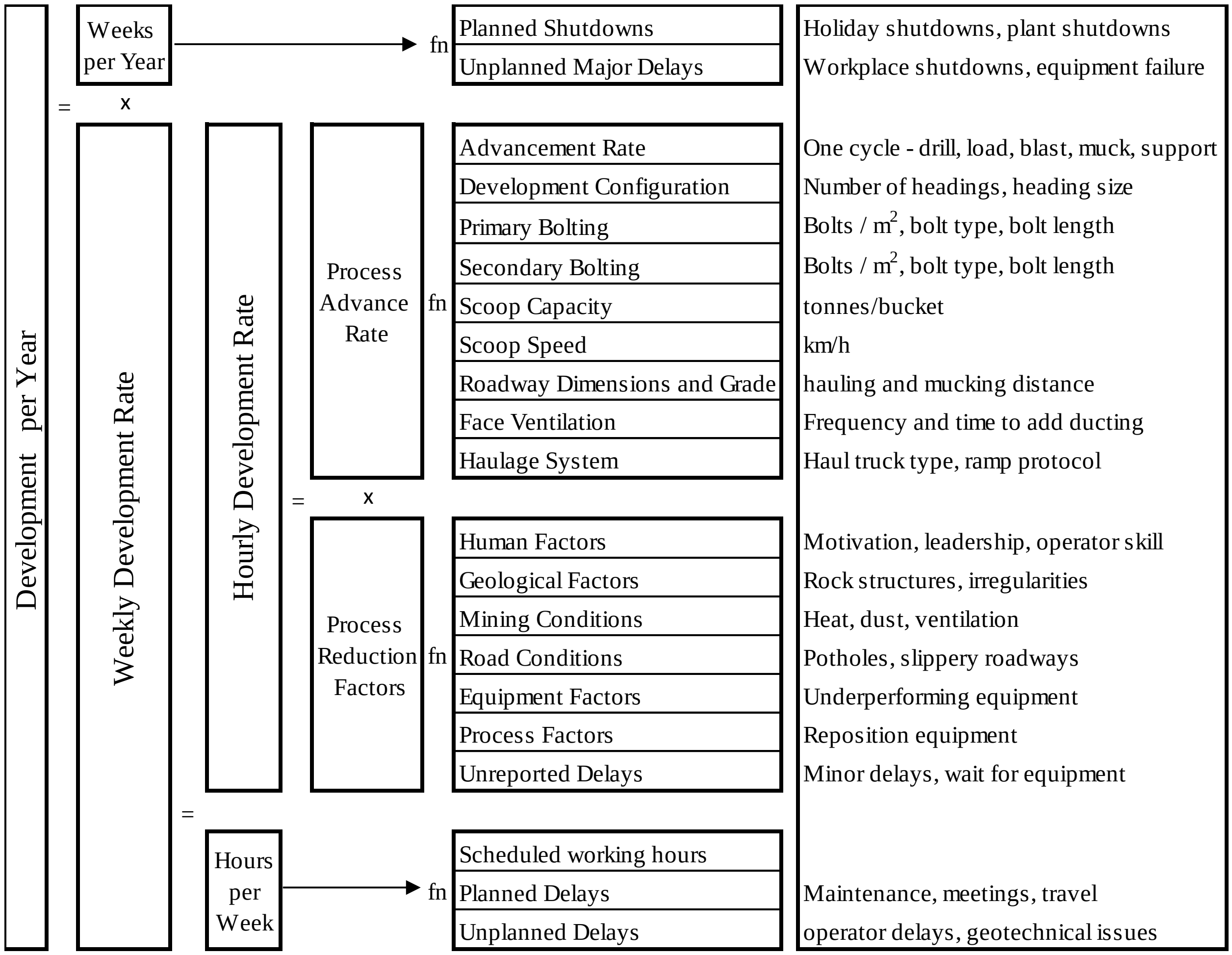



Figure 1.5 Factors influencing development rate in hard rock mines (after Darling, 2011)

The development cycle is often a production restriction in Canadian mines, and the ground support installation portion of the development cycle is often perceived to be the bottleneck (Spearing & Naismith, 1999, DeGagne et al., 2000; Atlas Copco, 2007; Skawina et al., 2014, Morrison et al., 2014; Moss, 2009; Proudfoot and Swan, 2007; Suorineni et al., 2005).

An analysis of the development rate in mining was performed to determine which process is the most variable and time consuming, a compilation of the results are shown in a box plot in Figure 1.6.

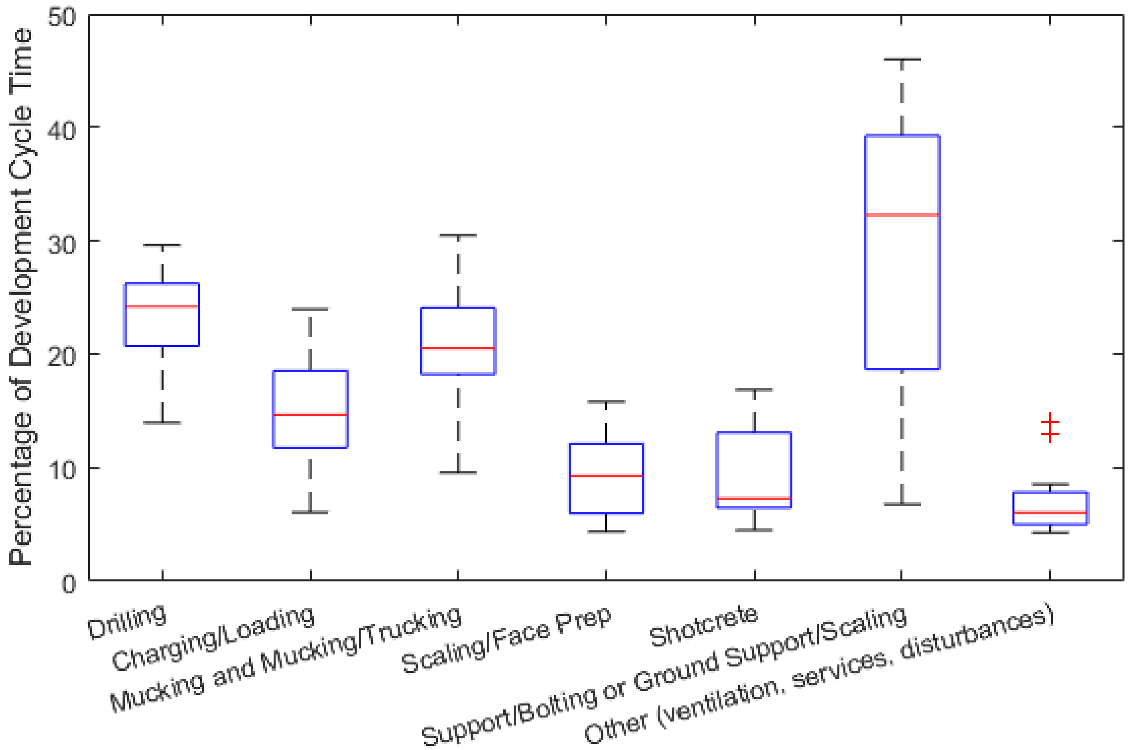



Figure 1.6 The bolting process is on average the most time consuming and most variable portion of the mining and tunneling drill and blast cycle[3].

The installation of ground support has not significantly improved since the 1980s; there is little indication that this process has substantially improved outside of Canada despite improvements in equipment automation and mechanization (Lovejoy, 2010; Gustafson et al., 2014). There is also a lack of literature to quantify the rock bolting process. Therefore, the measurement of the ground support installation cycle for the purposes of comparing semi-mechanized and mechanized equipment and identifying opportunities to improve productivity is the focus of this thesis.

[3] Data shown is aggregated from Song et al., 2015a; Skawina, 2013; Moss, 2009; Sandvik, 2009; Tanner & Nord, 2009; Wilcox, 2008; Yuiry & Vayenas; 2008; Peloquin, 2007; Proudfoot & Swan, 2007; Stewart et al., 2006; Suorineni et al., 2005; Peake & Ruppercht, 2002; Espley-Boudreau, 1999.

Anecdotally, mechanized ground support installation equipment is less productive than semi-mechanized or manual support installation (Lovejoy, 2010). Multiple reasons are stated for the status of ground support installation productivity. Human operators are more productive than mechanized systems since a person can complete multiple tasks at once, and as mines become deeper, there is greater need for strong and dynamic support systems due to the capacity requirements for support in high stress rock conditions (Lovejoy, 2010; Suorineni et al., 2005).

Suorineni et al. (2008) hypothesizes that drift advancement rates can be significantly improved by reducing the number of bolts installed in drifts. This may not be a feasible option for deep Canadian mines where more ground support is installed to mitigate the risk of rock bursts (Goodbody, 2014; Choquet, 1991).

## 1.8 Characterizing Mining Processes

Based on the challenges faced when quantifying mining processes as described in section 1.5, an investigation into the ideal way to quantify mining processes has been carried out by means of literature review (Chapter 3).

The majority of literature describes principles derived from various procedures in manufacturing which have been occasionally implemented with some success however the methodology to measure performance of the mining processes is often not shown (Lööw, 2015, Lööw & Johansson, 2015, Dunstan et al., 2006). Lööw & Johansson, 2015 state that while the Lean Production standards are applicable in mining, the standardization of procedures, and presumably measurement of processes, must be flexible due to a high level of variation and uncertainty. After a thorough review of industries, it was found that the forestry industry has to deal with similar levels of environmental variability which causes process uncertainty.

Forestry is far more similar to mining than manufacturing. Furthermore, the way in which forestry equipment operates is similar to drill and blast mining which is a set of discrete cyclical destructive processes which take place in a hostile environment (Ortlepp, 1997).

Therefore, methods used in forestry to measure processes should be considered for mining. An overview of work study from which forestry work measurement methodologies are derived, and how it is applied in forestry and ways in which it can be practiced in mining is contained within the thesis.

By measuring these processes, the variability of the development cycle can be reduced. Sloan, 1983, describes how measuring processes in mining have an inherent self-improving feature. By identifying non-value adding processes to management who then implements corrective actions, the incidence in high times to complete a task will decrease, and by completing follow-up studies, the process performance will gradually improve (see: Figure 1.7).

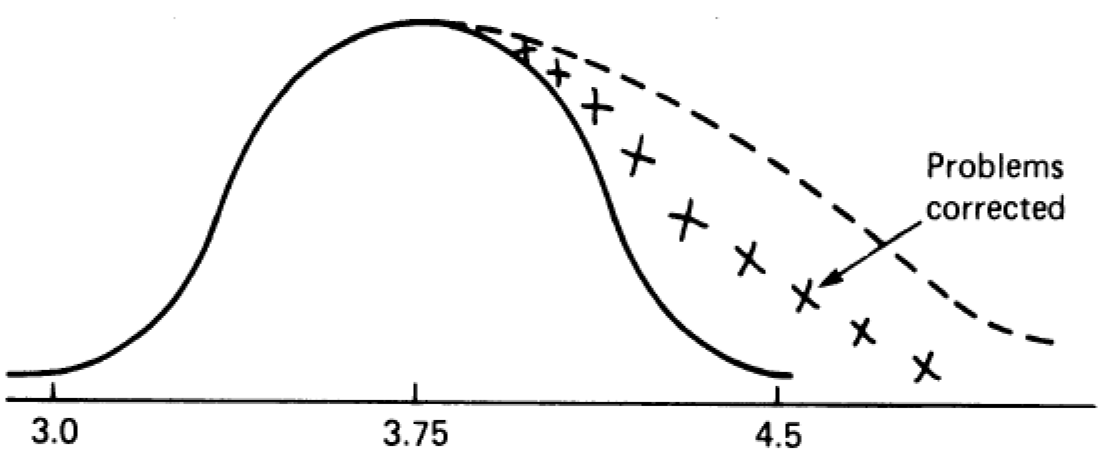



Figure 1.7 Diagram of the expected performance improvement after process control is introduced; long process times have been eliminated which reduce the positive skew of the distribution of task completion time (Sloan, 1983)

# Chapter 2

## Background on Ground Support in Underground Mining

The purpose of this chapter is to provide the reader with a brief review of the equipment and processes that were investigated in the case study.

The chosen processes to be investigated for this thesis are the activities involved in the installation of ground support in mine development drifts. Ground support is installed in underground excavations to prevent gravity-driven falls of ground (structure-controlled failure) and rockbursting (stress-controlled failure) to protect workers and equipment from falling rock.

During the scaling and ground support installation part of the mining development cycle, loose rock is removed with equipment or a scaling bar, and rock bolts and surface support are installed into the rock to stabilize excavations by providing the following three functions (see: Figure 2.1):

- **Reinforce:** Strengthen the rock mass to keep it cohesive and allow it to support itself (Kaiser et al., 2000; Hoek & Brown, 1980);
- **Retain:** Prevent small rocks from falling between reinforcing elements, and to prevent unravelling of the rock mass (Kaiser et al., 1996);
- **Hold:** Tie the retaining elements of the ground support system which are anchored in stable ground to prevent gravity-driven falls of ground (Kaiser et al., 1996).

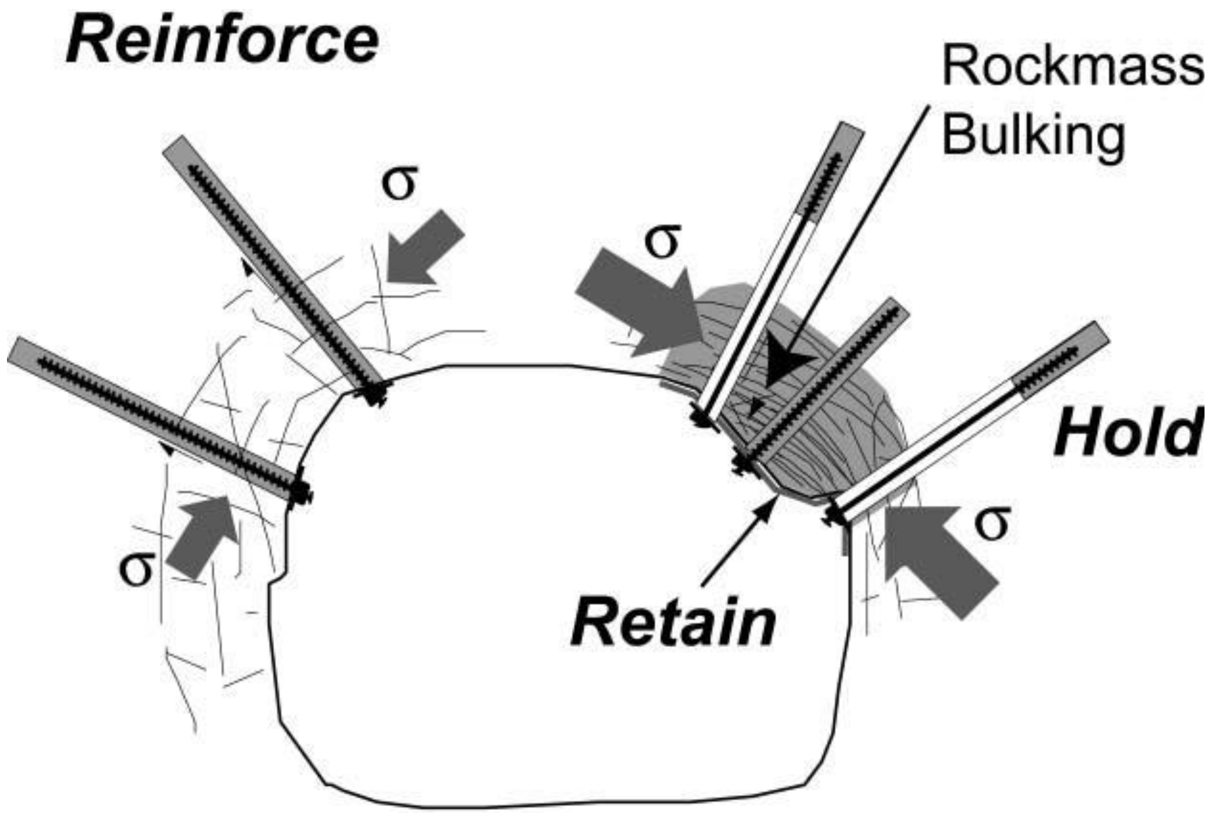



Figure 2.1 The three functions of ground support (Kaiser et al., 1996)

Bolts and surface support elements which provide the functions of ground support are shown in Table 2.1 below.

Table 2.1 Characteristics of common support elements (Kaiser et al., 1996)

| | Reinforce | Hold | Retain |
|---|---|---|---|
| Stiff | grouted rebar | grouted rebar | shotcrete arch or ring |
| Soft | — | long mechanical bolt | chain-link mesh |
| Strong | cable bolt | cable bolt | mesh-reinforced shotcrete |
| Weak | thin rebar | Split Set bolt | #9 gauge mesh |
| Brittle | grouted rebar | grouted rebar | plain shotcrete |
| Ductile | Cone bolt | yielding Swellex bolt | chain-link mesh; lacing |

The support elements studied in this thesis will be described in detail in later sections.

The general overview of the steps involved in ground support installation cycle is shown in Figure 2.2.

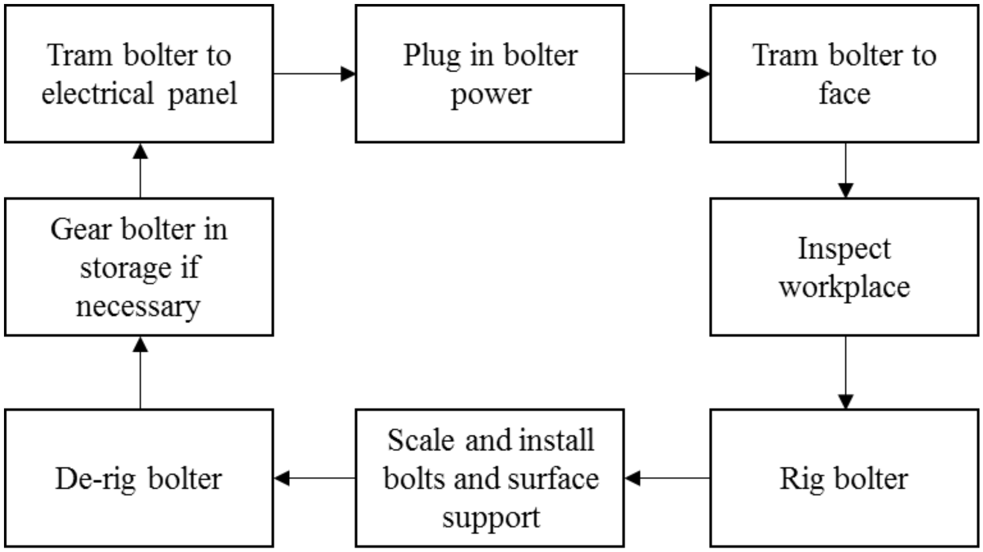



Figure 2.2 Ground support installation cycle for rockbolters

The details of the ground support installation cycle depend on many factors such as machine types available to install ground support, mine-specific procedures, legislative requirements, rock mass conditions, and mine logistics. Detailed flow charts and illustrations of the ground support installation process are shown in Appendix B.

## 2.1 Description of Rock Bolts and Surface Support

The types of ground support to be installed depends on the mine's ground conditions, the static and dynamic loads that the support system is subjected to, the cost of the support system, and other factors such as corrosion, expected lifespan and function of the excavation, and machines available to install the ground support. The ground support strategy can vary in different locations in the same mine depending on local mining conditions. The ground support installation pattern, bolt types and required surface support to be installed are described in the mine's ground support plan, and communicated to machine operators for installation.

Rock bolts are generally classified into three categories as shown in Figure 2.3 where:

- CMC = continuous mechanical coupled;
- CFC = continuous friction coupled;
- DMFC = discrete mechanical and friction coupled.

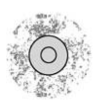
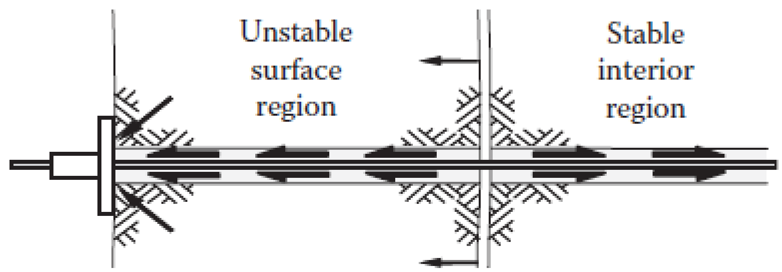
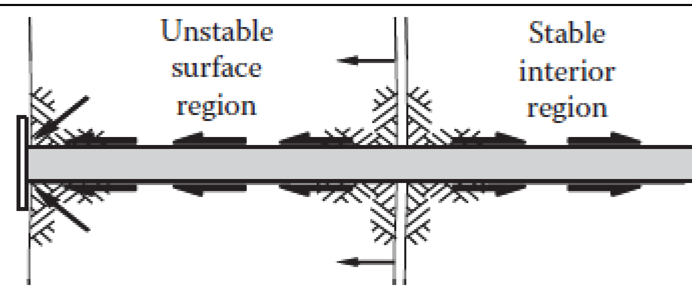
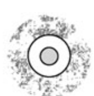
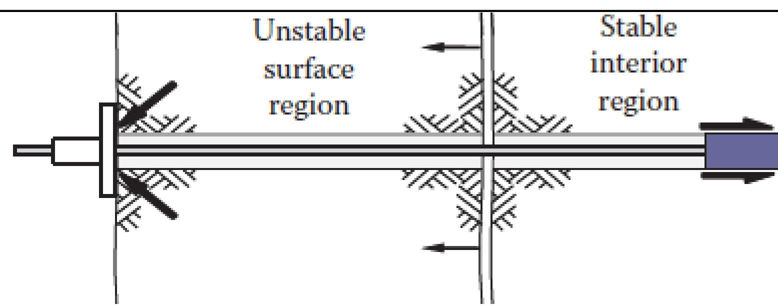
| Type | X-Section | Longitudinal view of reinforcing element |
|---|---|---|
| CMC |  |   |
| CFC |  |   |
| DMFC |  |   |

Figure 2.3 Diagram of typical reinforcing elements (Thompson, 2012 et al.; Villaescusa, 2014)

Resin rebar (resin grouted bolt) and Split Set[4] bolts are the most frequently installed bolts in Canadian mines due to the low cost of Split Sets and the reinforcing strength of resin rebar.

Sections 2.1.1-2.1.3 describe the types of bolts and surface support which were installed during the course of the case study which is described in detail in Chapters 5 and 6.

### 2.1.1 Resin Rebar and Modified Cone Bolts

Resin rebar and Modified Cone Bolts (MCBs) are anchored bolts typically used to support the back[5] in Canadian mines. Diagrams of rebar and cone bolts with fixture such as plates and nuts are shown in Figure 2.4 and Figure 2.5.

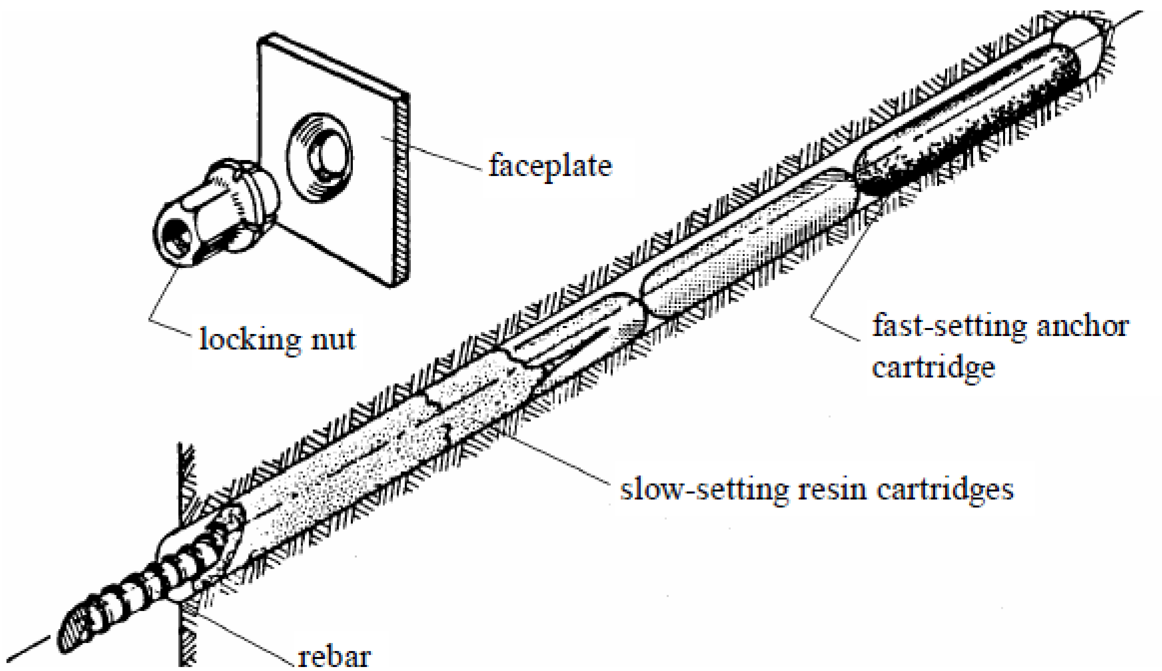



Figure 2.4 Setup for a resin anchored and grouted rock bolt (Hoek et al., 2000)

[4] Trade mark name by the Ingersoll-Rand Company
[5] Known as the “roof”, the upper part of a mining excavation


Figure 2.5 Modified cone bolt (Mansour Mining, 2012)

Resin rebar is installed where a high level of static support is required. Modified cone bolts are installed where yielding and dynamic support is required in highly stressed ground. For both bolt types, the installed bolts are encapsulated with four resin cartridges. The installation process is similar for both bolt types; Figure 2.6 shows an illustration the rebar installation process. In addition to rock bolts and screen, plates are installed on the collar of the rock bolts to provide contact between the bolts and rock or screen. A threaded nut with a shear pin is used to tension the bolts with the bolting tool.

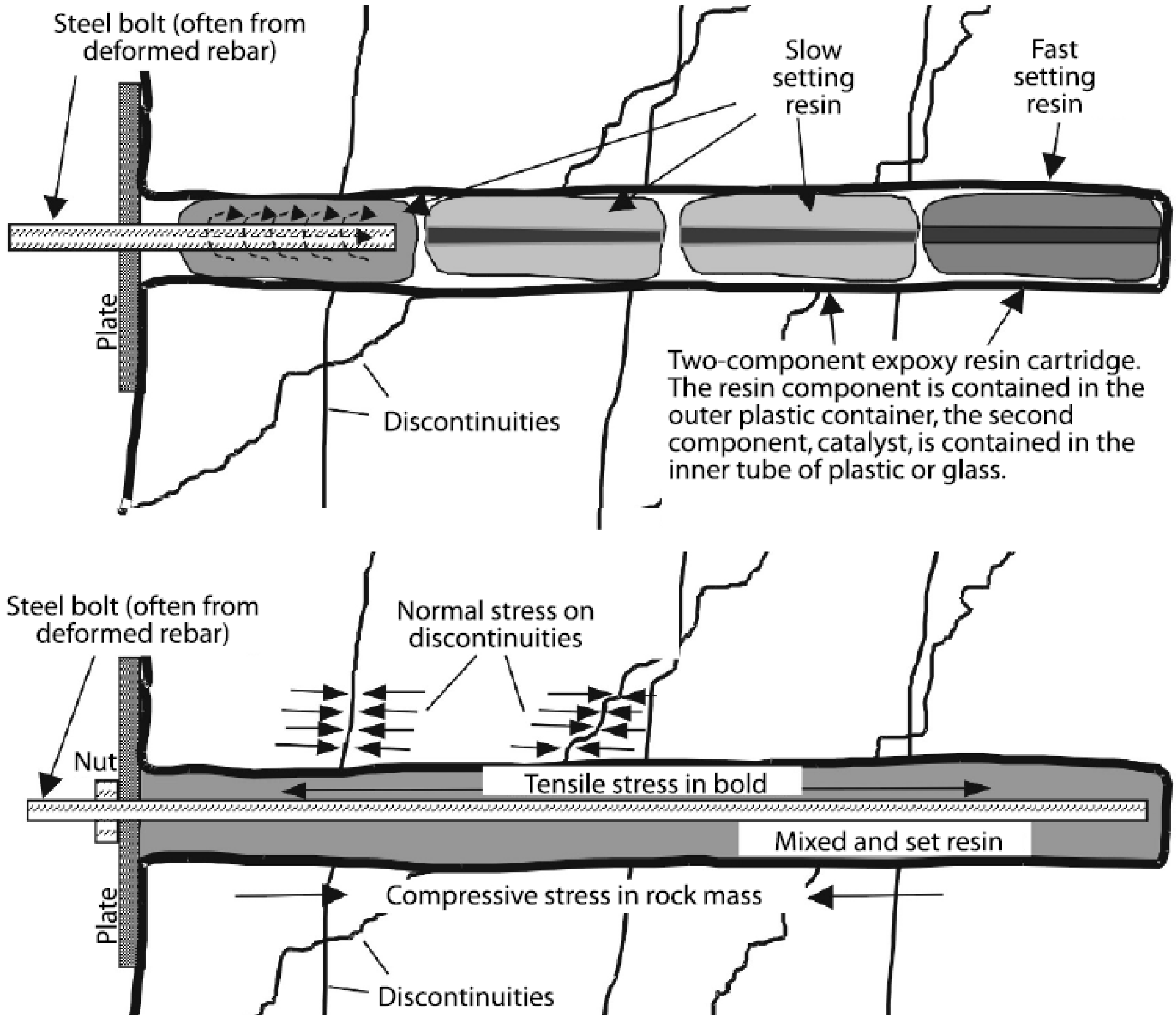



Figure 2.6 Illustration of resin rebar installation and related terminology (Price, 2008)

Details of the bolt installation procedures are described in Chapters 5 and Appendix B.1.

## 2.1.2 Split Sets and Swellex

Split Sets and Swellex[6] bolts provide frictional reinforcement through the contact between the reinforcing element and the wall of the borehole (Kaiser et al., 2000). Split sets provide this reinforcing capability by driving an oversized tube into an undersized hole. Swellex provide

[6] Trade mark name owned by Altas Copco Aktiebolag

reinforcement by expanding an undersized tube into an oversized hole using water pressure (Villaescusa, 2014). A diagram and image of a Split Set is shown in Figure 2.7. An illustration of a Swellex bolt and its installation procedure is shown in Figure 2.8.

Figure 2.7 Picture of a Split Set bolt with plate (Scott, 1983)

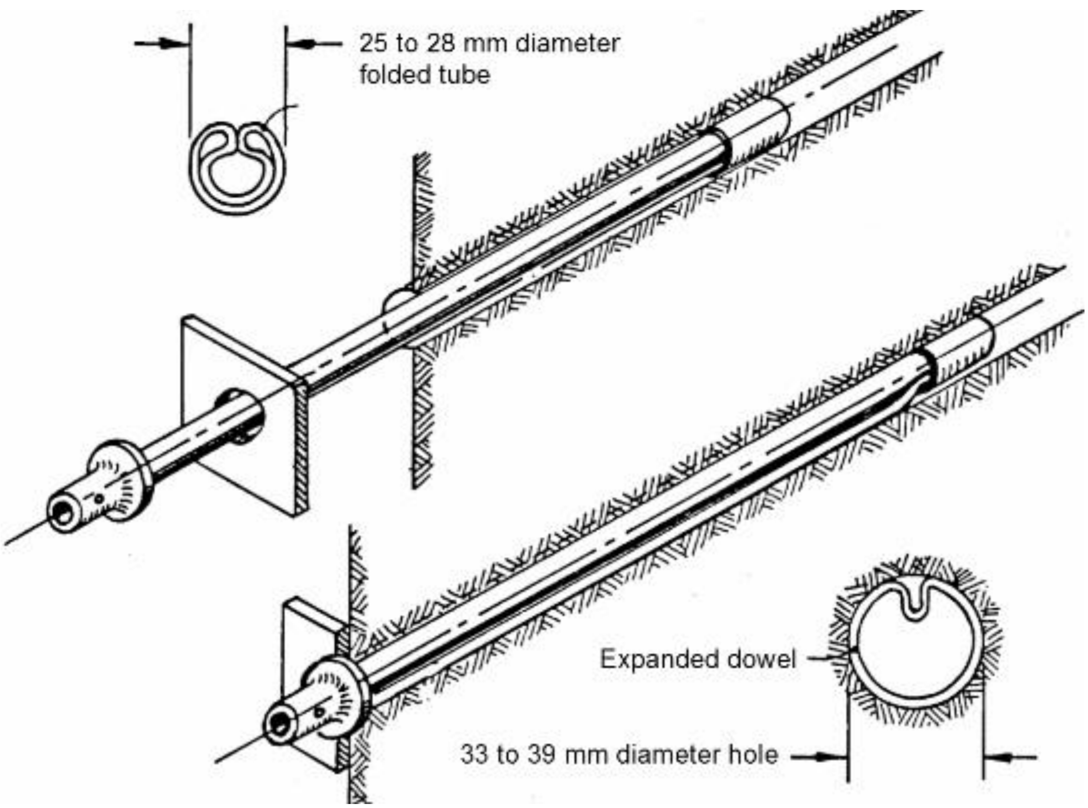



Figure 2.8 Atlas Copco Swellex bolt before and after inflation (Hoek et al., 2000)

Other types of rock bolts can be installed for ground support, but these bolts are less common than the ones discussed in this section and will not be discussed here.

## 2.2 Surface Support

In addition to bolts, surface support is installed to retain falling rock, and in some cases, reinforce the rock mass. The three types of surface support commonly used in mining are shotcrete, Thin Spray-on Liners (TSLs), and mesh.

Shotcrete is sprayed on concrete which is used to retain falling rocks and reinforce the rock mass. Welded wire mesh is often embedded in shotcrete to create a composite structure to create tensile strength, and protect the mesh and rockbolts from corrosion. Shotcrete is often sprayed as-needed in Canadian mines since this adds another component to the development cycle.

Similar to shotcrete, TSLs can be used to retain falling rock. TSLs are not often used in operating mines in Canada since it adds another phase to the development cycle, and after application, the work area must be cleared from contaminants which are released into the air during installation. There are also concerns about fire hazards created by TSLs.

Both shotcrete and TSLs require rock surface preparation, are costly, require purpose-built equipment, specialized training, and are prone to quality control issues. Therefore, mesh (or mesh embedded in shotcrete) is the most common type of surface support installed in Canadian mines.

Mesh and screen come in a variety of types and sizes from different suppliers. The most common types of mesh that are used in mines are welded wire mesh, and chain link mesh (see: Figure 2.9). Welded wire mesh is transported underground in sheets, and chain link mesh is usually transported in rolls. The type of mesh that is installed depends on the desired load-displacement characteristics of the mesh, and the equipment available to install it.

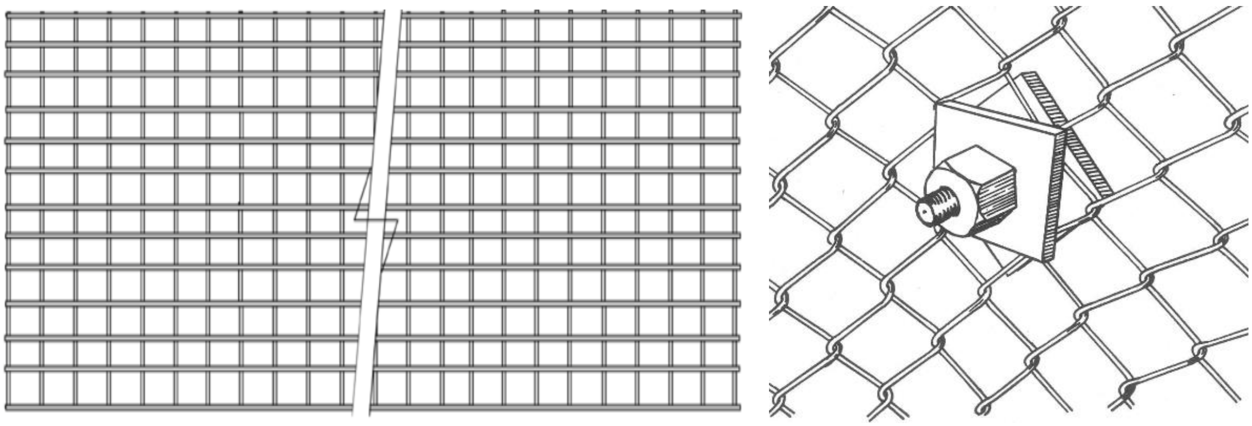


Figure 2.9 Left: Illustration of welded wire mesh (Mansour Mining, 2012); Right: Chain link mesh (Hoek et al., 1995)

Low gauge mesh plates and straps are often used to improve the contact between the bolts and mesh, and low gauge mesh straps are used to “link” the bolts together for improved retaining and load transfer capability (see: Figure 2.10).

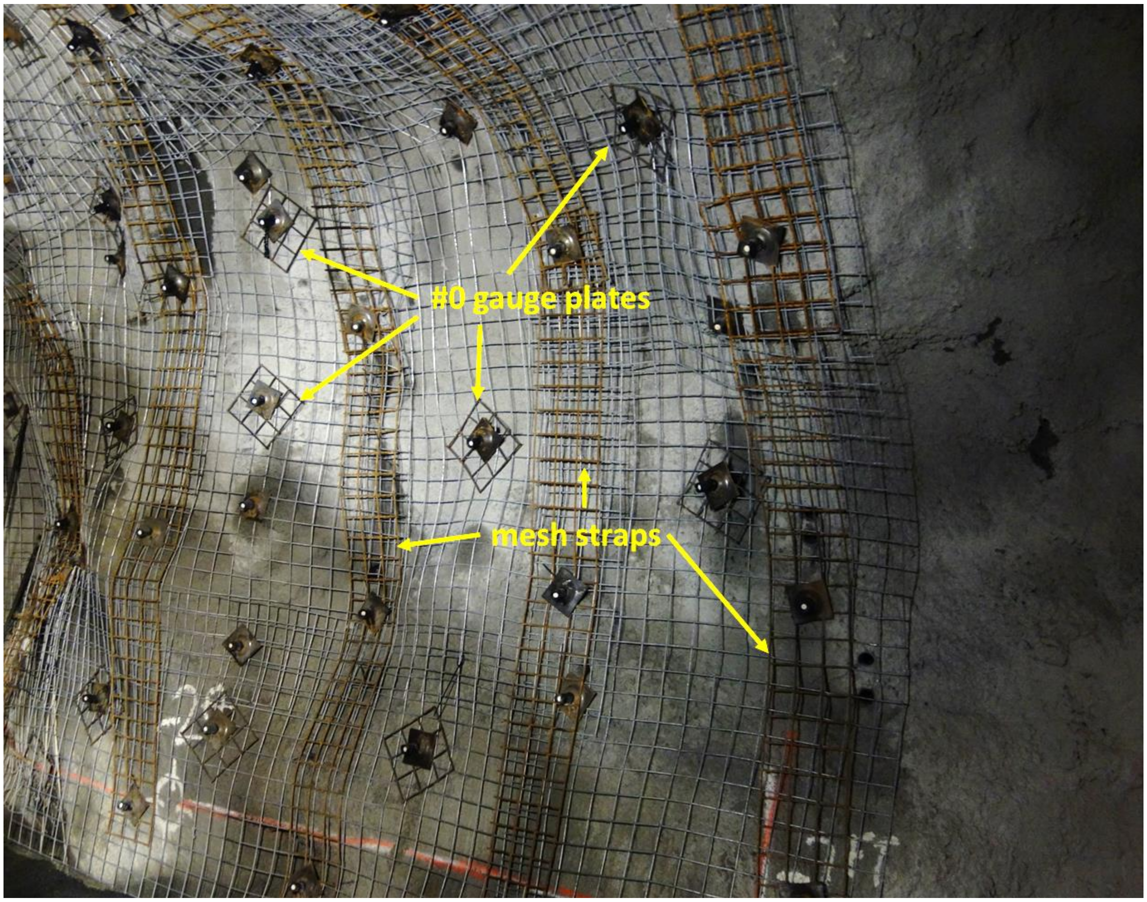



Figure 2.10 Bolts installed through #0 gauge plates, mesh straps, typical #4 gauge mesh, and mesh embedded in shotcrete (enhanced support system for permanent excavations at a mine site)

Depending on the estimated ground support requirements, combinations of rock bolts and surface support are chosen to be installed systematically by ground support equipment.

## 2.3 Ground Support Installation Equipment

Different equipment and methods are used to install bolts, screen and accessories. Figure 2.11 shows illustrations of the equipment typically used to install ground support. This equipment is generally classified based on the level of mechanization as:

a) **Manual bolting:** Hand-held bolting completed by one operator with a hand-held drill (Figure 2.11a).

b) **Semi-mechanized bolting with a jumbo:** Holes are drilled with a drilling machine such as a jumbo (machine designed to drill into walls or the back, or face). Bolts are installed by using a modified jumbo boom, or installed by hand after drilling is complete. This is typically a two-person operation since bolts are installed from a basket, or a helper is required to place bolts into the jumbo booms (Figure 2.11b).

c) **Semi-mechanized bolting from a scissor deck:** Holes are drilled with a boom attached to the front of a scissor deck. One operator places resin into the hole, and the places bolts into the boom for installation (Figure 2.11c).

d) **Mechanized bolting:** An operator drills and installs bolts by controlling a boom from an enclosed cab. The operator exits the cab to reload a bolt magazine or carousel (Figure 2.11d).

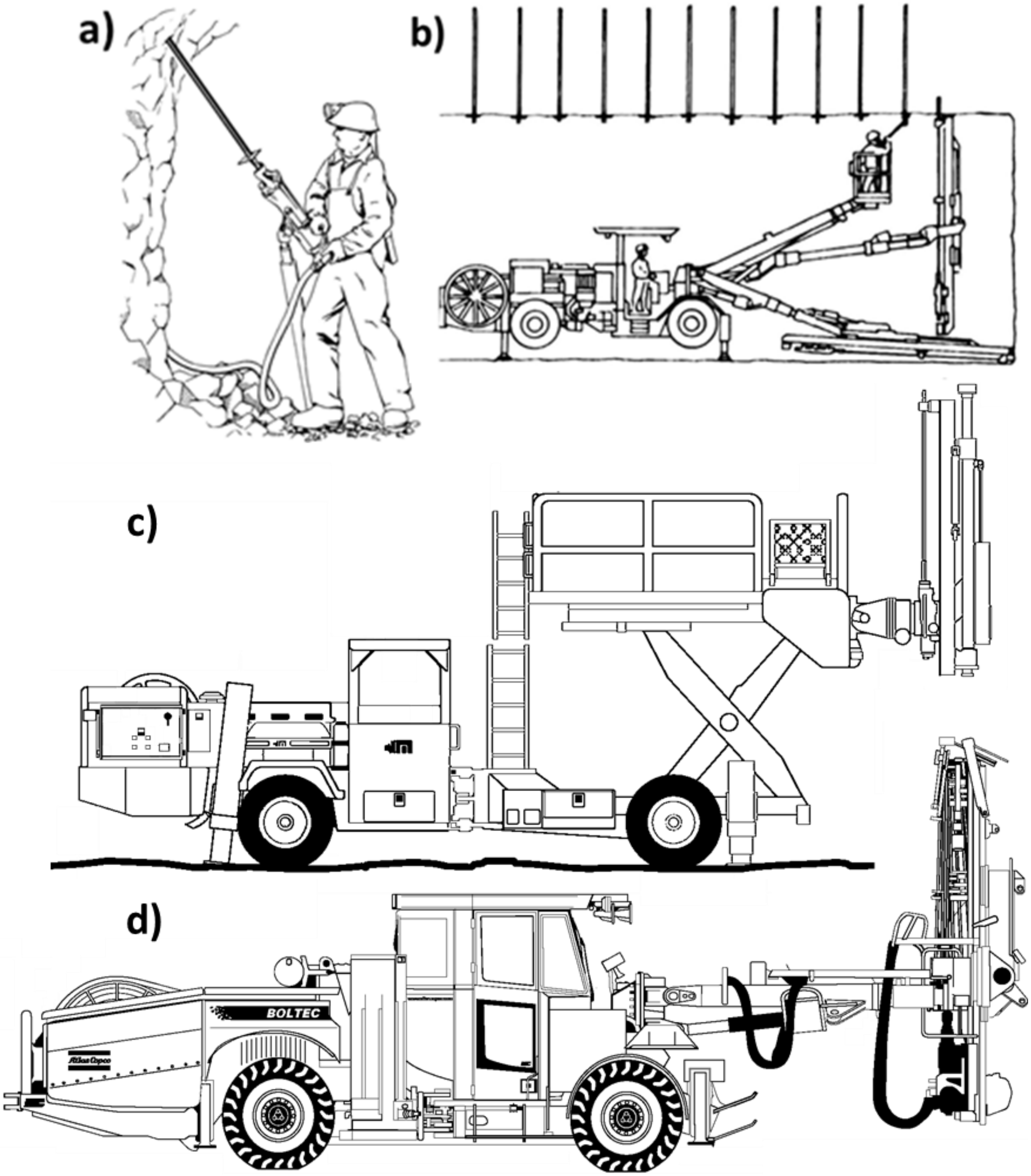



Figure 2.11 a) Manual bolting (Stillborg, 1994), b) Semi-mechanized bolting with two operators (Stillborg, 1994) c) Semi-mechanized bolter, single operator (MacLean Engineering, 2015); d) Mechanized bolter (Atlas Copco, 2015)

Bolters can be modified from the original manufacturer's specifications to suit mine-specific bolting, safety and maintenance requirements. Details about mine-specific bolter operation is shown in Chapter 5.

Despite improvements drilling and bolting technology, the more advanced equipment is often not found to be more productive than less sophisticated equipment in the mining industry (Laverdure & Fecteau, 2004).

# Chapter 3

# Literature Review

## 3.1 Introduction to the Literature Review

The objective of this chapter is to review literature addressing the ways in which processes and equipment are measured and compared in disparate environments.

To the Author's knowledge, there is no standardized methodology or metric used to analyze the productivity of underground mining equipment and processes that is extensively applied in the available literature. This makes it difficult to compare the productivity of mining equipment based on the current literature, in particular, literature on the productivity of ground support installation equipment which is the primary focus of the thesis.

Standardized terminology, methodology and metrics are prevalent within the manufacturing industry to measure and compare processes and equipment. Lööw (2015) conducted a literature review to extract relevant findings from articles and papers published about applying manufacturing (or "lean") principles in a mining context to improve mine process productivity. The general findings from Lööw's literature review are that while manufacturing principles can increase the productivity of mining processes, practical application of the methodology and measures used in manufacturing may be hindered when applied to mining processes which interact with the natural environment which are more variable than manufacturing processes. This limits the ability for mines to successfully implement lean philosophies in the same way that the manufacturing sector has been able to accomplish. Unfortunately, for the majority of the literature reviewed in the mining context, the methodology to *measure* the productivity of equipment is not clearly defined, and this makes comparing the productivity of equipment difficult.

Dunstan et al. (2006) showed examples of how applying lean principles from the automotive sector has been successful at different mine sites for improving productivity. The authors didn't specify measurement techniques to measure the equipment in sufficient level of detail so that the equipment productivity could be quantified in the same way, or compared to equipment productivity at other mines. The authors developed a table to compare the automotive industry to the underground mining industry to show the differences between industries which can cause issues with the implementation of lean manufacturing philosophies. After conducting a thorough review of how equipment is measured and compared in different industries and which industries have standardized measurement methods, it was found by the Author that forestry industry has similar work environments as mining, and also has harmonized (not standardized so different measurement and analysis techniques can be used) ways of measuring and analyzing equipment productivity.  A table was created to compare industries by Dunstan et al. (2006); it was expanded (Table 3.1) to show the similarities and differences between these three industries – underground mining, manufacturing and forestry.

Table 3.1 Comparison of the underground mining, manufacturing, and forestry industries (modified and expanded from Dunstan et al., 2006)

| **Underground Mining** | **Manufacturing** | **Forestry** |
|---|---|---|
| Variable and often extreme temperature and humidity | Indoor environment, controlled | Outdoor environment |
| Remote locations | Large centers | Remote locations |
| Generates dust | Little dust | Presence of dust |
| Continuous cyclical processes, extractive | Discrete or continuous production | Continuous cyclical processes, extractive |
| Variable and controlled raw materials and interfaces | Controlled raw materials | Variable raw materials |
| Spread out teams | Compact plants | Spread out teams |
| Travel time during shift | Little travel time during shift | Travel time during shift |
| Lower equipment effectiveness than manufacturing | High equipment effectiveness | Lower equipment effectiveness than manufacturing |
| Noisy environment and processes | Noise varies by process | Noisy environment and processes |
| Workers are exposed to machine vibration | Vibration exposure is limited | Workers are exposed to machine vibration |
| Machine and cap lamp lighting, variable lighting, impaired by shadows, water and dust | Controlled lighting | Variable outdoor and machine lighting, impaired visibility from outdoor elements |

Since equipment in the forestry industry interacts with a natural and variable environment, there are many more similarities between underground mining and forestry industry processes than between mining and manufacturing processes. Furthermore, the forestry industry has standardized work measurement and analysis procedures which are likely to be compatible with the mining industry due to the similarities between the industries. Work studies which are published in the literature are common in the forestry industry. The sources of process measurement methods in forestry, mining and manufacturing have the same origin – a publication by F.W. Taylor in 1895 entitled “[a] piece-rate system being a step toward partial solution of the labor problem” where a scientific approach to work study was developed. This publication is the foundation for modern work measurement in most industries.

Given the similarities between mining and forestry, an investigation into forestry equipment measurement and analysis procedures will be shown later in this chapter.

Literature about the quantification and analysis of equipment productivity will be investigated for the mining and forestry sectors to find a suitable procedure to measure and compare the productivity of mining processes. Specifically, the focus of the review is to find an appropriate method to quantify and compare the rock bolting process in different conditions at different mines.

## 3.2 Metrics Used to Analyze Equipment Productivity in Mining

Several data collection methods and analysis methods are used in available literature to quantify the productivity of mining equipment (for example: Boudreau-Trudel et al., 2014; Boudreau-Trudel et al., 2015; Dindarloo, 2016; Fourie, 2016; Lanke & Ghodrati, 2016; Stecuła & Brodny, 2016; Hawkes et al., 1995, 1994; Kumar et al., 2013). While the general definition of productivity is a ratio of unit of output and input, there are multiple approaches to measuring and analyzing equipment productivity in the mining industry. This makes it difficult to compare equipment productivity and the factors that contribute to equipment productivity (such as work methods, external conditions, maintenance practices etc.) based on the available literature. The following metrics will be described and assessed for how the metric and data collection methods are applicable for the purposes of comparing equipment at different mines:

- Overall Equipment Effectiveness,

- Mine Production Index,
- Maintenance Analysis, and
- Delay Analysis.

Kenzap (2006) used the data collected for the thesis by Peloquin (2007) to simulate how drift quality affects the performance of the development cycle. Multiple statistical methods based on manufacturing were used to analyze development processes including rock bolting. Kenzap (2006) used process capability charts, control charts, and other statistical methods to characterize the performance of mining processes. This is a good example of how manufacturing analytics can be applied to the mining development cycle, particularly the rock bolting process.

## 3.2.1 Overall Equipment Effectiveness and Mine Production Index

OEE is a measure of Availability, Performance, and Quality of equipment output to calculate if equipment conforms to its output requirements (Muchiri & Pintelon, 2008). OEE is calculated as shown in Equation 1.

$$OEE = Availability * Performance * Quality \quad (1)$$

Paraszczak (2005) suggests that mining equipment can be measured using Overall Equipment Effectiveness (OEE), which is a metric that is commonly used in the manufacturing industry, and was originally described in Nakajima (1988). Many authors criticize the applicability of the Quality term in the OEE calculation since it may not be relevant or easily quantifiable for all mining processes (Paraszczak, 2005, Dindarloo et al., 2016). This is important because the relevance of OEE in the context of mining can mean that the metric may not be appropriate for mining process comparison.

Elevli & Elevli (2010) used OEE to measure mine trucks, however they used hypothetical data. They conclude that "[t]he importance of proper data collecting system to estimate OEE is also emphasized. If data are not properly collected then the resulting OEE will not be meaningful."

A literature review about OEE was completed by Lanke et al. (2014) and Lanke (2016). In this work, the author assigned weights to each component of OEE to develop a Mine Production Index (MPi) for the purposes of determining how processes affect each other.

OEE is not a suggested measure for comparing the productivity of mining equipment because:

- OEE may not be an effective measure of the drill-and-blast mining method due to the discrete cyclical nature of the process; utilization of the equipment can be affected by the production of the previous equipment (Elevli & Elevli, 2010)
- Since the work environment a mine varies over time and in different work locations, the OEE of equipment is not one number for an entire operation (Burt & Caccetta, 2014)
- The definition of "availability" is not agreed upon in literature (Williamson, 2006)
- The definition of "utilization" may include or exclude supportive work such as tramming equipment from work face to work face and gearing equipment,
- The quality or performance components of processes such as rock bolting are dominated by the quality of the drill-and-blast components of the development cycle where it is difficult to standardize processes such as rock bolting where performance of the process can be dominated by rock conditions and bolt type, and not the effectiveness or efficiency of the equipment (Lööw, 2015).

Therefore, OEE will not be used as a metric to measure the productivity of the ground support installation process.

## 3.2.2 Maintenance Analysis for Productivity Characterization

To measure the availability (which is a component of productivity) of mining equipment, maintenance analysis is commonly used to quantify equipment downtime. Many authors state multiple challenges with how mine maintenance records are generated, standardized and interpreted (Dunn, 1997; Hall, 1997; Hauge et al., 2010; Metso, 2013; Zimmerman, 2000; Ho, 2015), and large amounts of uncertainty in the records introduces error in the equipment performance measurement.

According to Paraszczak (2000), maintenance analysis alone is insufficient to measure equipment effectiveness. Depending on the data collection practices at mines, the information recorded about delay time is often inconsistent and/or meaningless as a measure of equipment performance (Paraszczak, 2001). Paraszczak (2001) emphasizes the need for standardization of maintenance terminology and reliability nomenclature, and data collection procedures. There is also a need to standardize reliability and maintainability terminology as well as standardization of data collection procedures (Paraszczak, 2001). Therefore, comparing the productivity of mining equipment based on equipment maintenance records would introduce large amounts of error, and doesn’t account for differences between different mining operations that affect equipment performance.

### 3.2.3 Delay Analysis

Since maintenance is only a component of downtime analysis, all delays that affect the productivity of mining processes and the cause of the delays should be quantified to compare equipment. Eshun & Temeng (2011) conducted a study to analyze delays that affect lateral development rates in an underground mine. Delays were quantified over the course of one year, however the method to gather the delay information was not described in detail. The authors analyzed delays using methods derived from the manufacturing sector such as fishbone and Pareto analysis to isolate the causes of delays. They found approximately 80% of the delays were caused by less than 20% of the causes of delays. Their analysis could be applied to measuring individual pieces of mining equipment, or the development process as a whole since their analysis method is visual and effective.

### 3.2.4 Observations About Mining Productivity Metrics

Since metrics used to measure mining equipment are derived from the manufacturing sector, and the metrics are not always suitable for mining processes, it is necessary to search for an industry that has similar problems, and has successfully measured and compared equipment productivity in a standardized way. Also, many of the measurement methods used to measure mining processes fail to account for mine-specific factors that affect equipment output for the purposes of comparing equipment productivity.

## 3.3 Productivity Studies Completed in the Area of the Research Application: Rock Bolting

A review of literature was done on published studies which quantify the productivity of the rock bolting process. The purpose of this section is to assess which factors affect the performance of rock bolters, and to find out if there is a standard measurement and analysis methodology to compare rock bolters in different conditions.

Peloquin (2007) measured rock bolting in Canada and Sweden to compare the quality of lateral development in mines. He obtained productivity results using time studies, but the method used to conduct the time study was not described in detail. In this study, it was found that drifting quality could affect the productivity of the bolting cycle. For example, poor blasting practices result in the need for more bolts to be installed.

Franklin (2008) used Ishikawa diagrams to illustrate the causes for low bolter productivity and to find meaningful components of the bolting process which can be improved to achieve the mine's productivity targets.

Forsell (2013) and Harpila (2013) conducted time studies[7] on mechanized bolters in Europe to study the suitability of mechanized bolters for specific projects, and to quantify whether the bolters can meet worksite productivity requirements. Their data collection protocol was not disclosed in detail. Forsell (2013) reported that there were data quality issues in his study to measure work capacity of the bolter because of how downtime and work time was defined was

[7] Measurement and analysis of a process to characterize its productivity

different among individuals. It was emphasized that standardized time definitions would improve the statistical accuracy of the study and reduce variability in the results.

Gustafson et al. (2014) reported on the bolting procedure at Kemi mine in Finland. They attempted to quantify the productivity of mechanized bolters in an ideal maintenance scenario that would be atypical at most mines. They state, "[i]t is somewhat difficult to describe the productivity data for a mechanised bolt rigs" and they propose time categorizations for quantifying bolter productivity. This work was expanded on by the Mining Initiative on Ground Support Systems and Equipment (MIGS) published a suggested categorization of time to measure the productivity of the rock bolting cycle (see: Figure 3.1).

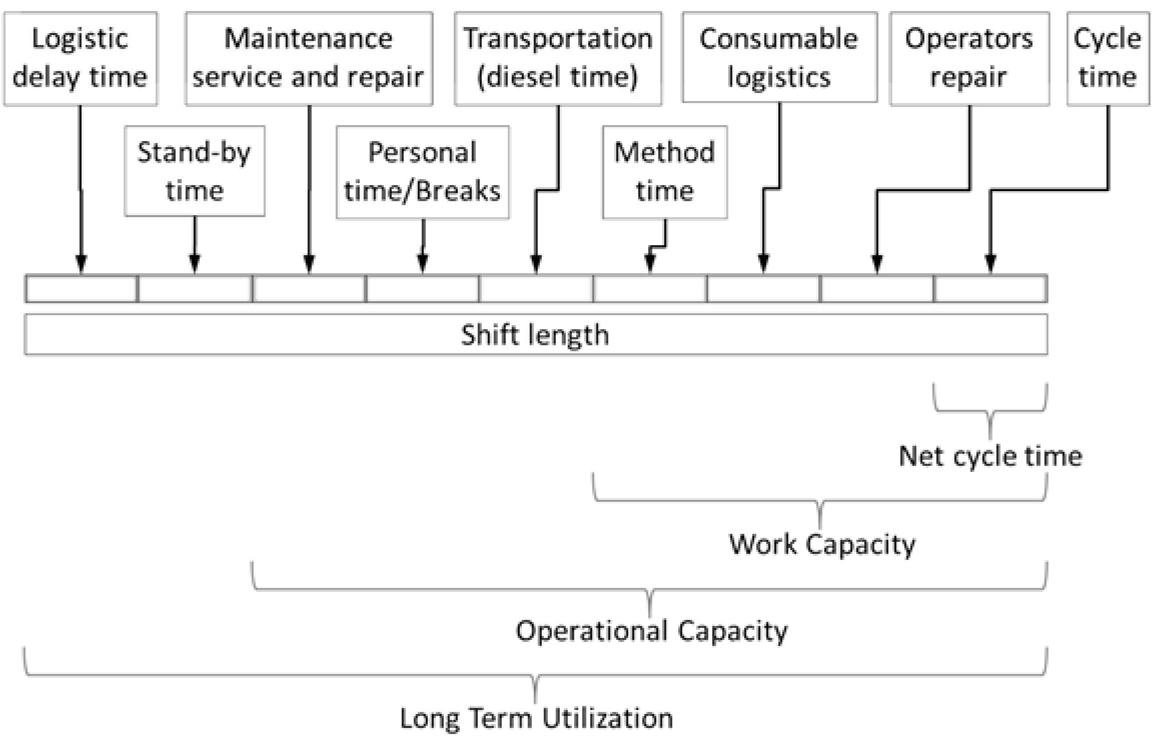



Figure 3.1 Classification of the unit times for rock reinforcement (MIGS, 2014a)

This categorization of time is similar to that used in other industries such as forestry. The methodology to collect data to fit into these time categorizations, and statistically analyze the data was not standardized.

Expanding on this proposed time data classification, Gustafson et al. (2016) published data to compare the productivity of different types of bolters (Table 3.2).

Table 3.2 Measured productivity of bolters at different mines (Gustafson et al., 2016)

| | Expanding friction bolts (Swellex) Mine 8* | Resin-grouted bolts Mine 3 | Cement-grouted bolts Mine 1** | Resin-grouted bolts Mine 6 | Resin-grouted bolts Mine 7 | Cement-grouted bolts Mine 5 (in-house) | Cement-grouted bolts Mine 5 (contractor) |
|---|---|---|---|---|---|---|---|
| Net cycle time (bolts/hour) | 30 | 17.6–20.6 | 19.5 | 15.3 | 13.6 | | |
| Work capacity (bolts/hour) | 13–19 | 10 | 11.3 | 7.88 | 7.61 | 4.15–6.57 | 7.27–8.21 |
| Long-term utilization (bolts/hour) | 5.69 | 4.45 | 2.62 | 3.63 | 4.05 | 2.07 | 3.95 |
| Number of bolts/year | 29130 | 21400 | 17300 | 20000 | 20000 | 10300 | 19300 |

*Optimized maintenance, **complicated logistics

The authors concluded that mechanized bolting is superior to semi-mechanized bolting, however all of the bolters were installing different types of bolts in different ground conditions in countries that have different work cultures. Also, the data were collected in different ways. For the studies in Canada, data were collected through manual time study, and the data collected in Sweden was digital machine records data. Some of the results demonstrate that even at the same mine, contractors were measured to have nearly double the annual work capacity (bolts/year/machine) compared to in-house bolting. In the results table above, one mine is described as having “optimized maintenance”, and another has “complicated logistics”. These factors that affect the equipment performance are not described in detail in the paper. The duration of the studies and specifics about the work practices at each mine were not specified.

The work methods and activities used to mine drifts are different in Canada and Sweden (Peloquin, 2007). Also, mine drifts are typically covered in shotcrete in Sweden, but this is not typical work practice in Canada (Peloquin, 2007; Gustafson et al., 2016). Supported by the findings of Peloquin (2007), Canadian operators are expected to scale from the bolting rig at the face, whereas Swedish mines have scaling machines to scale. Scaling using the bolter in Canadian mines can contribute to additional maintenance at the face due to rocks falling on the equipment.  If Canadian mines used the same work practices as Swedish mines (or vice versa), then the performance of the equipment would likely be different what was measured in the field. These external variables should be accounted for, and the conclusion by Gustafson et al. (2016) that fully mechanized bolting equipment is superior to other equipment from a productivity standpoint could be due to the different data collection protocols, external conditions, work methods or statistical significance of the data.

Numerous studies have been done to quantify the productivity of the rock bolting cycle, and other mining processes, for example, (Menasce & de Jager, 2006; Stewart et al., 2006; Proudfoot & Swan, 2007; Wilcox, 2008; MEDIATech, 2009; Farrokh et al., 2011; Hubert, 2015; Healy et al., 2016; Lanke & Ghodrati, 2016), however different methods were used to collect data, or the data collection methods are not described in enough detail to replicate the results. Literature which describes measurement of forestry processes will be examined to see if there is a standardized way to analyze and compare processes in a reproducible way which can be applied to mining equipment and processes.

## 3.4 Work Measurement Methods in the Forestry Industry

The forestry industry has similar challenges as the mining industry for the ability to compare process performance. Forestry work studies are affected by many influencing variables due to working in a natural environment such as tree size, tree type, tree spacing, workplace layout, weather, slope, and human factors (Olsen et al., 1998). This is similar to the mining environment where productivity of equipment is affected by similar factors (see: Figure 3.2).

**Commonly Measured Failure Costs:**
Secondary drilling & blasting, delays

**Hidden Failure Costs:**

- The performance of a particular process,
- Compounding effects,
- Breadth of training,
- Equipment & materials performance,
- New technology implementation,
- Ground problems,
- Shift schedules,
- Integration of primary/secondary mucking and parallel activities in heading,
- Engineering time,
- Management time,
- Over-break,
- Geological structure,
- Lost opportunity

Figure 3.2 Factors that affect mining processes, both natural and man-made which are similar to the factors that affect equipment performance in the Forestry Industry (modified from Kenzap, 2006)

It was recognized by forestry researchers that to compare forestry processes internationally, a common set of terminology had to be used (Koŝir et al., 2015). Björheden (1991) published

“Basic time concepts for international comparisons of time study reports” which was further refined by researchers belonging to the International Union of Forest Research Organizations (IUFRO), which resulted in the publication “IUFRO Work Study Nomenclature” (Björheden et al., 1995). This terminology has been the basis of time study in the forestry industry, and it has been scrutinized, expanded and improved upon.

Guidebooks have been developed to describe how to collect and analyze data since work study is a mature topic in the forestry industry. There are two major publications which are commonly referenced and used in the forestry community:

*Statistical Comparison of Methods Used in Harvesting Work Studies* by Olsen et al. (1998) - The primary focus of this book is how to deal with variation in work study data to statistically compare different forestry processes, and to allow collected data to be used in a predictive capacity. Olsen et al. (1998) also focuses on the granularity of data required to statistically analyze processes, and how much data is required based on the amount of detail contained in the data.

*Good practice guidelines for biomass production studies* by Magagnotti, N. & Spinelli (2012) – This is a practical guidebook for how to conduct work studies to meet the study goals. Magagnotti et al. (2013) published a survey about the usefulness of the book showing that it was well received, it is emphasized that if users follow the methods described in the book, results could be translated between different types of studies (or harmonization of work methods).

The primary goal that various initiatives and publications seek to achieve is the harmonization (not standardization) of work study terminology and methods for international comparison of forest production studies (Koŝir et al., 2015). Observational studies describe the current state of a process where no modifications to the process are introduced (Kanawaty, 1992).

Methods to collect, categorize, and analyze data have further been developed, scrutinized and refined within the forestry community. For example, Spinelli & Visser published articles (2008, 2009) about how the measurement of delays varies locally, and they perform delay analysis based on large amounts of time study data for different processes.

Despite some local variation in methodology, enough publications and studies have been completed to conduct meta-analysis for different forestry operations. For example, Ghaffariyan et al. (2013) compiled a meta-study of 201 individual case studies for a forestry process, and was able to develop a statistically significant model that accounted for different sources of variability (natural and unnatural) observed in the case studies.

Another example of a large meta-study was completed by Hiesl & Benjamin (2013) where 27 studies on different machine types collected over the course of 25 years were compiled to predict the productivity of harvesting systems in Maine. The authors concluded that individual equipment as well as the harvesting system as a whole should be measured to reduce bottlenecks in a system.

Studies have been conducted to compare the time study observers (For example: Spinelli et al., 2013 and Nuutinen et al., 2008) to investigate the variability that the observer's interpretation of work elements introduces to studies. Spinelli et al. (2013) compared timekeepers studying a tree processing operation to gauge the variability among observers. Work elements and break points (the point at which time elements begin and end) were described to the observers. It was found that variability among observers was seldom significant. The study concludes that work elements should be divided into as many elements necessary to meet study objectives and too many work elements will lead to loss of accuracy and reliability of results, particularly when studies last for more than two hours. The study emphasizes the need for harmonization of time study methodology and nomenclature for comparative time studies completed in different countries. Keeping the time study method as simple as possible will allow the study to be replicated accurately by multiple researchers regardless of their level of experience. Studies such as this contribute to further refinement of the methodology used to measure forestry equipment and processes, and account for variability caused by the researchers conducting such studies.

Specific methodology and terminology used in forestry will be applied in combination with methodology and terminology from other industries in Chapter 4 to develop a methodology to measure and compare the productivity of mining equipment.

## 3.5 Conclusions

Minimal work has been done to study the productivity of rock bolting equipment and processes. Studies that have been completed to measure rock bolting equipment have not used consistent data collection and analysis procedures. Therefore, it is difficult to account for variables that affect the process, and predict or model how bolting equipment would perform at different work sites in different conditions.

The categorization of data used by the forestry community is similar to that proposed by MIGS (2014a) however it has widespread use within the forestry community to measure the productivity of many processes.

Many existing metrics such as OEE or delay analysis are insufficient to quantify and compare mining equipment productivity in variable conditions. Also, the methods used to collect data, and statistical analysis of the data is often not described which makes comparing equipment productivity data even more challenging.

Given the successful and widespread implementation of a methodology used for equipment productivity comparison found in literature in the forestry industry, components of analysis completed in mining and forestry industries combined with data collection protocols will be described in detail in the next chapter to formulate a harmonized way of measuring mining equipment productivity. The results of applying this methodology to measure, analyze and compare the rock bolting process at three underground mines will be shown in Chapter 6, and the applicability of these methods will be discussed in Chapter 7.

# Chapter 4

# A Methodology for Completing a Work Study in Underground Mines to Quantify the Productivity of the Installation of Ground Support

## 4.1 Introduction

This chapter describes a work study methodology that was developed for the purposes of this thesis. The chapter structure is the following:

- Description of the background to develop the methodology,
- Time classifications,
- Statistical methods to determine the study length,
- How to gather qualitative data to support the results,
- Description of tools and charts used to report the data.

## 4.2 Work Study Methodology Development

The work study method described in this chapter in the specific context of the ground support installation process in underground mines based on methodologies used in the manufacturing, forestry and mining sectors. The purpose of this method is to harmonize mining work study terminology and measurement methodologies. By collecting, describing, reporting and classifying work study data in an appropriate framework, meaningful comparisons of similar processes can be made. Additionally, causes of variation during work processes can be identified to quantify the causes of equipment productivity to improve productivity. Similar approaches have been successful in other industries such as manufacturing and forestry (Ackerman et. al, 2014; Bjorheden & Thompson, 2000; Magagnotti and Spinelli, 2012; Montgomery, 2007; Olsen et. al, 1998). To perform a work study, quantitative and qualitative data is collected to measure work cycle time, describe the study, the work study setting and determine the root causes for delays and productivity losses based on previous work done in the manufacturing, forestry and mining industries. The work study methods could in expanded or improved upon for future studies.

*Cycle level* time studies are common in environments with high variability and limited or sporadic access to production and maintenance data (Olsen et. al, 1998). Work study methodology, terminology and classification of time study data applied to semi-stationary underground mining processes such as rock bolting and development drilling are developed in this chapter. This study methodology can be applied to a variety of mining processes such as rock bolting, development drilling, production drilling, crushing, explosives loading, hoisting, and installation of services. The study method could be modified to include mining activities such as mucking and hauling. The methodology presented in this chapter is applied to rock bolters in Chapter 5.

Based on the measurement and analysis techniques described in the literature review (Chapter 3), the methodology for performing productivity studies on mining equipment is described in this chapter. Examples of results from work studies on rock bolters and productivity results from studies completed in other industries are used in the data analysis and reporting section.

## 4.3 Defining the Objectives of the Work Study

Objectives of a work study must be clearly defined so that the outputs of the work study meet the study goals.

Typical goals of work studies processes are:

- To locate inefficiencies in a process,
- Assess root causes for downtime and delays,
- Develop a model for a machine or process which can be used to estimate future productivity,
- Compare the productivity of systems and processes,
- Measure how changes to work methods affect a process.

In industries such as mining and forestry, there are three major types of work study: observational studies, experimental studies, and modelling studies (Ackerman et. al, 2014). The focus of this chapter will be on the framework for an observational cycle-level and element-level time study to describe the productivity of mining equipment and processes.

In this context, typical objectives of an observational mine work study are to measure the relations between:

- *work inputs* such as energy, time, monetary and physical resources and
- *work output* such as the number of holes drilled, number of bolts installed, length of production holes drilled, volume of explosives loaded, tonnes of material moved.

There are many ways in which mining processes can be quantified and analyzed:

- Obtain and analyze work cycle data,

- Describe and quantify process delays and non-value adding processes,
- Identify which delays are mine-specific,
- Estimate shift-level productivity,
- Use cycle-level data combined with shift-level data and maintenance records to estimate the annual productivity of equipment and processes,
- Interview mine workers and mine staff to identify ways in which productivity and processes can be improved,
- Quantify mechanical limitations of equipment in different environmental conditions,
- Allow studies completed in a similar way to be compared; which general equipment and productivity limitations and improvements can be reported,
- Provide qualitative information to describe the study setting and external factors which affect process productivity.

Sufficient amounts of work study data could be used to quantify processes long term by:

- Provide inputs for a cost model of development and production processes,
- Provide input for production modelling, schedule optimization and operational constraints (Song et. al, 2015b),
- Determine theoretical limits for underground development and production rates (Stewart et. al., 2006),
- Quantify the effects of operational and process improvements.

## 4.4 Work Study Design

The work study is designed to meet the overall study objectives applicable to stationary and semi-stationary mining equipment such as rock bolters and jumbo drills since these pieces of equipment complete similar functions. The specific work study design described below is applicable to stationary or semi-stationary mining equipment such as rock bolters and jumbo drills. Cycle-level and element-level time studies completed by field study researchers are effective for determining machine productivity and causes of productivity losses. To conduct the study, researchers shadow operators over the course of a shift, and record and classify the time usage over the course of a shift. For the purposes of this thesis, data is collected using time sheets, and the *cumulative timing method* is used (Freivalds & Niebel, 2013). The time of elements are recorded at the beginning and end of each *work element*, and elapsed time for work elements are obtained by subtraction of time elements.

Based on work completed to define work study terminology in the forestry industry, the general categorization of work (equipment usage or a mining process) is shown below in Figure 4.1.

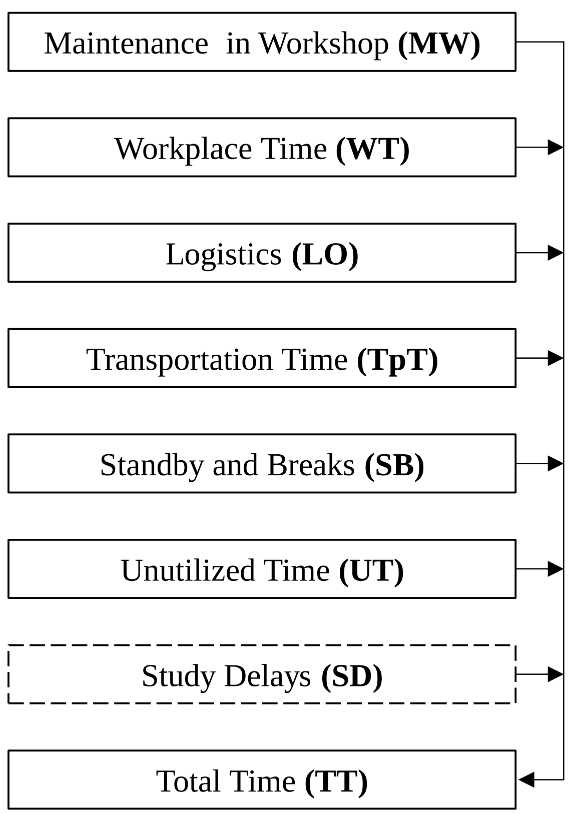



Figure 4.1 Breakdown of Total Time (TT) of equipment usage (after Bjorheden & Thompson, 2000)

The data collected throughout the course of a shift are categorized:

- Maintenance of equipment in the workshop (MW) and routine maintenance is estimated using mine maintenance records.
- Workplace time (WT) is the time which semi-stationary equipment is at the work face to complete the primary work task (for example: bolting or drilling). The general classification of operator activities over the course of a shift is shown in Figure 4.2.

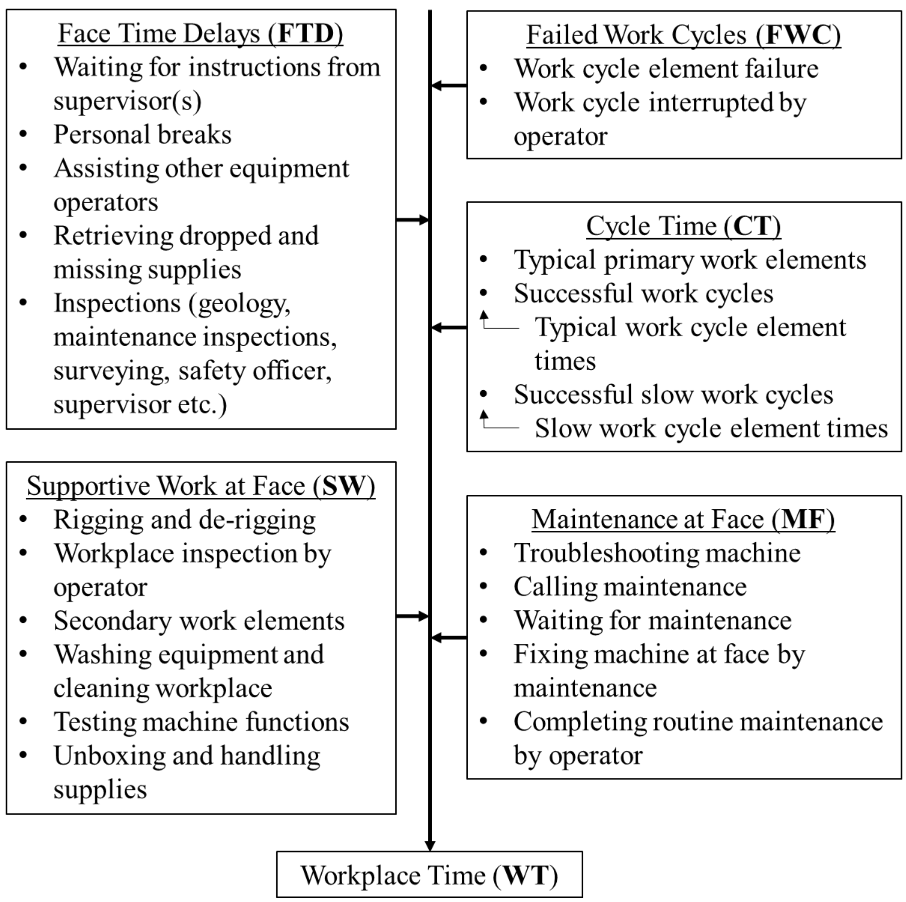



Figure 4.2 Breakdown of Workplace Time (WT) for mine development equipment

- Logistics time (LO) is the time used to gear up equipment, transport personnel, transport supplies to the workplace.

- Transportation time (TpT) is the time used to transport the primary work object (such as tramming equipment and moving equipment to storage).
- Standby and Breaks (SB) is time where equipment could be used, but remains idle due to scheduled breaks and unscheduled breaks. For example: waiting for clearance to enter a work area.
- Unutilized time (UT) is estimated using mine production records, analyzing long term digital machine data (if available) and by interviewing supervisors and operators. Unutilized time designates time between the shifts where equipment is idle, time for blast clearing, training time, mine shutdown time, holidays, time where equipment is available but not used, and time where there is no work to be completed by the machine.
- Study delays (SD) are delays caused by the study researcher during the course of the shift which includes time when the operator waits for the researcher, and when there are safety discussions with the operator during the shift. Study delays are minimized by answering operator's questions about the study before the start of the shift. Study delays are insignificant and are thus omitted from shift time.
- Total Time (TT) is the total shift time excluding study delays.

The researcher measures and categorizes the work completed during the course of a shift. Time categories are defined based on the type of process being observed. Shift time for equipment working at a mine face such as bolters and development drills includes all operator activities (see: Figure 4.3).

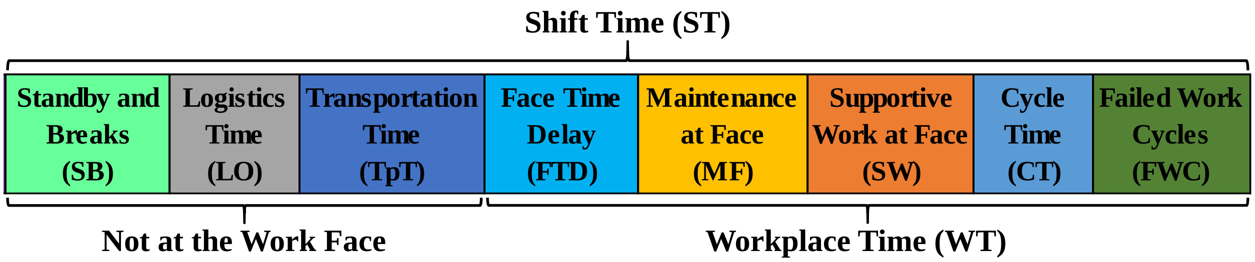



Figure 4.3 Breakdown of Shift Time (ST)

## 4.5 Determining the Length of the Study

The following must be considered when choosing a sample size to measure equipment productivity (NIST, 2001):

- Which parameters are being estimated,
- Cost of sampling,
- What is known about the process, and previously acquired data,
- Variability of the of the process,
- Practicality of collecting the data,
- Desired precision and resolution of the estimates of the process to be studied.

For example, the size of a harvesting study in the forestry industry to measure equipment work cycle length was found using the Equation 2 (Murphy, 2005):

$$n = \frac{t^2 * Var(WCT)}{(E * \overline{WCT}/100)^2} \tag{2}$$

where n = number of work cycles to be studied,

t = student's t value (assuming a 95% confidence interval, $t^2$ = 1.96),

Var(WCT) = estimated variance of work cycle time,

E = level of precision required (e.g. 10%),

$\overline{\text{WCT}}$ = estimated mean work cycle time.

The estimated mean work cycle time can be obtained through literature review, from the mine's documentation or from equipment suppliers. In some cases, where there is not sufficient background information, it may be necessary to complete a pilot study to identify work elements to be measured, *break points* between work elements, and estimate the mean work cycle time and the estimated variance of the work cycle time. Identification of the start and end of work elements is described by break points such as audio or visual cues (Freivalds & Niebel, 2013). Clear descriptions of break points and the use of video of the process to be studied will ensure consistency and reduction of subjectivity of measured work elements among multiple researchers.

To account for variability of work cycle time among operators, it is advised that multiple operators are shadowed to represent average productivity among operators with different levels of skill, training and work pace.

Time sheets customized for the process to be studied are created which contain the primary and secondary work elements as well as shift-time elements to be logged during the time study.

## 4.6 Work Study Preparation and Tools

The data to be collected, data collection method and study objectives are presented to the equipment operators, mine crews and supervisors. Based on feedback from mine operators, it may be necessary to modify the study plan. Involving the workers who are to be studied in the study plan reduces *observer effect* - when workers modify their behaviour while they are being studied (Magagnotti and Spinelli, 2012). The observer effect is reduced when the researcher is not affiliated with the mining company, mine contractors or equipment suppliers. It has been found that over the course of long term studies that workers adapt to the presence of researchers at their workplace which also reduces the observer effect (Olsen et. al., 1998).

Researchers log the machine number, operator ID, work location, working conditions and study date. Tasks are broken down into work elements, the duration of each work element is logged over the course of the equipment operator's shift (for example, the daily report shown in Figure 4.4). This quantitative and qualitative data can be used to determine factors which influence the productivity of the mining equipment. For example: high temperatures can contribute to worker fatigue or poor ground conditions can affect bolt installation cycle time.

Date: Jul 16 Machine #: 053 Operator ID: E Location: M3
Drift Height: 18ft Drift Width: 20ft Round Depth: ~16ft
Drift Irregularities: Corner to be wrapped with screen and bolted
RMR: ~70, measured 3 times
Number of half-barrels: 0
Machine status reported by supervisor: Geared and rigged
Machine status at beginning of shift: Geared and rigged
Road conditions: good
Presence of water: none
Temperature: 28°C (measured at 10:30am), increasing Humidity: 70%
Notes: Some loose rock
Loose feed chain, reported to cross-shift

Figure 4.4 An example of a daily report sheet describing working conditions relevant to the work object

For processes which are affected by rock mass conditions such as development drilling and bolting, the rock mass rating (RMR) is measured with a compass during the daily workplace inspection. Drift sizes are measured using a range finder.

If permission is granted, the researcher can take photographs or video of the workplace and equipment in operation to support measurements and qualitative observations. Other observations or irregularities are logged in the notes section. Often, this information is not used in quantitative analysis, however it can be useful to identify root causes of process delays and non-value adding activities. Qualitative descriptions of opportunities to improve productivity by equipment operators provide supporting evidence for quantitative descriptions of delays observed during the time study (such as the productivity questionnaire shown in Figure 4.5).

**Questionnaire** **Operator ID:** *B* **Day:** *3*

**Operator's education and training:**

*College degree, Common Core, Atlas Copco training*

**Operator's experience:** *8+ years, over 15 years as a development miner*

**In your opinion, what are the factors that influence productivity of the bolter?**

*Maintenance is a major issue, maintenance is completed by contractors who don't earn incentives. Supervisors can assist more with coordinating maintenance.*

*Communication with the cross-shift about the machine status*

*Condition of supplies and forklifts*

*Alignment and indexing time affect cycle time*

*Irregular rounds and misfires cause delays since the blast needs to be re-fired*

**What can be done to increase the productivity of the bolter?**

*Improving maintenance response time*

*Troubleshooting of intermittent issues could be improved*

*The quality of re-sharpened drill bits can be improved*

*Relocating the storage and better organization of the storage*

*Improving maintenance of the forklifts used to transport supplies*

*Eliminating day-to-day delays*

*Aligning the machine in the shop would improve indexing time*

*Training could be improved, operators could watch experienced operators to learn tricks and troubleshooting of daily issues*

*Services often need to be installed by the development crew and it takes time away from increasing the development rate*

Figure 4.5 An example of a productivity questionnaire for a rock bolter

Due to the long duration of the mining equipment studies, low reliability of electronics in the underground environment (due to heat, dust etc.), the precision required to quantify equipment productivity during mining studies may be lower than typical work studies. A convention to record time to an accuracy of seconds is shown in Figure 4.6.

| Consecutive reading of watch in decimal minutes | Recorded reading |
|---|---|
| 0.08 | 8 |
| 0.25 | 25 |
| 1.32 | 132 |
| 1.35 | 35 |
| 1.41 | 41 |
| 2.01 | 201 |
| 2.10 | 10 |
| 2.15 | 15 |
| 2.71 | 71 |
| 3.05 | 305 |
| 3.17 | 17 |
| 3.25 | 25 |

Figure 4.6 Convention for accurate timing using the consecutive timing method (Freivalds & Niebel, 2013)

*Break points* (the beginning and end of a work element or sub-element) are determined by the researcher by using visual or audio cues (Freivalds & Niebel, 2013). Video of typical work elements is useful for demonstrating the *break points* during work cycles and reducing the subjectivity of break points among different researchers. Break points for the processes studied in mining from screenshots of video of the bolting process are shown in Appendix B. To replicate the mining equipment studies, the video could be used to educate other researchers.

Handheld devices such as laptops can be used to log information using time study software. It is found that when measuring development activities, time sheets are preferred since digital data can easily be lost when memory cards and hard drives are exposed to changes in humidity, vibration, pressure and temperature over the course of a shift.

Digital machine records can be used to quantify equipment productivity, but equipment operators said that sensors on mining equipment are often partially functional or non-functional, and the data quality may not be reliable or accurate for productivity measurement. If digital records are used to quantify productivity, how the records are translated into categorization of time must be declared for study repeatability. It is advised that both short term studies and digital records are used together to reduce the amount of error introduced by errors, omissions or unknowns in digital records. Records can be obtained from systems on the machine, or by instrumenting the machine to be studied. Video of the process studied can also be used to supplement the study results.

Operator reported productivity reports can also be used to measure equipment performance over long periods of time with the assumption that the records will have a large amount of error (Olsen et al., 1998). If workers are motivated by an incentive system, then operator reported machine productivity can be skewed to favour higher incentive rates.

In less harsh environments, digital recordkeeping provides more accurate machine data sampling, an example of a time study tool for forestry can be found at forestenergy.org, 2015.

Time study sheets are printed on waterproof paper due to the high humidity and presence of water in mines.

A typical time study sheet for mining equipment is shown in Figure 4.7.

Date: Page No. Operator ID: Observer ID: Location:

| **Work Element** | ST | ET | ST | ET | ST | ET | ST | ET | ST | ET | ST | ET |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cage Time | | | | | | | | | | | | |
| Transport Personnel to Workplace | | | | | | | | | | | | |
| Transport Machine | | | | | | | | | | | | |
| Rigging/De-Rigging | | | | | | | | | | | | |
| **Notes:** | | | | | | | | | | | | |
| Scheduled Break | | | | | | | | | | | | |
| Reload Supplies from Machine | | | | | | | | | | | | |
| Gear Up/Load Supplies | | | | | | | | | | | | |
| Grease Machine and Fill Lubricants | | | | | | | | | | | | |
| Workplace inspection by operator | | | | | | | | | | | | |
| Wash machine, clean workplace | | | | | | | | | | | | |
| Clear Dust | | | | | | | | | | | | |
| Scaling | | | | | | | | | | | | |
| Supervisor Visit | | | | | | | | | | | | |
| **Primary Work Cycle:** | | | | | | | | | | | | |
| Sub-Element 1 | | | | | | | | | | | | |
| Sub-Element 2 | | | | | | | | | | | | |
| Sub-Element 3 | | | | | | | | | | | | |
| Sub-Element 4 | | | | | | | | | | | | |
| **Work Cycle Irregularities:** | | | | | | | | | | | | |
| Supportive Work Element 1 | | | | | | | | | | | | |
| Supportive Work Element 2 | | | | | | | | | | | | |
| **Work Element Irregularities:** | | | | | | | | | | | | |
| **Maintenance Task:** | | | | | | | | | | | | |
| Routine Maintenance at Workplace | | | | | | | | | | | | |
| Call Maintenance | | | | | | | | | | | | |
| Wait for Maintenance | | | | | | | | | | | | |
| Troubleshoot Machine | | | | | | | | | | | | |
| Test Machine | | | | | | | | | | | | |
| Fix Machine | | | | | | | | | | | | |
| **Other Description** | | | | | | | | | | | | |
| Other Task Time | | | | | | | | | | | | |
| **Other Description** | | | | | | | | | | | | |
| Other Task Time | | | | | | | | | | | | |
| **Other Description** | | | | | | | | | | | | |
| Other Task Time | | | | | | | | | | | | |
| **Other Description** | | | | | | | | | | | | |
| Other Task Time | | | | | | | | | | | | |

Figure 4.7 Example of a time sheet for development mining equipment

An example of primary work cycle sub-elements for rock bolters include drilling, inserting the bolt, and waiting for resin to set. Supportive work elements for bolting include scaling and the installation of screen. In the time sheet shown on the previous page, ST = Start time of a work task, ET = End time of a work task. ST and ET are separated by clearly defined break points.

## 4.7 Logging Delays

Since delays in mining are variable, time sheets should be specific to the process being studied but general enough to account for variability, for example, when uncommon events occur such as fire drills or rare equipment failures. Blank spaces are left in the time sheet to record the cause of delays and how delays and downtime are managed. If delays occur during a work element, the delays are assigned a code and described in the notes section of the time sheet. If more detailed descriptions of delays are needed, the researcher records delay descriptions in a separate notebook and assigns an error code to the delays. Often, the cause of the delays is not known, and the researcher will ask the equipment operators about the details of the potential causes and correction of delays during break time and personnel transport time.

## 4.8 Data Analysis and Reporting

Data recorded in time sheets is transcribed into a spreadsheet where calculations of equipment work capacity and statistical analysis can be performed (Figure 4.8). Data can be inputted at set intervals over the course of the study to verify that the process being observed will converge into statistically relevant observations, and adjustments to the study duration can be made to meet study objectives. The data is then analyzed through the use of various charts to quantify the productivity of a processes and determine the root causes for the productivity results.

| Date | 30-May | Bolter # 1 | | | Operator ID: C | Level 4 |
|---|---|---|---|---|---|---|
| Element ID | Sub-Element ID | Time Start | Time Finish | Time | Delay/Observation | Cycle Time |
| Screen | | 12:07:00 | 12:08:00 | 0:01 | | |
| ResinRebarBolt | MoveLineUp | 12:08:00 | 12:09:00 | 0:01 | | |
| ResinRebarBolt | Drill | 12:09:00 | 12:11:00 | 0:02 | | |
| ResinRebarBolt | InsertResinRebar | 12:11:00 | 12:12:00 | 0:01 | Loose Rock in drill hole | |
| ResinRebarBolt | WaitForSetTighten | 12:12:00 | 12:13:00 | 0:01 | | 0:05 |
| ResinRebarBolt | MoveLineUp | 12:13:00 | 12:13:00 | 0:00 | | |
| ResinRebarBolt | Drill | 12:13:00 | 12:15:00 | 0:02 | | |
| ResinRebarBolt | InsertResinRebar | 12:15:00 | 12:16:00 | 0:01 | | |
| ResinRebarBolt | WaitForSetTighten | 12:16:00 | 12:18:00 | 0:02 | Resin Won't Set | 0:05 |
| Scale | | 12:18:00 | 12:33:00 | 0:15 | | |

Figure 4.8 An example of sample data input for rock bolting equipment into Excel where work cycle times are calculated using subtractive timing

If maintenance records are available, the number of hours that the equipment is maintained per year can be estimated. The type of maintenance analysis that is completed depends on the amount of detail available in the records. By analyzing long term maintenance records and classifying maintenance and shift time (Figure 4.9), estimates of the annual work capacity of the equipment can be calculated by using Equation 3.

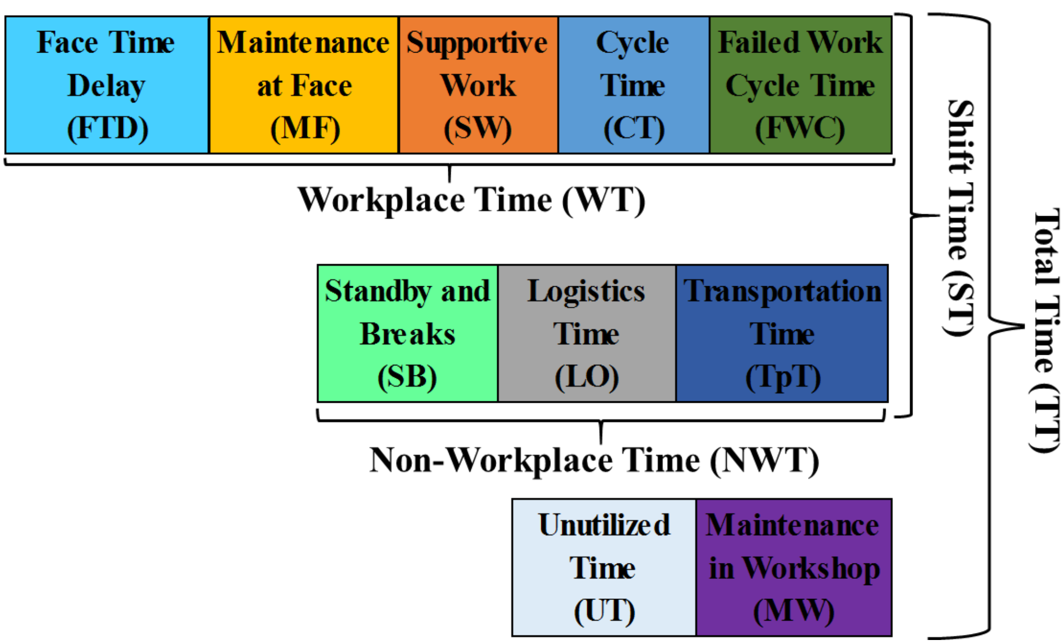



Figure 4.9 Breakdown of rock bolting equipment including recorded preventative maintenance and unutilized time

$$Estimated\ Annual\ Work\ Capacity\ (AWC) = \left(\frac{Shifts}{year} * \frac{hours}{shift} - \frac{MW}{year} - \frac{UT}{year}\right) * ST\ Capacity \quad (3)$$

It is assumed that there may be large amount of error in the annual work capacity estimate since unutilized time and maintenance time are estimated, and short-term data for utilization during shift time are used to make long term estimates. Despite the estimation error, this could be a good starting point to implement process and long term documentation improvement to reduce the error and measure increases in productivity.

## 4.9 Pie Charts to Quantify Process Time

Observed equipment usage can be represented as pie charts (see: Figure 4.10). Components of pie charts can be further broken down into data distributions to determine where productivity improvements lie, and which non-productive time can be reduced by improving the process.

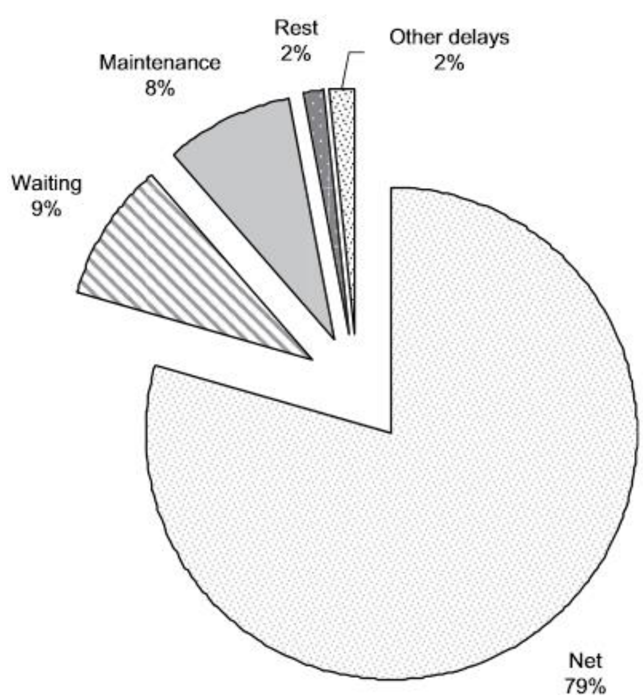



Figure 4.10 A breakdown of worksite time for forestry equipment (Spinelli et. al., 2009)

## 4.10 Histograms to Quantify Work Cycle time

The distribution of work cycle time can be represented using histograms. For example, the time required to install rock bolts is shown in Figure 4.11.

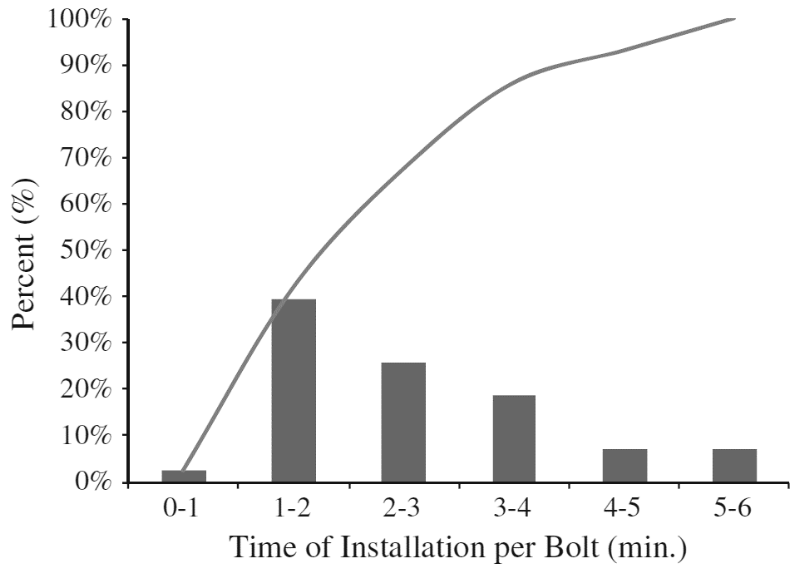



Figure 4.11 Bolt installation time in a tunnel (Farrokh et. al., 2011)

The distribution of work cycle times can be analyzed, and reasons for abnormal cycle times are qualitatively described in the productivity report. To analyze time-dependent trends in process cycle time and to potentially find assignable cause to abnormal work cycles or failed work cycles (for example: a bolt gets stuck during insertion). These control charts show where abnormal work cycles occur and researchers can note the cause of the abnormal work cycle, and ways to correct and eliminate work cycles which fall outside of control limits. Causes of both small and large variation can be quantified, and if possible, corrected (Nakajima, 1988; Sehic, 2002; Juuso, 2015; Juuso & Galar, 2016).

## 4.11 Control Charts to Statistically Analyze a Process

Control charts are a statistical tool used to indicate whether a measured process is in a controlled state as shown in Figure 4.12.

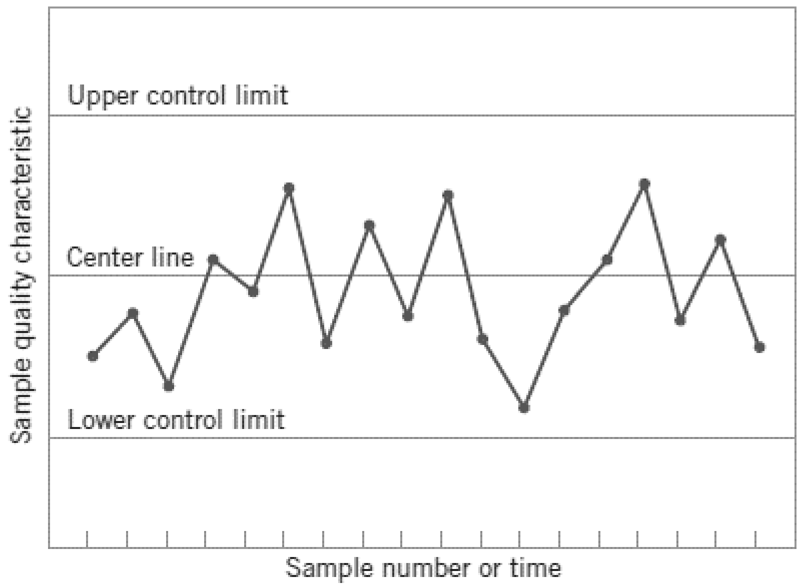



Figure 4.12 A typical control chart (Montgomery, 2007)

Work cycles which lie outside of the lower control limit (LCL) and upper control limit (UCL) are assigned root causes outside of chance causes of variation and are said to be "out of control". Processes which are out of control can typically be assigned causes such as improperly adjusted machines, operator errors or defective raw materials. The control limits are calculated as the following (Montgomery, 2007):

$$UCL = \mu_w + L\sigma_w \quad (4)$$

$$Center\ line = \mu_w \quad (5)$$

$$LCL = \mu_w - L\sigma_w \quad (6)$$

where $\mu_w$ is the mean of the work cycle time,

$\sigma_w$ is the standard deviation of the work cycle time,

L is the "distance" of the control limits from the centerline expressed in units of standard deviation.

Control charts can be used to systematically remove sources of variability through process monitoring and apply corrective actions to improve productivity of mining processes.

Through the implementation of quality control measures to improve short term and long term mining equipment productivity, the long term development rate in mines can be significantly improved which is represented by a long term control chart in Figure 4.13.

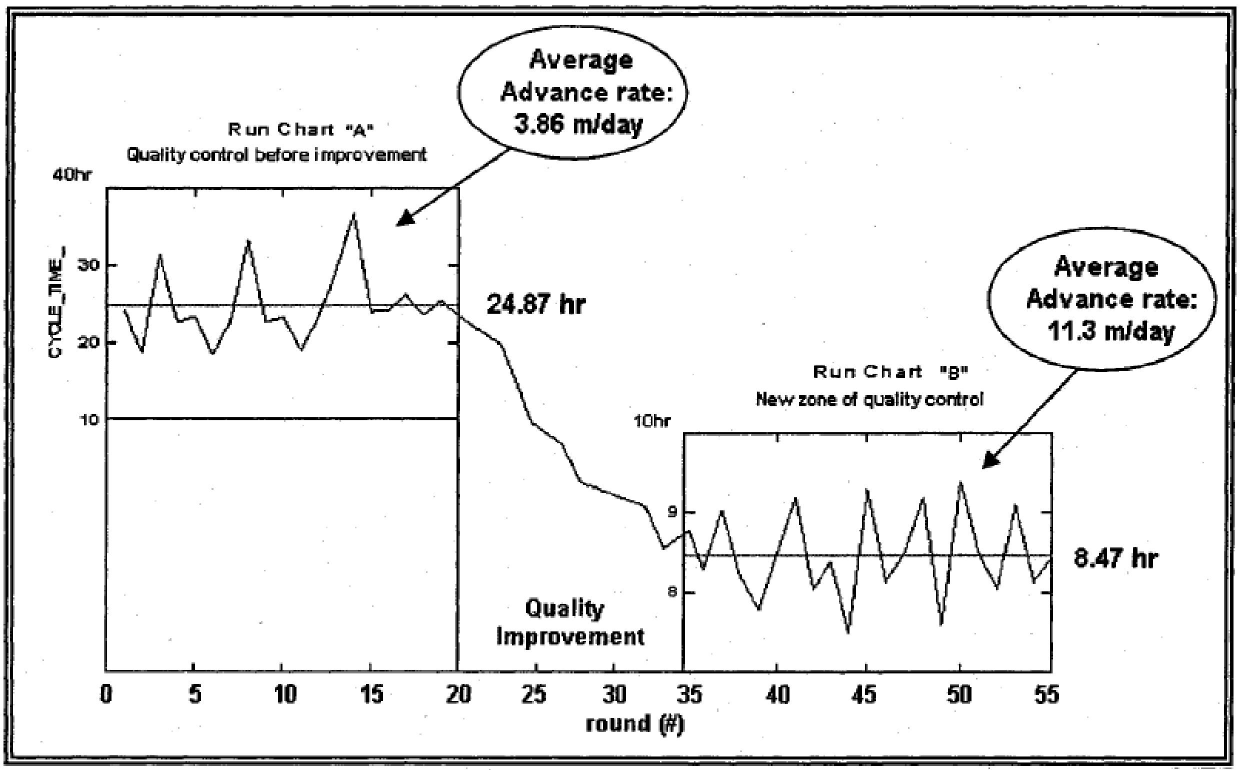



Figure 4.13 Example of a control chart to quantify long term process productivity, and to show the change in a process when improvements are made (Kenzap, 2006)

Control charts to represent short work cycles, and long term control charts such as development rate and tons mined can be useful for management to assess when a process is out of control, and investigate root causes through investigation of sub-processes which resulted in uncontrolled output. A change in the control charts can also indicate a change which working environment (for example: increased rock stress) which can warn decision makers about whether changes to design, equipment or processes need to be made to reach development and production targets.

## 4.12 Cause and Effect Diagrams

Cause-and-effect diagrams can be used to identify factors which affect equipment performance and cause work cycles to fall outside of control limits. A combination of quantitative data collected during the time study and qualitative data from the study questionnaire supported with observations during the time study is used to create cause-and-effect diagrams to represent factors which affect process productivity. Each cause and effect can be quantified in terms of how it contributes to process variability in the control chart, and corrective actions can be prioritized. For example, Lanke (2014) identified reasons for low crusher performance using a cause-and-effect diagram as shown in Figure 4.14.

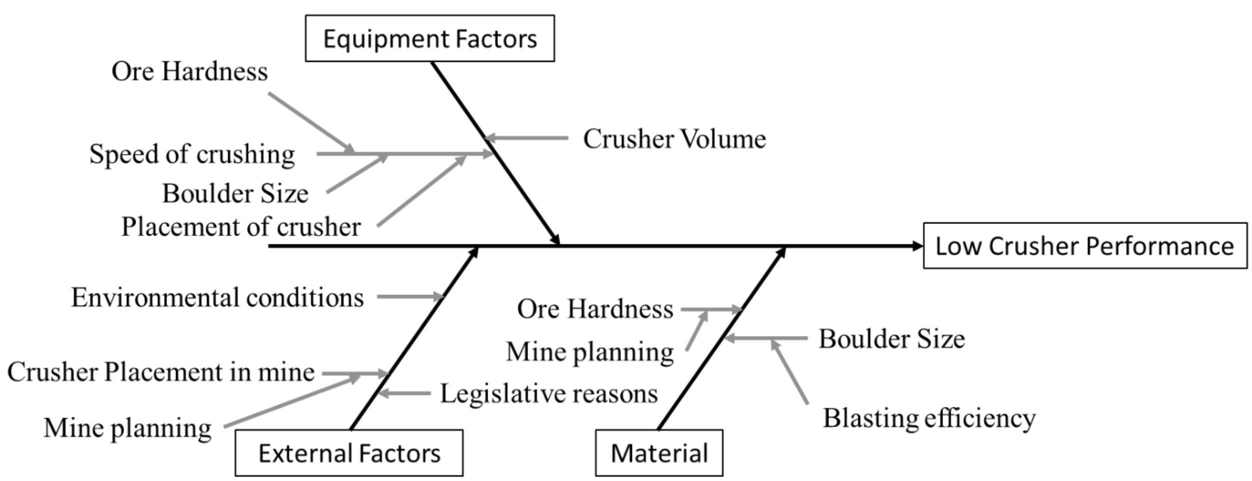



Figure 4.14 Possible criteria for low crusher performance (Lanke, 2014)

Using these diagrams, controllable causes of low equipment performance can be identified and modified to increase equipment productivity.

## 4.13 Measuring a System for the Purposes of Process Improvement

Follow-up studies can be completed to measure how changes to a mining process affect productivity as shown in Figure 4.15.

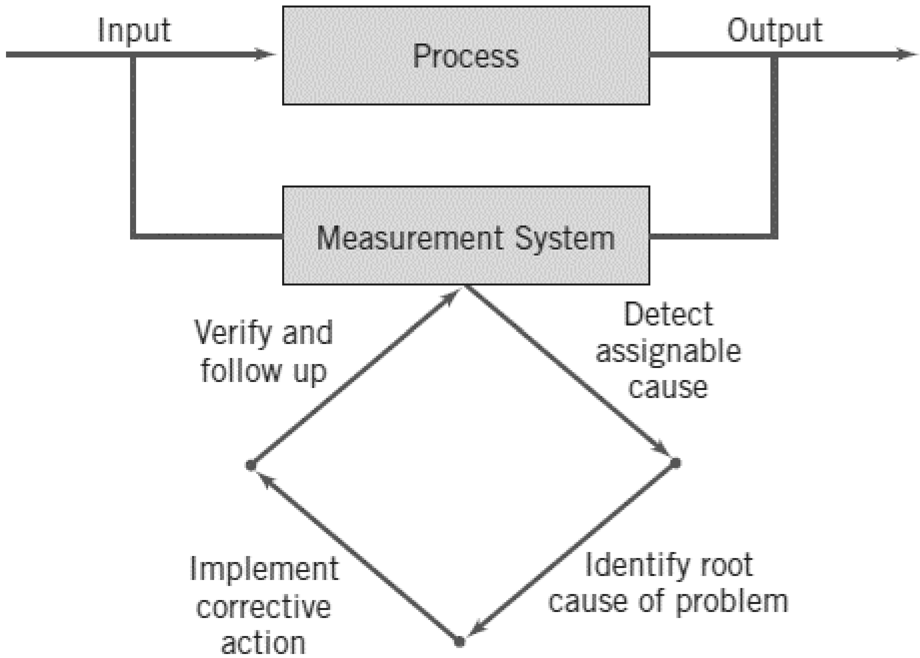



Figure 4.15 Process improvement using the control chart (Montgomery, 2007)

The goal of process studies is to eliminate root causes of variability of work cycles and identify corrective actions which could be taken to eliminate assignable causes of processes which are out of control. When the processes are improved, follow-up studies can be conducted to quantify the results.

## 4.14 Detailed Delay Analysis

Delay charts show the types of delays and which delays contribute to productivity losses in a process. An analysis of causes of delays indicates opportunities to increase productivity. For example, delays of a harvester in the forestry industry are categorized and graphed by duration range as shown in Figure 4.16.

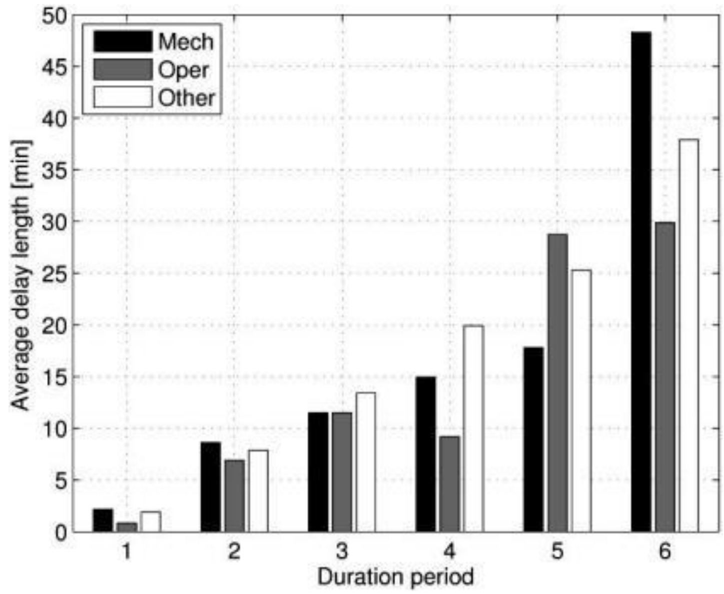



Figure 4.16 Duration of delays for a forestry machine with 75% utilization rate (Ringdahl et. al., 2012)

Qualitative descriptions of delays are tabulated and described in a productivity report. When reporting delays to mine management, delays which can be reduced through process improvement are identified. Delay time analysis is used to calculate overall equipment effectiveness and analyze the major root causes of delays.

Through process improvement, the operational capacity, long term utilization and of mining equipment can be increased. If operational improvements are implemented, follow-up studies should be conducted to quantify the process improvements.

## 4.15 Compiling the Information in a Productivity Report

A productivity report is written after the study is complete and is generally written in the following format:

- Introduction – motivation for study, background information, study objectives,
- Description of the work object studied and how the work object time consumption is classified, descriptions of work elements measured, work process diagrams,
- Description of the mine, environment and study duration with relevant pictures,
- Description of study measurement methods,
- Calculated work capacity,
- Control chart analysis,
- Observed percentage equipment usage averaged over the course of the study,
- A table of number observed delays, classification of delays and delay duration,
- Inferred and anecdotal productivity limitations observed during the study,
- Quantitative statistics of observed work cycles,
- A report of limitations and factors that could affect the results of the study and potential sources of error,
- Discussion of what can be concluded by the study,
- Identification of best practices observed and opportunities to improve productivity,
- Potential for follow-up studies,
- Digital data (such as videos of the process) used to quantify the process can be attached to assist with repeatability of the study.

When sources of variability are identified and corrective measures are taken to increase process productivity, follow-up studies can be completed to verify the corrections and identify other sources of productivity loss. The sources of variability that are uncontrolled (for example: rock properties) can be quantified in meta-analysis studies to statistically determine factors that influence machine productivity to be able to compare similar mining processes in different conditions.

## 4.16 Summary

This chapter presented a methodology for measuring to measure mining equipment and report causes of variation during work processes which can be reduced to improve productivity.

The time study methodology can be modified for different equipment types and mine sites to accommodate mine-specific constraints.

By combining cycle level studies and shift-level studies for multiple types of equipment, productivity and cost of mining cycles can be analyzed and optimized. Chapter 5 shows the results of two time studies on rock bolting equipment at a deep mine using the methodology described in this chapter. The effectiveness of the methodology for work study in mining described in this chapter is discussed in Chapter 6.

# Chapter 5

# Semi-Mechanized and Mechanized Bolter Case Study

## 5.1 Introduction

The purpose of this chapter is to demonstrate how the study methodology described in the previous chapter meets the study objectives for analyzing the productivity of semi-mechanized and mechanized bolters in a deep Canadian mine. Some results from two pilot studies conducted by the author at Mines A and B to develop the methodology are shown to support the case study results obtained from Mine C. Details about the description of the mines is shown in Section 5.2.

Two pilot studies were conducted over the course of 15 shifts at two Canadian mines to develop the case study data collection protocol and analysis tools. Based on the pilot studies, the research methodology was modified to account for anticipated variation among different mine sites and management to meet the study objectives. A third study was conducted over the course of a longer time period term using the refined methodology as presented in chapter 4 which can accommodate expected variation among different mine sites:

- Mine-specific maintenance strategy
- Mine depth and equipment/supplies storage layout
- Communications standards
- Ground conditions
- Acceptance of study method(s) by operators, supervisors and management
- Work culture
- Availability and quality of supporting documentation such as production and maintenance records
- Availability and scheduling of personnel transportation
- Logistics strategy
- Operator training and experience
- Organizational structure
- Variance of work method(s) and cycle times among different operators
- Ancillary work to be done by equipment operators; for example: installing services
- Amount and type of paperwork to be filled out by study investigator(s) and mine workers
- Mine air temperature
- Road conditions

## 5.1.1 Study Objectives

Objectives of the study were defined by the author, the research group who initiated the study, mine management and feedback from mine crews (see: Table 5.1).

Table 5.1 Description of study objectives, data collected, and analysis used to meet the objectives

| Work Study Objectives and Sub-Objectives | Data Collected to Meet Study Objectives | Analysis Tools Used to Meet Objectives |
|---|---|---|
| **Quantify factors that compose shift time (ST), workplace time (WT) and total time (TT)**<br>• Document abnormal cycle times<br>• Measure productivity of bolters in a deep mine | • Discretization of work cycle data through the use of process flow diagrams and identification of logical break points<br>• Manually filled out time sheets<br>• Daily reports filled out by mine workers<br>• Long term production and maintenance data | • Pie charts representing the observed time breakdown of activities during the study period<br>• Estimates of long term equipment time usage extrapolated from short term and long term data<br>• Calculation and estimation of work capacity for different periods of time<br>• Statistical analysis of data |
| **Identify opportunities to improve productivity of the bolters**<br>• Identify root causes of bolter productivity rates<br>• Identify mine specific and equipment specific delays | • Documentation about the causes of abnormal cycle times in time sheets<br>• Interviews with operators to identify root causes for abnormal cycle times and causes of delays, and identify opportunities to improve the productivity of the equipment<br>• Comparison of observed delays with the across studies on semi-mechanized and mechanized bolters | • Fishbone diagrams<br>• Quantification and categorization of observed delays<br>• Compilation of results from interviews with equipment operators<br>• Identification of opportunities to increase equipment work capacity by analyzing the components of the calculations |
| **Quantify productivity for different bolting systems and different rock mass conditions** | • Measurement of Rock Mass Rating (RMR[8]), drift abnormalities, bolt type installed<br>• Completion of follow-up study at the same mine on fully mechanized bolters<br>• Long term development and production records<br>• Pictures of the headings before and after bolting | • Tabulation of work cycles and shift time consumption in different rock mass conditions<br>• Histograms of rock bolt installation time for different bolt types |

[8] After Beniawski, 1989

The following chapter sections show examples of how these objectives are met through the use of the methodology described in Chapter 4 and the effectiveness of the methodology is discussed.

### 5.1.2 Preparation for the Case Study

The work study objectives and methodology was presented to supervisors and development crews during routine meetings. The data gathering method and analysis methods were approved by potential study participants provided that:

- Case study results are not used to adjust the workers' incentive ("bonus") system,
- Study participants and their supervisors are not named in reports,
- Equipment operators are not compared directly with each other, and results of the study are compiled and/or averaged,
- Consent from individual operators is required for pictures and videos to be taken to support the study results,
- The study observer is to use the development crew transportation for convenience, and to accurately record shift time consumption,
- The study observers interfere as little as possible with the operation of the equipment, and
- Analysis of safety of the bolting process is out of the scope of the research.

The work study observer completed underground mine safety training to allow the observer to work unsupervised and tag in at the work sites chosen for the study.

The following tools and equipment were obtained to conduct the study:

- Personal protective equipment (PPE), radio and cap lamp which meet the mine standards,
- A compass to measure RMR,
- RMR measurement sheets,
- Daily shift report sheets and interview questionnaire,
- Sony DSC-RX100 camera to obtain photographs in low light conditions[9],
- GoPro Hero 3 camera to obtain long term video if permitted[2],
- Waterproof time sheets modified for the machine-specific bolting procedure
- Waterproof markers,
- Items such as food to break the ice with the study participants and to decrease the observer effect.

Time study observers attended the equipment operator's pre-shift meeting where the worker and observer participating in the study are assigned equipment numbers, the location in the mine where work will take place, and informed of potential hazards present in the mine over the upcoming shift. During standby time, break time and transportation time, observers interview workers to fill out the qualitative analysis questionnaire.

[9] All electronic devices must be approved by the mine's head office to meet electronics safety requirements

## 5.2 Overview of Case Studies

Measurement of bolters was completed at three mines (see: Table 5.2).

Table 5.2 Productivity study details

| Study: | **Pilot Study 1** | **Pilot Study 2** | **Case Study 1** | **Case Study 2** |
|---|---|---|---|---|
| Mine: | Mine A | Mine B | Mine C | Mine C |
| Machine type: | MacLean Bolter | MacLean Bolter | Boltec MC | MacLean Bolter |
| Screen type | #4 gauge galvanized screen | #4 gauge galvanized and non-galvanized screen | #4 gauge galvanized screen, #0 gauge straps, #0 gauge plates | #4 gauge galvanized screen, #0 gauge plates |
| Material type(s) that were bolted | Granite, ore | Granite, ore | Granite, ore, sandfill | Granite |
| Average drift size | 18 ft x 18 ft | 18 ft x 18 ft | 20 ft x 20 ft | 20 ft x 20 ft |
| Mining method(s) | Stope mining | Cut and fill | Stope mining | Stope mining |
| Bolt types installed | 8 ft (2.4 m) rebar<br>FS-39 Split Sets<br>8 ft mechanical bolts | 8 ft (2.4 m) rebar<br>FS-39 Split Sets<br>8 ft mechanical Bolts | 8 ft (2.4 m) Coated Super Swellex<br>FS-46 Split Sets | 8 ft (2.4 m) rebar<br>8 ft (2.4 m) Modified Cone Bolts (MCB)<br>FS-46 Split Sets |
| Surveillance period | Eight 10.5 hour shifts | Eight 10.5 hour shifts | 16 10.5 hour shifts | 12 10.5 hour shifts |
| # Bolt installation cycles observed | 275 | 337 | 593 | 525 |
| Bolting locations observed | 625 m - 1330 m | 1100m -1300 m | 2300 m - 2440 m | 2200 m – 2480+ m |

Typical bolt installation patterns are shown in Figure 5.1. Where enhanced support is required, bolts are installed in a “4-3-4” pattern to reduce the inter-bolt spacing. At least two squares of screen must be overlapped to eliminate gaps between screens and prevent loose rock from falling between screen gaps.

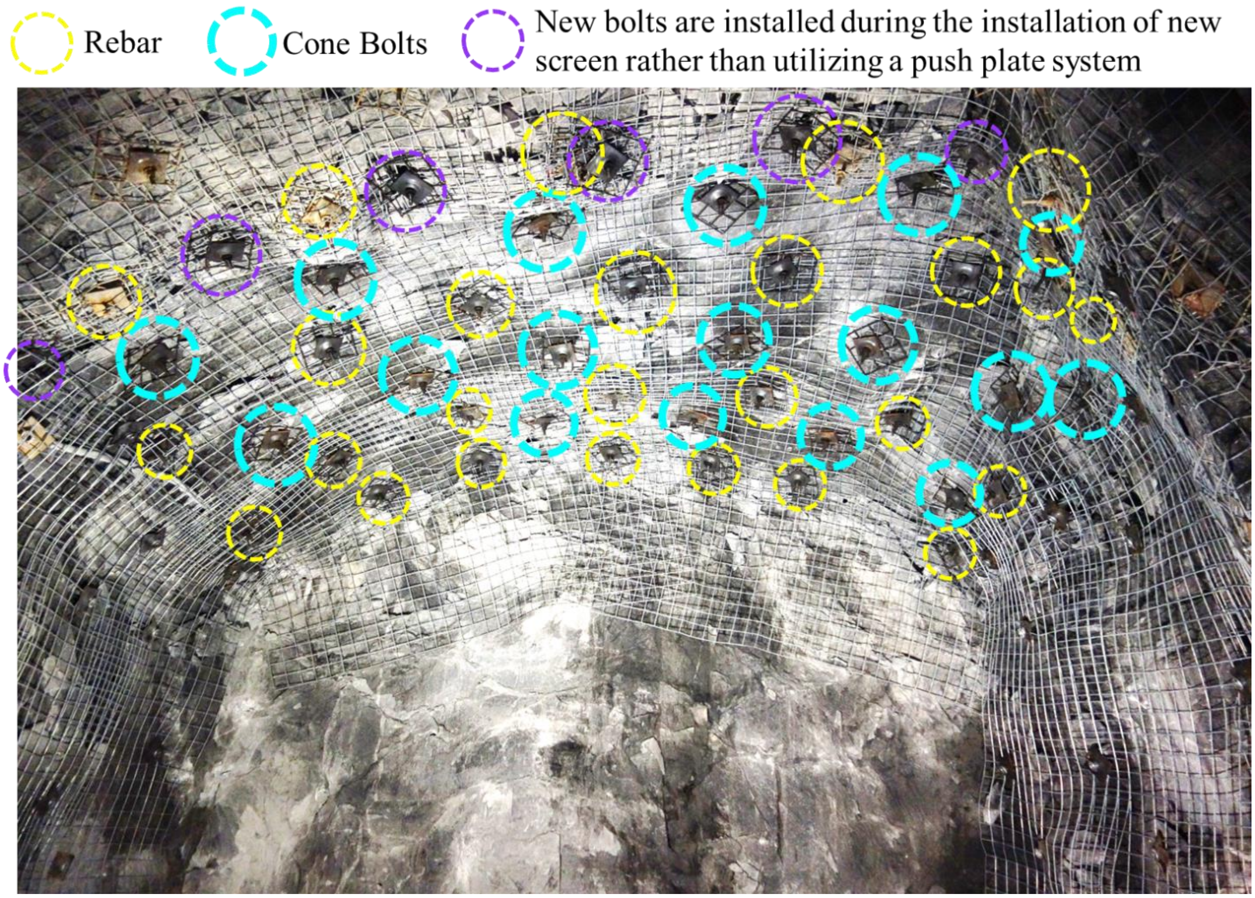



Figure 5.1 Typical “3-2-3” or “dice” bolt installation patterns through #4 gauge screen at Mine C, Split Sets are installed in the walls

RMR was measured in situ and UCS estimates of the rock in the observed work areas was obtained from mine geologists. The average rock mass properties in the areas where bolting was observed of at the three mines studied is shown in Table 5.3. The rock mass properties affect the drillability of the rock which is a non-linear relation (Heiniö, 1999; Thuro, 1997).

Table 5.3 Rock mass properties where bolting was observed

| **Mine** | **UCS (MPa)** | **RMR (1989)** | **Rock stress** |
|---|---|---|---|
| Mine A (Pilot Study 1) | 160-220 | 60-75 | Highly variable |
| Mine B (Pilot Study 2) | 210-240 | 70-90 | Moderate, burst-prone near diminishing pillars |
| Mine C (Case Studies 1 and 2) | 210-240 (ore and rock)<br>1-3MPa (backfill) | 57-74 | High, burst-prone |

The development cycle in fill and rock at the mines where the study took place is shown in Figure 5.2.

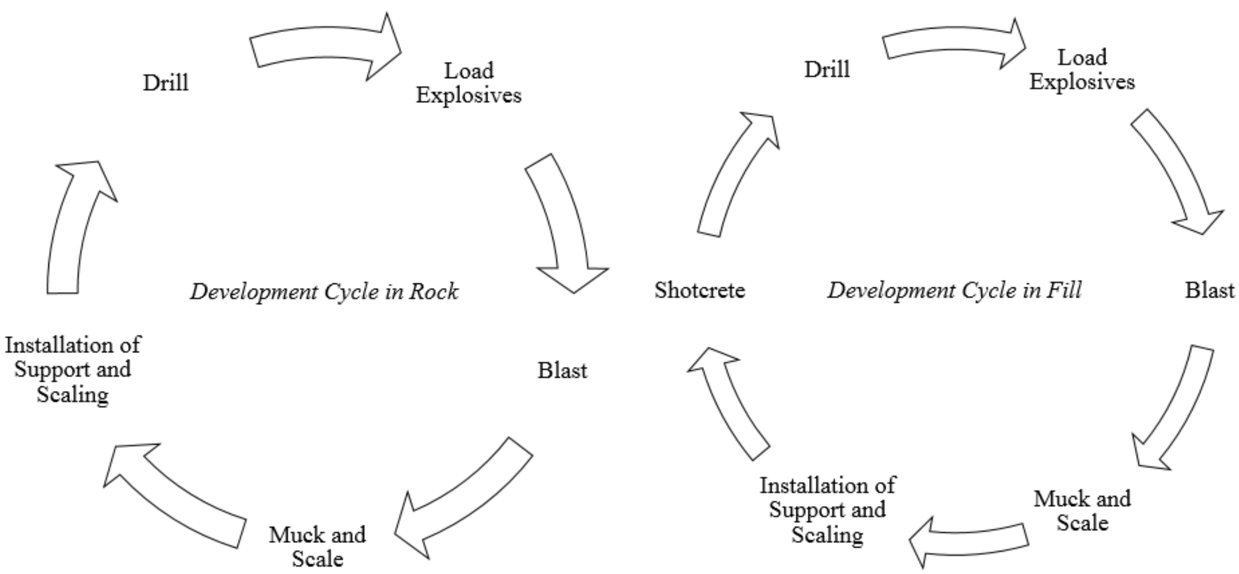



Figure 5.2 Development cycle at the three mines in rock and fill

At the mines in the study, MacLean operators are not permitted to bolt under fill therefore the Boltec is used to bolt all sandfill (hydraulic cemented fill) rounds at Mine C.

It is necessary to qualitatively demonstrate the conditions in which the bolting equipment is operating for the purposes of comparing equipment productivity. Comparing qualitative and quantitative descriptions of the mine drifts, shape and blasting quality improve the ability to compare equipment operating in different conditions. Examples of photos of typical development rounds which correspond to descriptions of working conditions are shown (see: Figure 5.3 and Figure 5.4). The observer takes photos of each development round before and after bolting, and anomalies in the development rounds are described as necessary; since mining terminology and drifting standards can vary greatly based on region, photos of the workplace assist with describing conditions in which the machine is working.

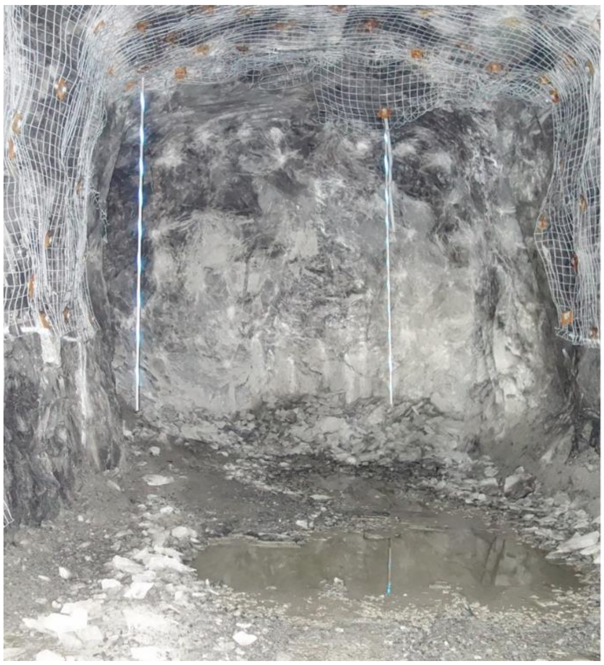


Figure 5.3 Left: Typical unbolted round; Right: MacLean bolter in an irregular heading

Bolting under sandfill (hydraulic cemented fill) is only completed with the Boltec at Mine C, other types of rounds are shown in Figure 5.4. The Boltec is typically used in areas that require Swellex and irregular or sandfill rounds that cannot be bolted with the MacLean bolter such as irregular rounds.

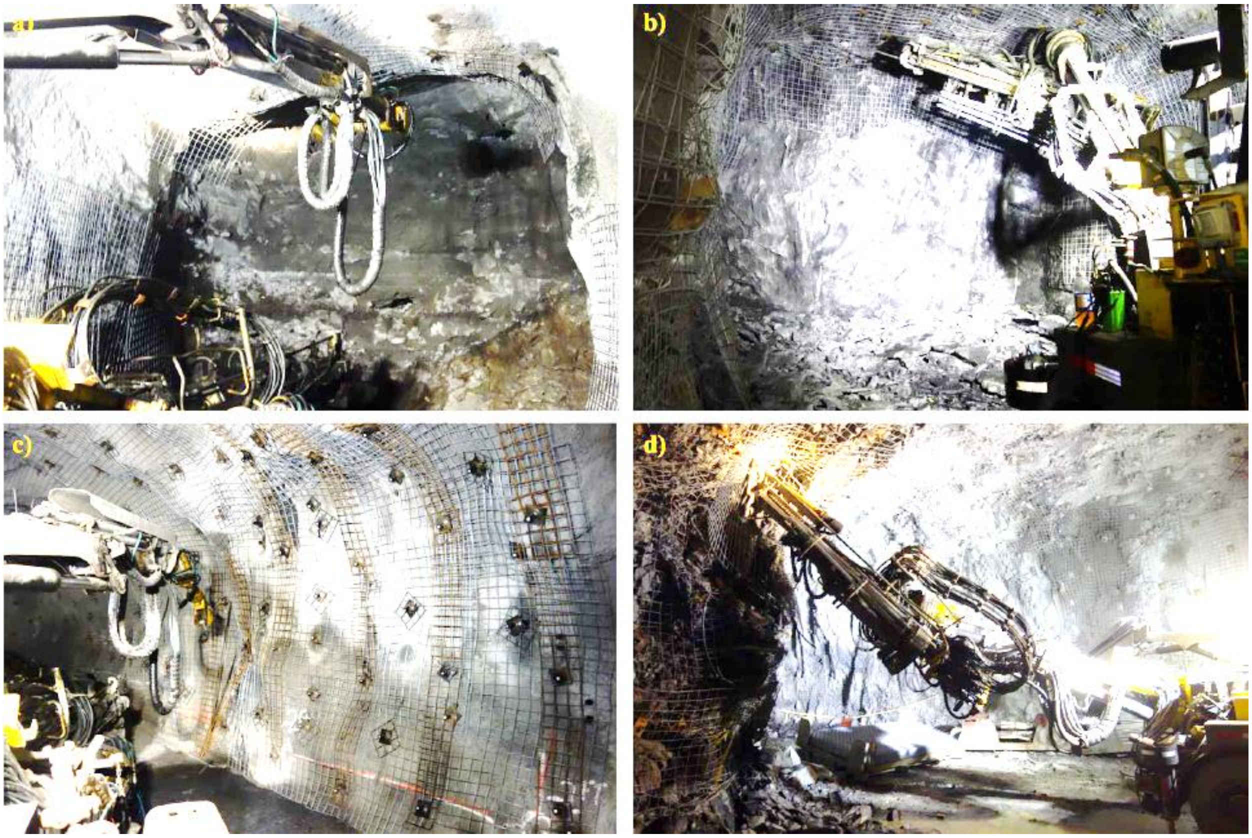



Figure 5.4 Boltec bolting conditions: a) sandfill b) rock round c) second pass d) reconditioning

The heading dimensions, RMR and irregularities must be logged to allow the results of studies of similar work elements in different (or variable) conditions to be compared, although this may not always be possible due to the presence of sandfill and shotcrete. A measurement while drilling technique could be used to classify RMR when installing bolts through shotcrete (Kahraman et al., 2015).

## 5.3 Identification of Shift Time (ST) Components and Establishing Break Points

To describe how components of shift time is categorized, work elements were identified and discretized through the use of mine documentation, literature review, training, interviews with workers, and during pilot studies. Two pilot studies were conducted to obtain preliminary study results, establish break points and work elements for the bolting process, and familiarize the observer with the function of the machine and working in an underground environment.

Video and descriptions of the work process were used to establish *break points*[10] between shift time work elements. It was necessary to define the break points of the process(es) being observed to ensure study repeatability. Work elements were recorded manually on time sheets. In some cases, small sub-work elements were grouped together to simplify the time study process and reduce observer fatigue. A simple breakdown of shift elements was used to classify the bolting process over the course of each shift (see: Figure 5.5). A visual example of break points and grouping of work elements applied to measuring the work task of installation of rebar is shown in Appendix B.

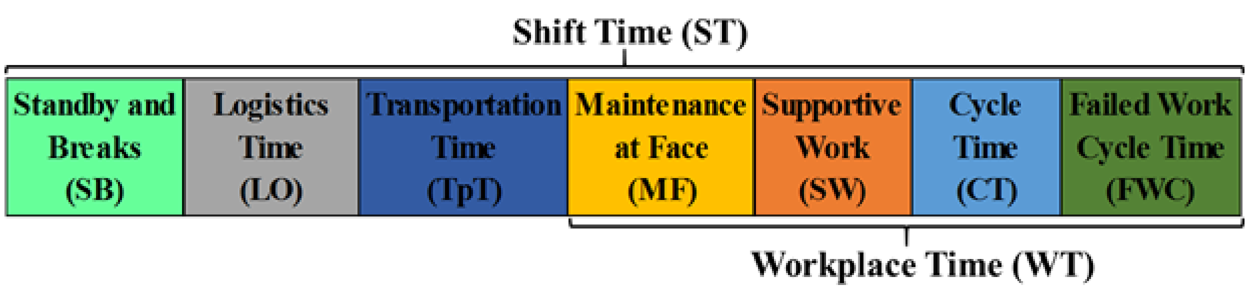



Figure 5.5 Shift Time classification

The bolters were often already set up and operators are tasked with finishing a round. Some tasks were skipped if it has been completed by the previous shift. To identify opportunities to increase productivity, components of the observed processes were analyzed.

Process flow diagrams are useful for ensuring that the study is repeatable by different observers. An objective description of work elements and break points allows the study to be repeatable

[10] Break points are the transition from one work element to the next, typically based on sound and sight cues.

among multiple investigators and provides clarity of the meaning of the study results.  Process flow diagrams of bolter operation are shown in Appendix B.

## 5.4 Statistical Analysis of Results

Prior to the study start, the number of work cycles to be observed to obtain statistically relevant results was estimated using Equation 2 from Section 4.5. Based on values obtained from equipment operators, the average bolt installation time was estimated to be 4.5 minutes with a variance of 1.2

$$n = \frac{t^2 * Var(WCT)}{(E * \overline{WCT}/100)^2} = \frac{1.96^2 * 1.2}{(10 * 4.5/100)^2} = 23 \qquad (7)$$

where n = number of work cycles to be studied,

t = student’s t value (assuming a 95% confidence interval, $t^2 = 1.96$),

Var(WCT) = estimated variance of work cycle time,

E = level of precision required (e.g. 10%),

$\overline{\text{WCT}}$ = estimated mean work cycle time.

To verify that enough shifts were logged to reach conclusions about the productivity of the bolter, an analysis is performed after Olsen, et al. (1998) to determine whether the number of observed work cycles over the course of multiple shifts falls within 95% confidence interval limits.  This analysis is shown for the study time period in Figure 5.6. Because the objectives of the study included recording time consumption over the course of an entire shift, more work cycles were logged than necessary to meet statistical significance.

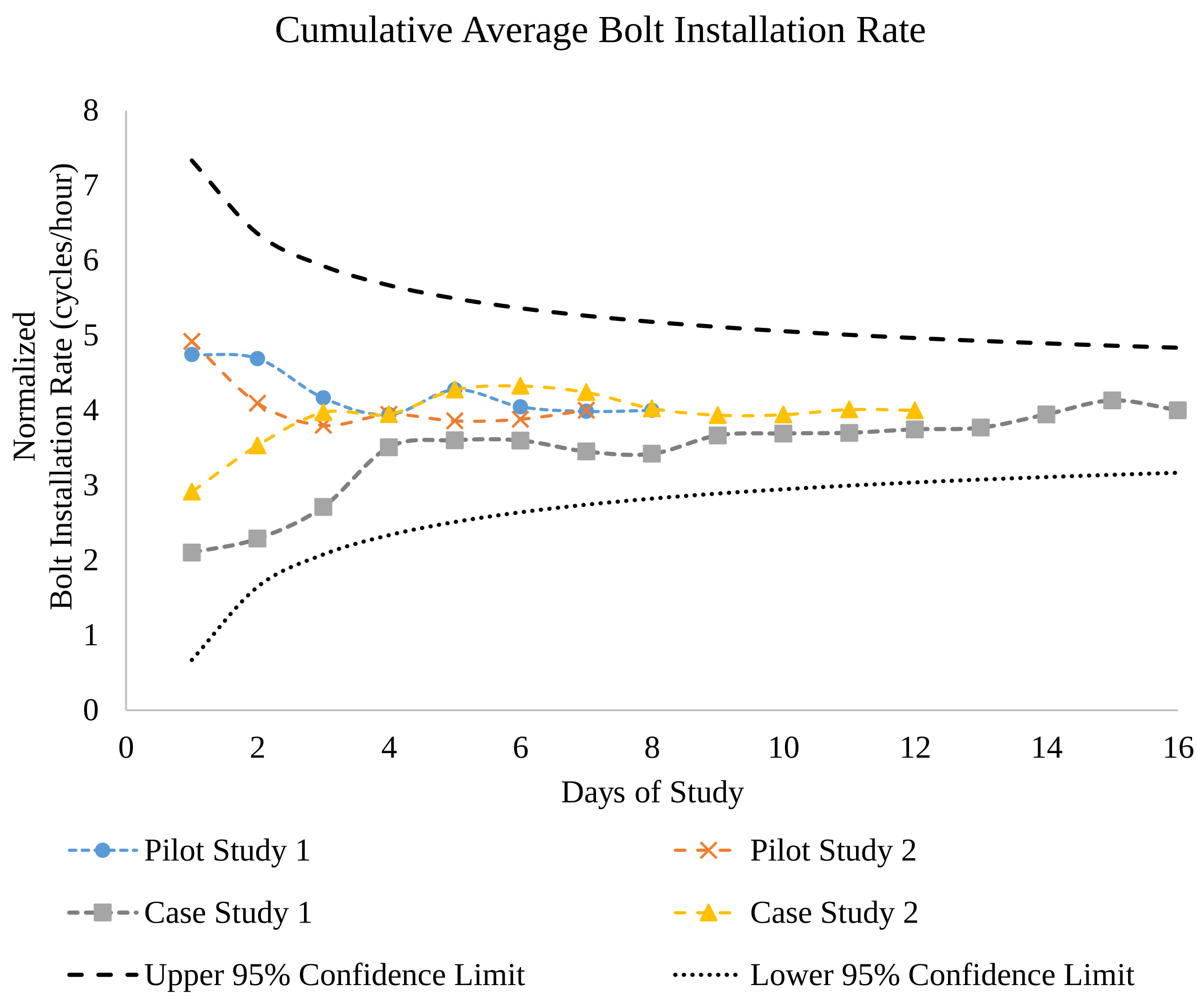



Figure 5.6 Cumulative average bolt installation time

The bolt installation time did not deviate outside the 95% confidence interval, and the measured average bolt installation stayed within acceptable error limits and converges during the study period. Therefore, enough observations were made during the study to quantify productivity of the bolters during the study period at this mine and to predict bolter productivity in similar conditions. By using shift-level reports, the study results could be used to model the productivity of bolters during long periods of time with small amounts of error. Combining shift-level reports with detailed time study data to estimate long term work capacity is discussed in Chapter 6.

The number of bolts installed over the course of the study and mean cycle time are shown in Tables 5.4-5.6.

Table 5.4 MacLean bolt installation time components for Rebar and Cone Bolts

| | Mine A Rebar | Mine B Rebar | Mine C Rebar | Mine C Cone Bolt |
|---|---|---|---|---|
| No. of observations (N) | 147 | 250 | 120 | 42 |
| Line up boom to drill hole | 22s | 33s | 1min02s | 54s |
| Drill hole, retract drill steel, pivot boom | 1min35s | 2min8s | 2min07s | 1min54s |
| Insert resin and bolt, spin and insert bolt, break shear pin | 1min58s | 1min43s | 2min20s | 2min09s |
| **Average installation time** | **3min55s** | **4min24s** | **5min29s** | **4min57s** |

Table 5.5 MacLean bolt installation time components for Split Sets

| | Mine A Split Set | Mine B Split Set | Mine C Split Set |
|---|---|---|---|
| No. of observations (N) | 126 | 75 | 363 |
| Line up boom to drill hole | 24s | 38s | 45s |
| Drill hole, retract drill steel, pivot boom | 1min13s | 1min37s | 2min08s |
| Insert Split Set, Hammer in Split Set | 39s | 46s | 1min9s |
| **Average installation time** | **2min16s** | **3min01s** | **4min02s** |

Table 5.6 Boltec bolt installation time components

| | Mine C | | | | | |
|---|---|---|---|---|---|---|
| | Swellex in rock and ore | Split Sets in rock and ore | Swellex in fill | Split Sets in fill | Swellex 2nd pass and reconditioning | Split Sets 2nd pass and reconditioning |
| No. of observations (N) | 105 | 239 | 61 | 52 | 49 | 11 |
| Index bolt and line up boom to drill hole | 1min 15s | 1min 18s | 53s | 1min 6s | 1min 2s | 3min |
| Drill hole, retract drill steel | 2min 41s | 2min 1s | 1min 2s | 1min 8s | 2min 50s | 2min 27s |
| Insert Bolt | 1min 28s | 1min 9s | 1min 8s | 52s | 1min 32s | 1min 38s |
| **Average installation time** | **5 min 24s** | **4min 28s** | **3min 3s** | **3min 6s** | **5min 24s** | **7min 5s** |

Based on the analysis of work cycle time, it is found that the results are statistically significant for quantifying the distribution of bolt installation time.

Based on the data formatted as shown in Appendix A which was classified according to Figure 5.5, the average time consumption over the course of a shift according to the framework described in Chapter 4 is shown in Figure 5.7 and 5.8.

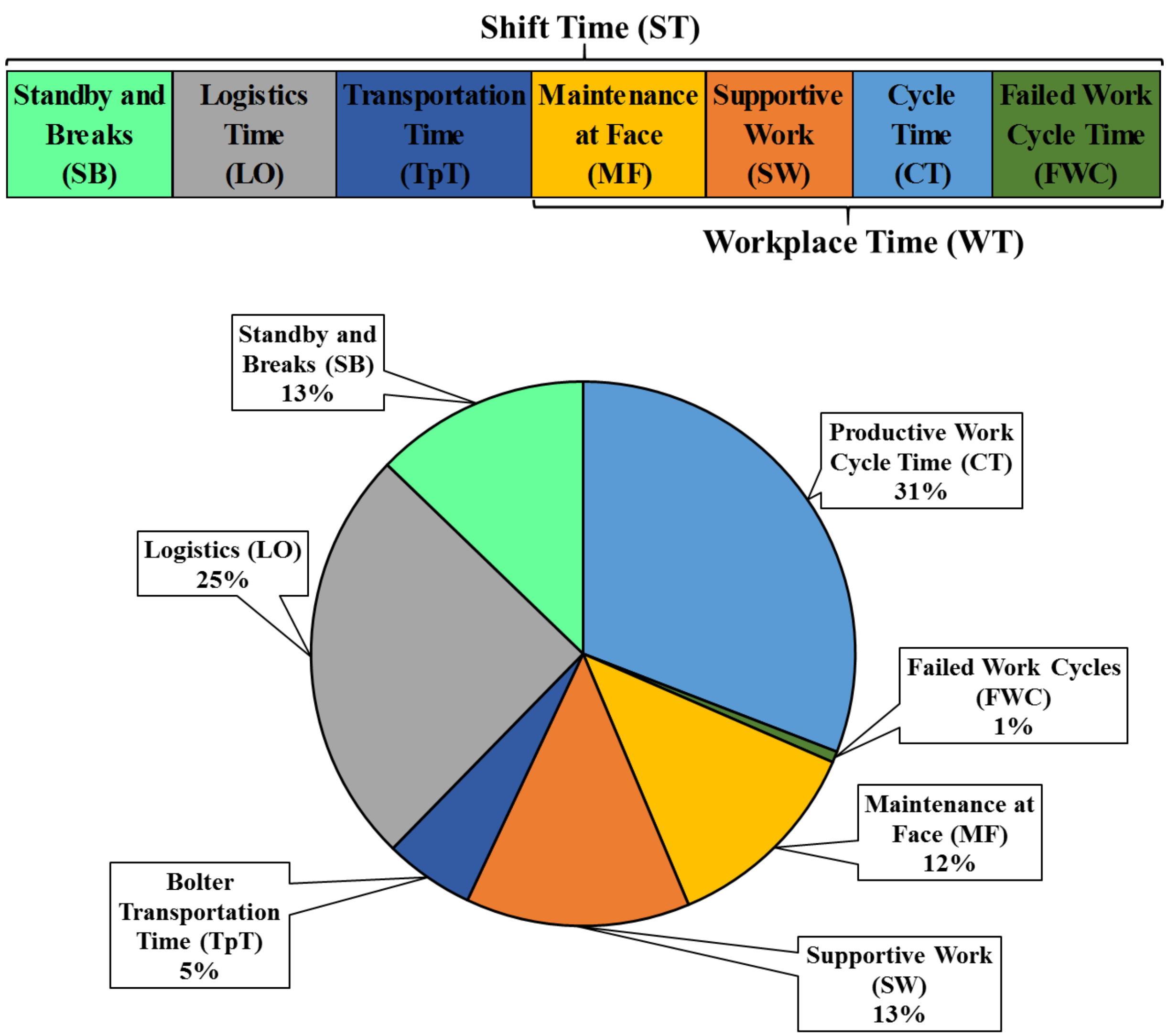



Figure 5.7 Observed MacLean bolter usage over the course of a shift

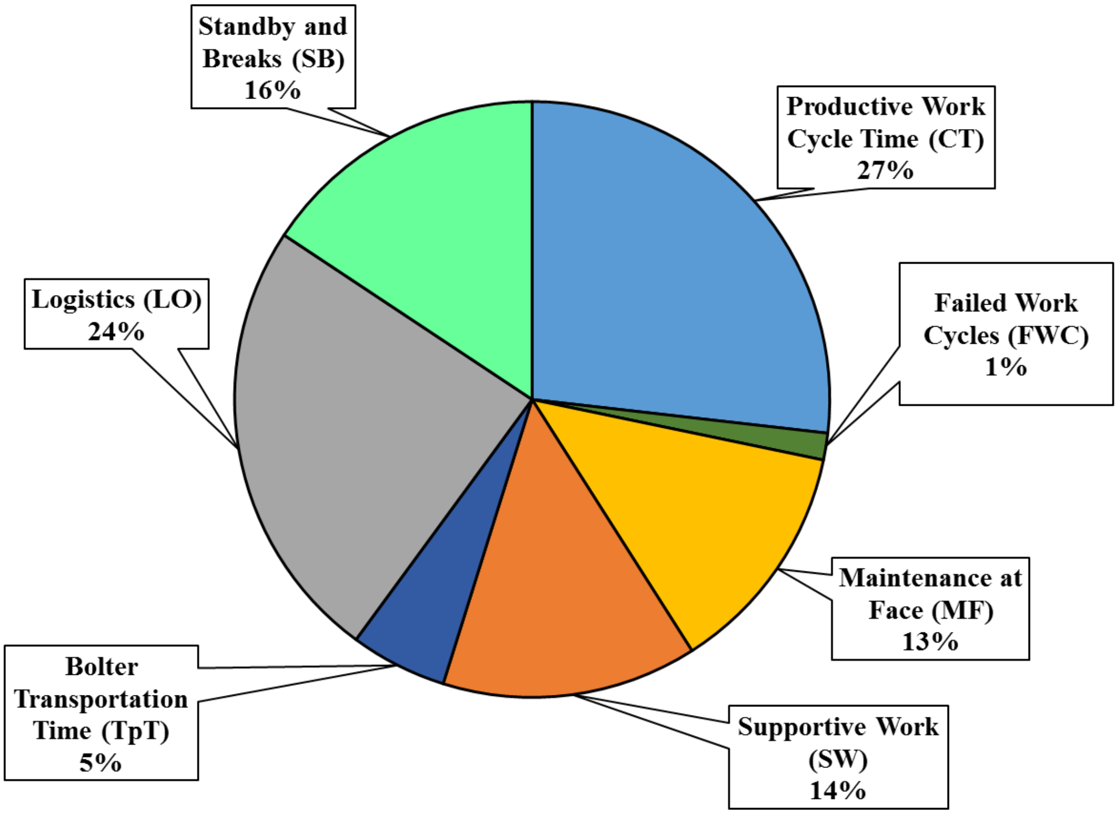



Figure 5.8 Observed Boltec bolter usage over the course of a shift

The correlation between the number of bolts installed (N) vs cycle time (CT) per shift is shown in Figure 5.9.

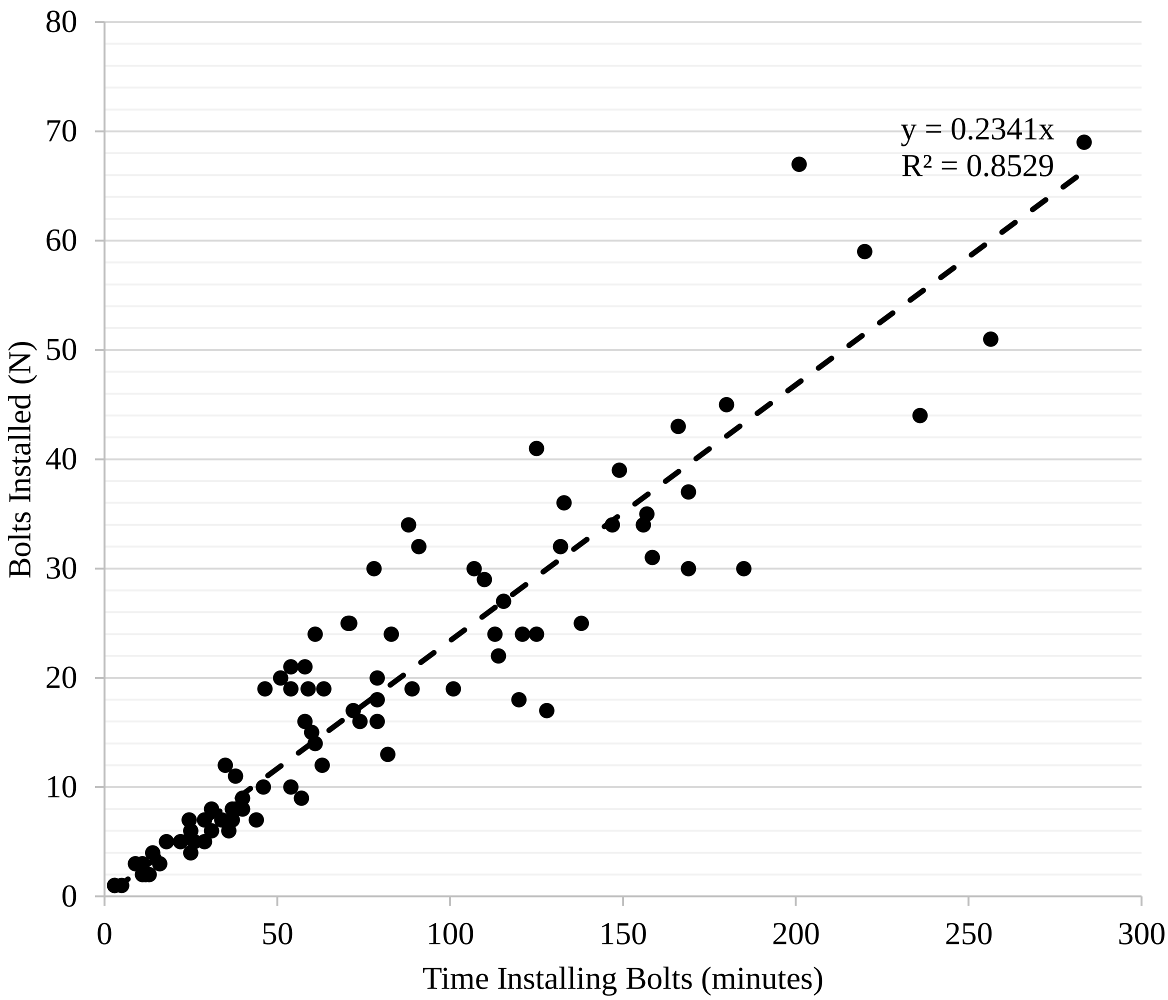



Figure 5.9 Number of bolts installed (N) vs cycle time (CT) per shift

Correlations between bolt installation cycle time per shift and number of bolts installed shows that there is not a large difference in bolt installation time among different machines and operators which validates the results, and also demonstrates that the productivity of the bolter per shift would increase in a linear way if productive face time is increased through the elimination of non-value adding processes and supportive work. A detailed version of the above figure is shown in Appendix A.

In the observed mining conditions, it the number of bolts installed per shift regardless of machine or bolt type can be calculated using an empirical equation:

$$n = 0.234 * Time\ Installing\ Bolts\ (minutes) \quad (8)$$

Detailed distributions for all observed machines and bolt types are shown in Appendix D. It is often assumed that bolt installation times are normally distributed however field results do not support this theory in this study and in literature (MediaTech, 2009; Farrokh et. al., 2011; MIGS, 2014b). Also, it is found that drilling rates typically follow a lognormal distribution. Drilling holes is a large portion of the bolt installation cycle time where the tail of the distribution is due to drilling in bad rock, for example, loose rock in the drill hole can reduce the bit penetration rate and bit extraction times (Schunnesson, 1997). Bolt installation in bad rock also contributes to the lognormal distribution of cycle times. Opportunities to maximize the productive work cycles per shift are quantified and discussed in section 6.4. Distributions of bolt installation times at Mine C are shown in Figures 5.10 - 5.14.

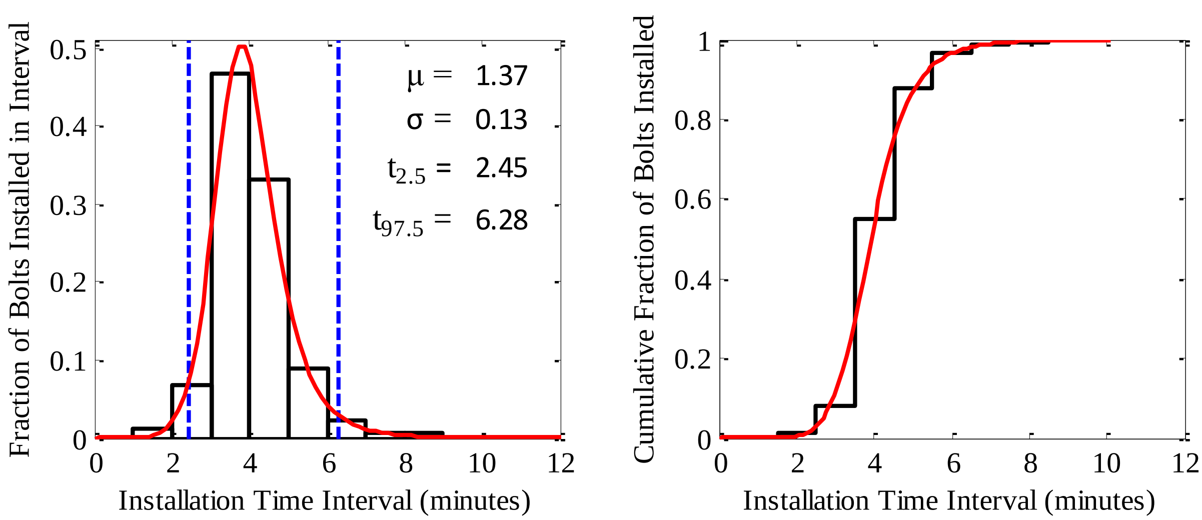



Figure 5.10 Mine C MacLean Split Sets, Log-Logistic Distribution

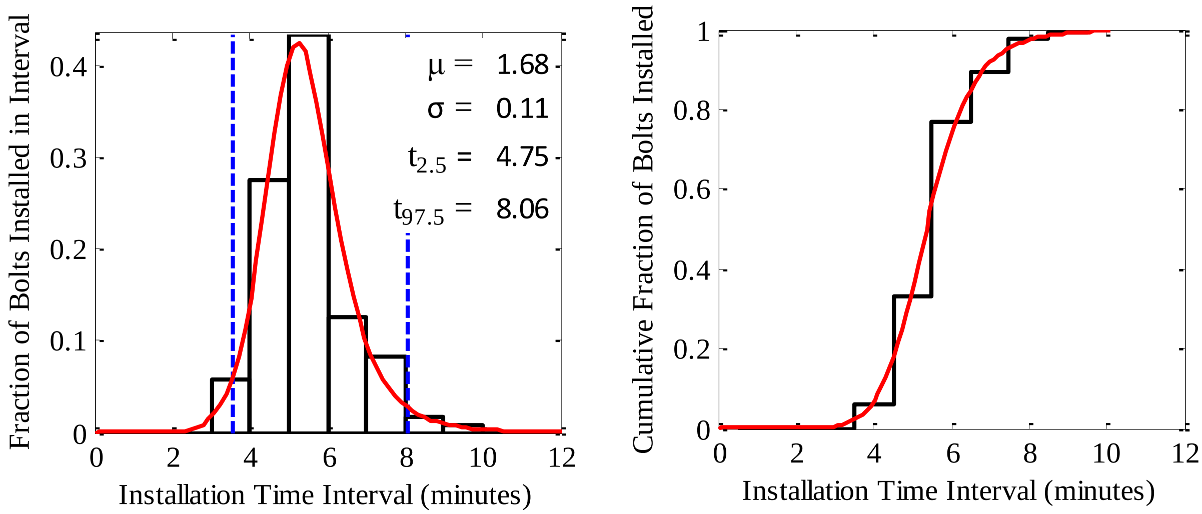



Figure 5.11 Mine C MacLean Rebar, Log-Logistic Distribution

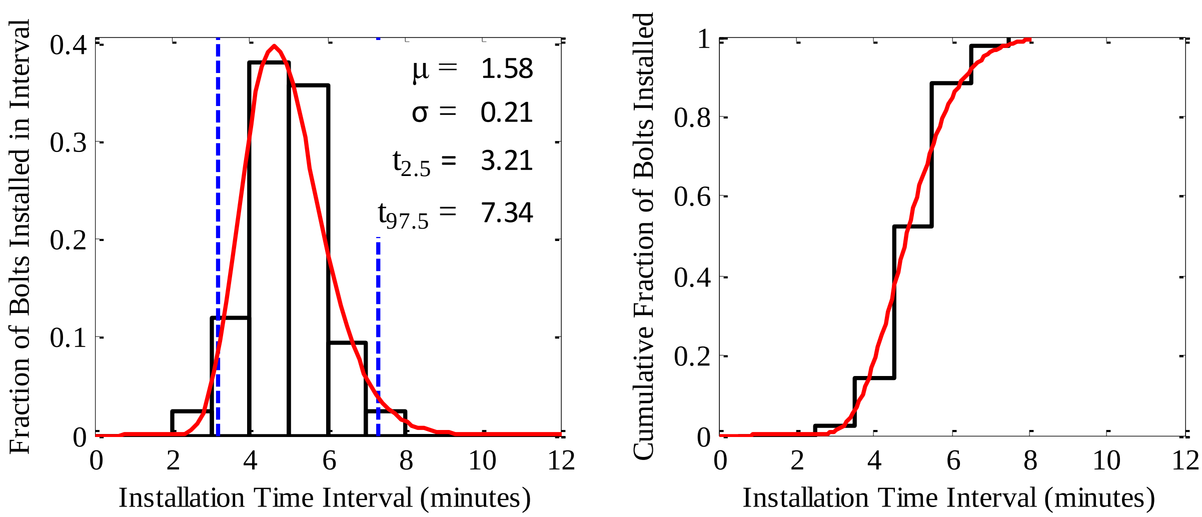



Figure 5.12 Mine C MacLean Modified Cone Bolts, Lognormal Distribution

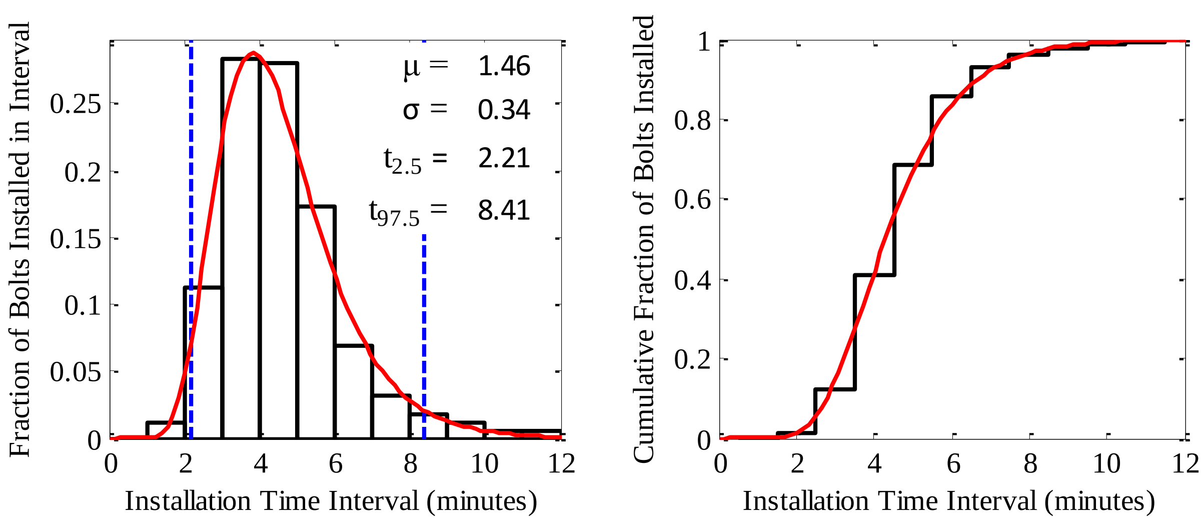



Figure 5.13 Mine C Boltec Split Sets, Lognormal Distribution

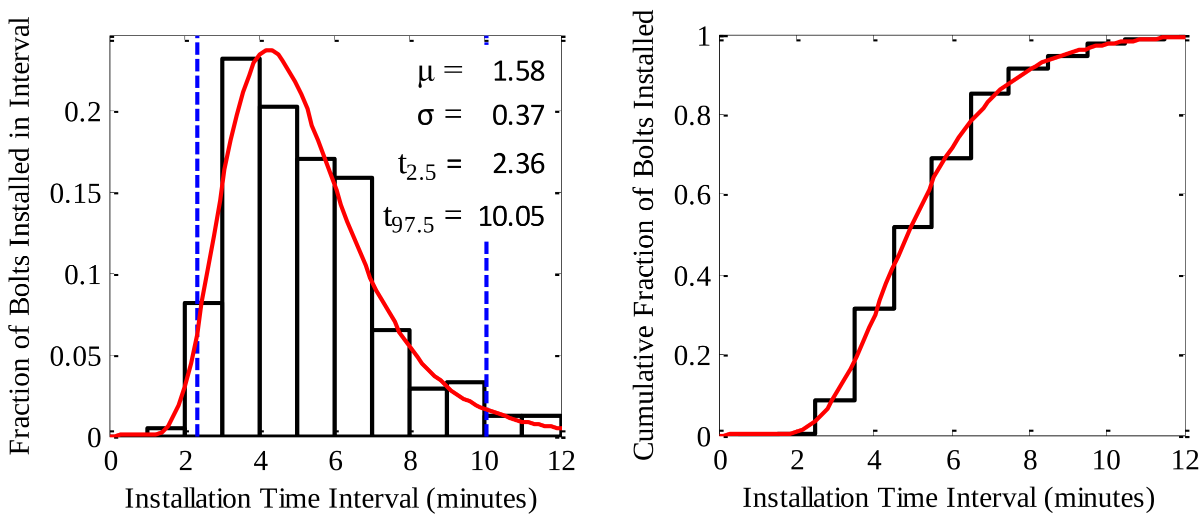



Figure 5.14 Mine C Botlec Super Swellex, Lognormal Distribution

Variability in the number of bolts installed per shift is dominated by logistics, bolt type installed and maintenance time at the face.

## 5.5 Control Charts

Work cycles are considered to be unproductive if the operator must terminate a bolt installation cycle and restart the work cycle.

Control charts are useful for analyzing the change in machine cycle time during the course of the study. Control charts for the three observed bolt installation types are shown in Figure 5.15 where **x** = failed work cycles, green arrows indicate the occurrence of a notable seismic event resulting in rock ejection, and the green text above the arrow describes the result of the seismic event. The upper and lower bounds are the 95% and 5% confidence intervals from the distributions shown in the previous section, and the centre line is the log mean of the distribution (see: Equation 9).

$$mean = \exp(\mu + \frac{\sigma^2}{2}) \qquad (9)$$

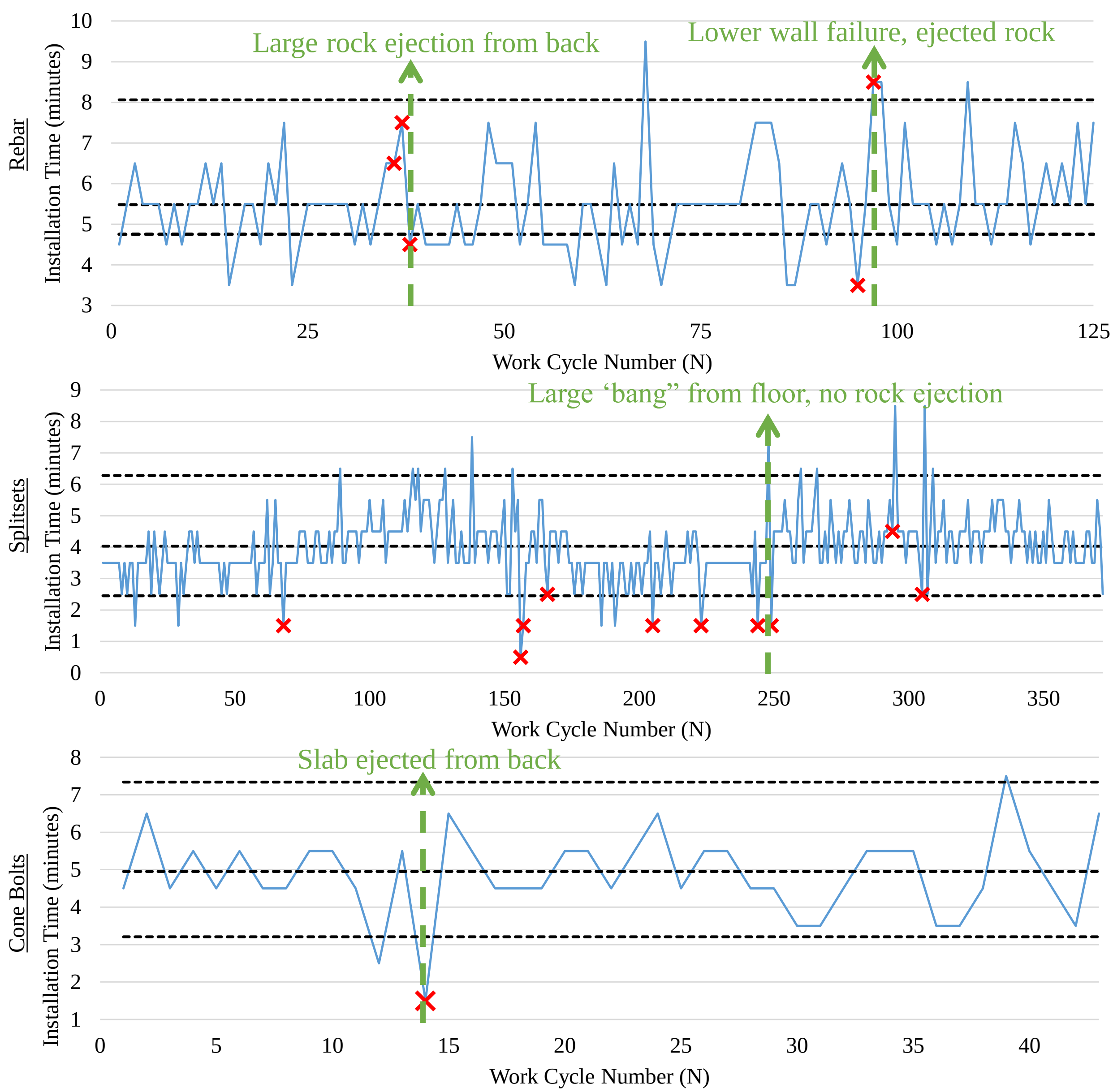



Figure 5.15 Control charts for bolt installation work cycle times

Failed work cycles and long cycle times tend to cluster when the bolter is partially functioning and in poor ground conditions. This could be an indicator that the bolter requires maintenance or that the heading should be re-scaled or inspected. Live monitoring of work cycles could be useful for indicating root causes of low bolter performance over a long period of time and determining when the bolter requires routine maintenance. Longer work cycles and failed work cycles are often observed in headings that have poor perimeter blasting and/or high amounts of seismic activity. Quantifying the relation between bolt installation times through the use of control charts would require long term data, however difficulty installing bolts and failed bolt installations can be a warning sign of failing ground (Lyle et al., 2014). Improved drilling and blasting quality could decrease the variability of the bolt installation process and increase a mine’s development and production rate by decreasing overbreak and underbreak (Kenzap, 2006; Dunn, 1997). Long term control chart monitoring could be used to predict bolt installation failures and be used to optimize preventative maintenance strategy.

Since the Boltec has a larger range of motion than the MacLean bolter, the Boltec is used to bolt irregular rounds (for example, around corners), and the productivity of the Boltec was significantly affected by poor drill and blasting practices where abnormal drilling patterns are used. Therefore, by improving the quality of the development drilling process, the bolter productivity will improve. Examples of underbroken headings are shown in Appendix D.

## 5.6 Analysis of Maintenance Records

Records of maintenance performed in the workshop were analyzed for the four MacLean bolters in the mine area of Mine C that was studied. It was found that ~2200 hours of maintenance is logged per year. Similar results were found from analysis of the two Boltec bolters in the same mine area. Bolters are maintained in the workshop every four weeks for approximately five to seven days. Estimation of the annual usage of the bolters is shown in Figure 5.16 - Figure 5.17

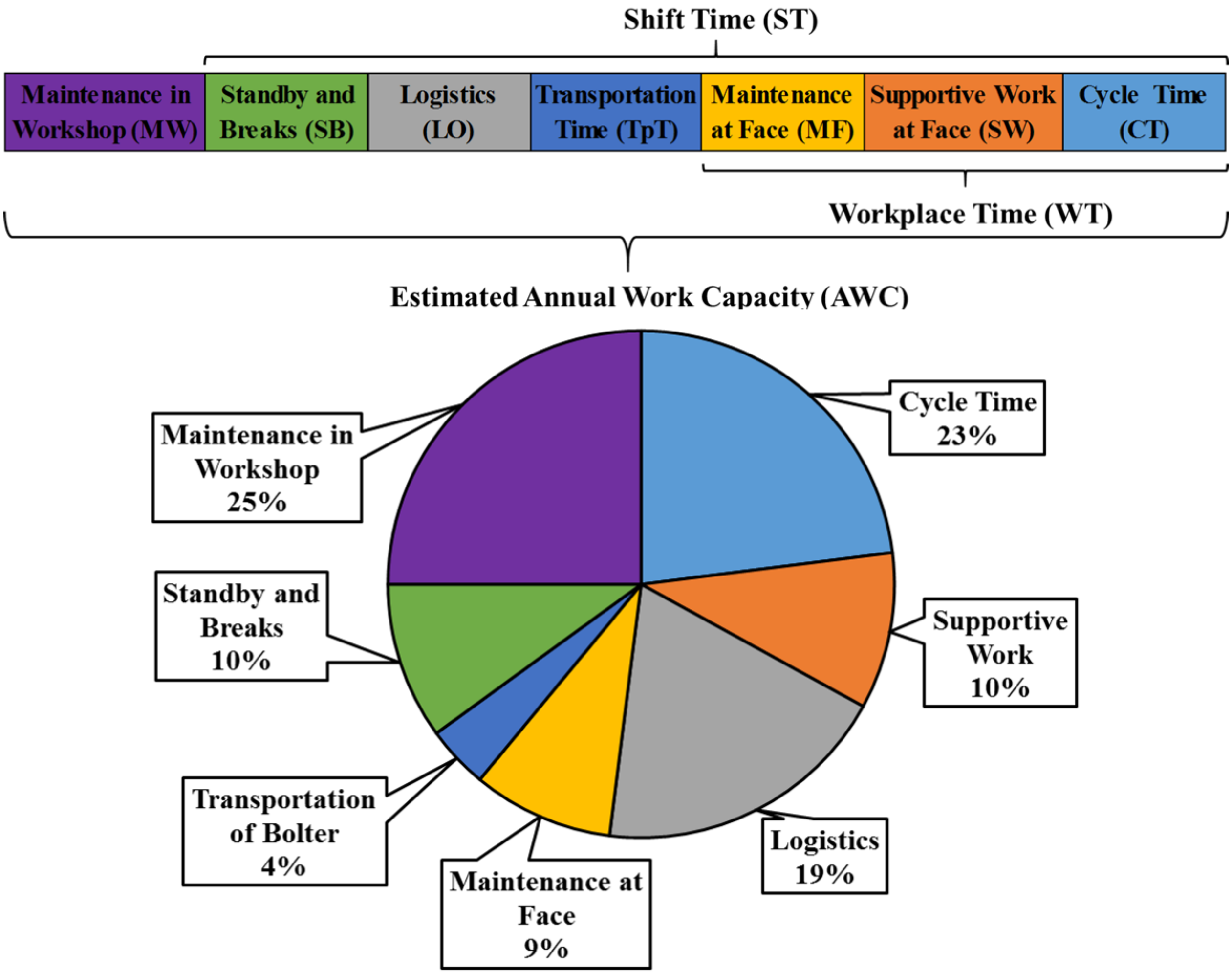



Figure 5.16 Estimated annual usage of MacLean bolter at Mine C based on maintenance record analysis

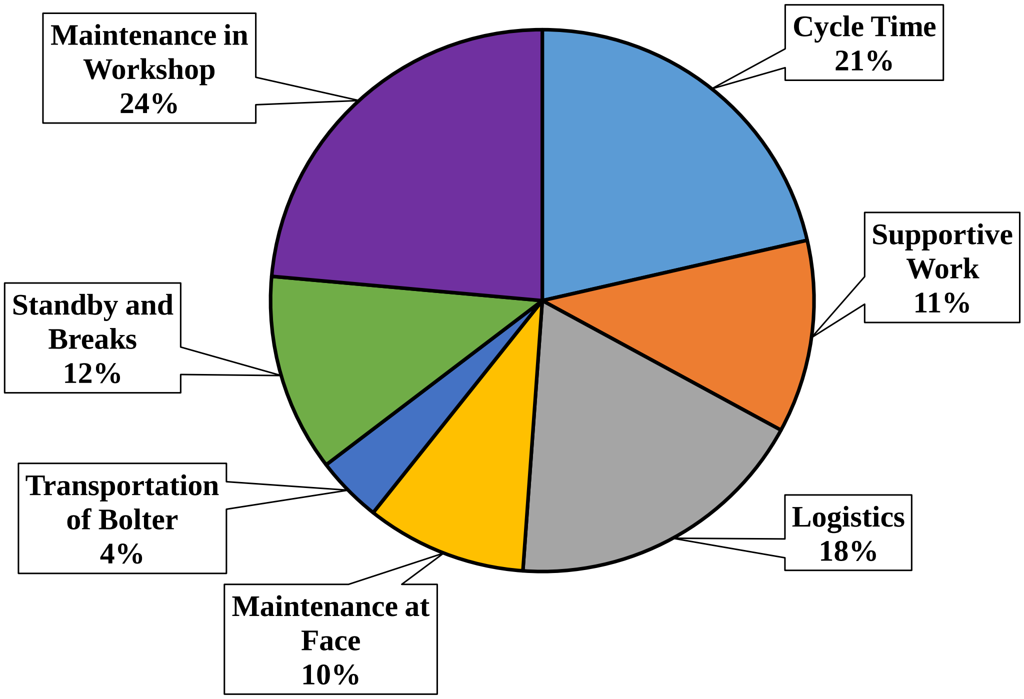



Figure 5.17 Estimated annual usage of Boltec bolters at Mine C based on maintenance record analysis

The annual bolter usage does not account for mine shutdowns, clearing time and non-shift time. By analyzing long term production records, unutilized time (UT) could be estimated. During the Boltec study, there were two shifts where no Boltec was utilized, one time was due to both Boltecs being maintained, and the other time, no Boltec operators were available due to their holiday schedule. This is a rough estimation of annual work capacity and may not be accurate, however studies could be completed on maintenance practices using similar techniques as described in Chapter 4 to find opportunities to optimize the mine maintenance process. The similarity between utilization of the two bolters is to be expected since usage time is dominated by mine-specific logistics and layout.

The measured work capacity of the bolters is summarized in Table 5.7.

Table 5.7 Measured bolter work capacity

| | Mine A MacLean | Mine B MacLean | Mine C MacLean | Mine C Boltec |
|---|---|---|---|---|
| Workplace Time Capacity | 7.9 bolts/hour | 7.6 bolts/hour | 8.3 bolts/hour | 6.5 bolts/hour |
| Shift Time Work Capacity | 6.5 bolts/hour | 5.1 bolts/hour | 5.4 bolts/hour | 4.4 bolts/hour |

A failure frequency analysis of a sample of the maintenance records shows that hoses are the component of the machine that fails most often as shown in Figure 5.18 and Figure 5.19.

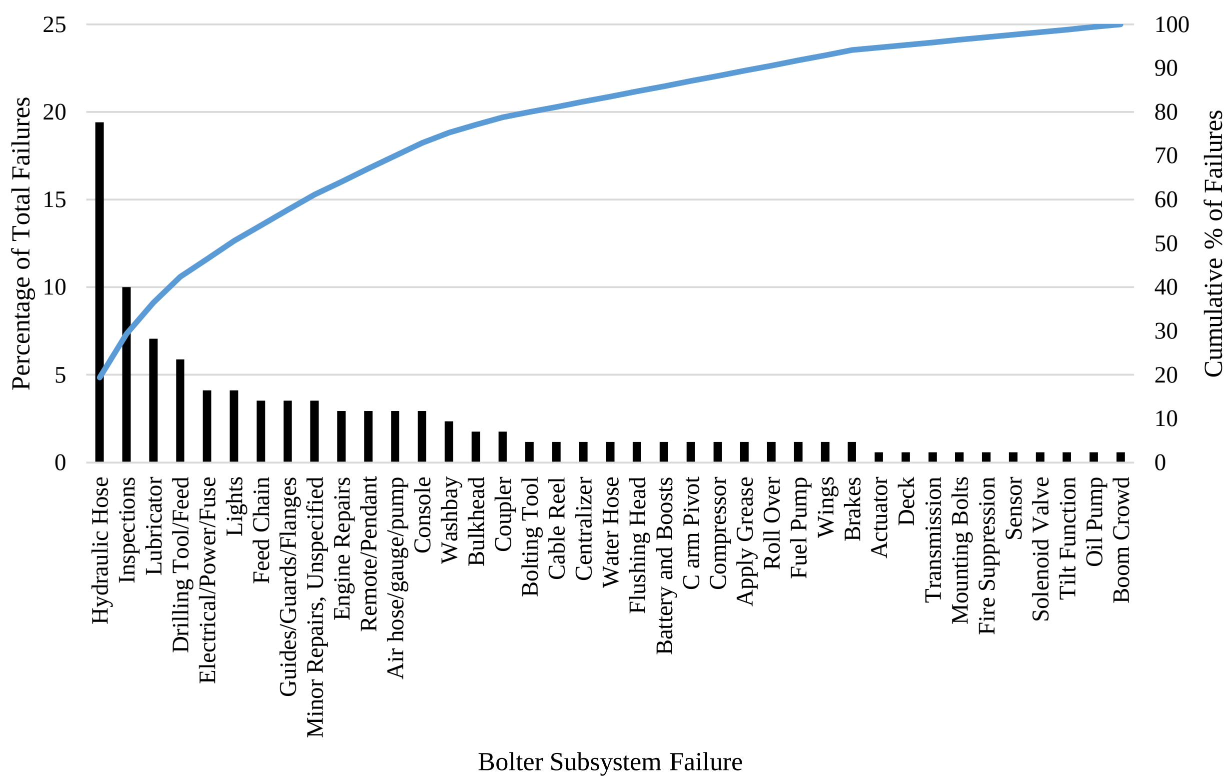



Figure 5.18 Pareto analysis of bolter failures based on MacLean bolter maintenance records

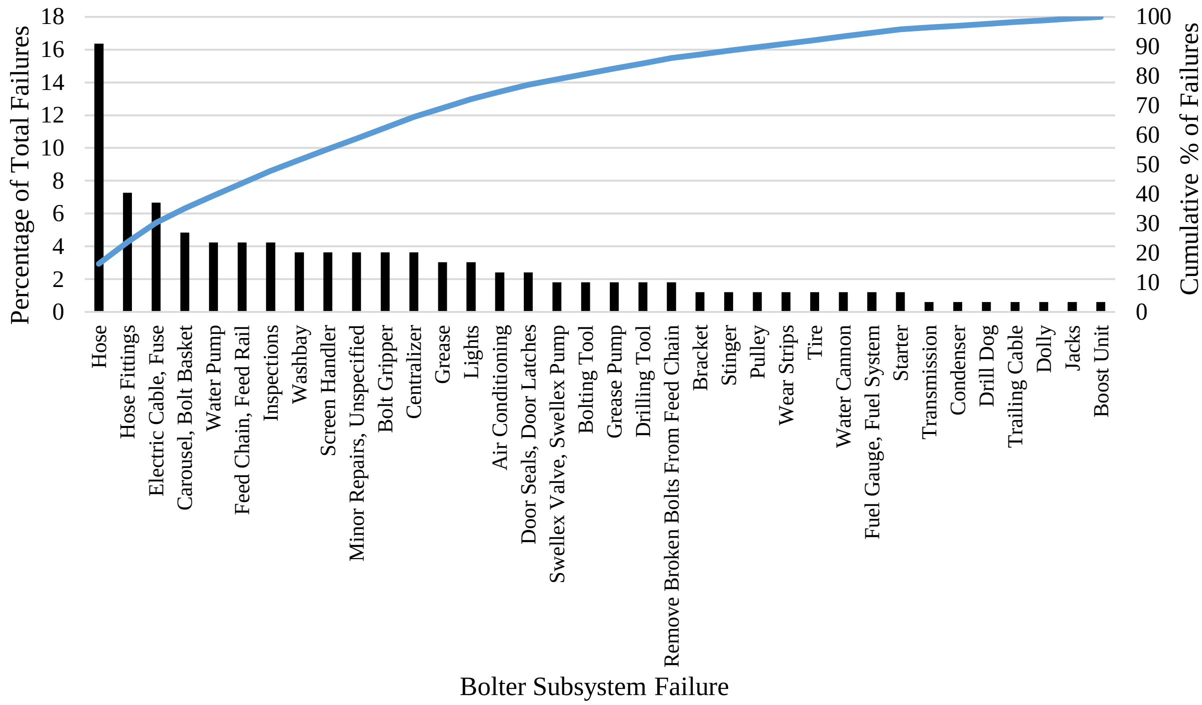



Figure 5.19 Pareto analysis of bolter failures based on Boltec MC bolter maintenance records

## 5.7 Delay Analysis

Delay types can be analyzed to decrease the variability in each part of the *shift time (ST).* A decrease in process variability will result in better correlation between *workplace time (WT)* and the number of bolts installed which would increase the overall productivity of the system.

Delays are considered to be any non-productive work time. Time components throughout a shift that are not bolting or installing screen are classified into four categories (after Spinelli and Vissier, 2009):

**Mechanical Delays:** breakdowns, routine maintenance, adjusting feed chains, maintenance at the face, replacing drill steel.

**Operator Delays:** rest, breaks, physiological delays.

**Mining Delays:** transportation of personnel and equipment, inspections, logistics.

**Other Delays:** interference with other operations, reconnaissance, refuel, rigging, preparation, cutting screen, washing equipment, clearing dust and scaling.

The percentage of total delays are categorized and shown in Figure 5.20, and the duration of delays as a percentage of total delay time is shown in Figure 5.21.

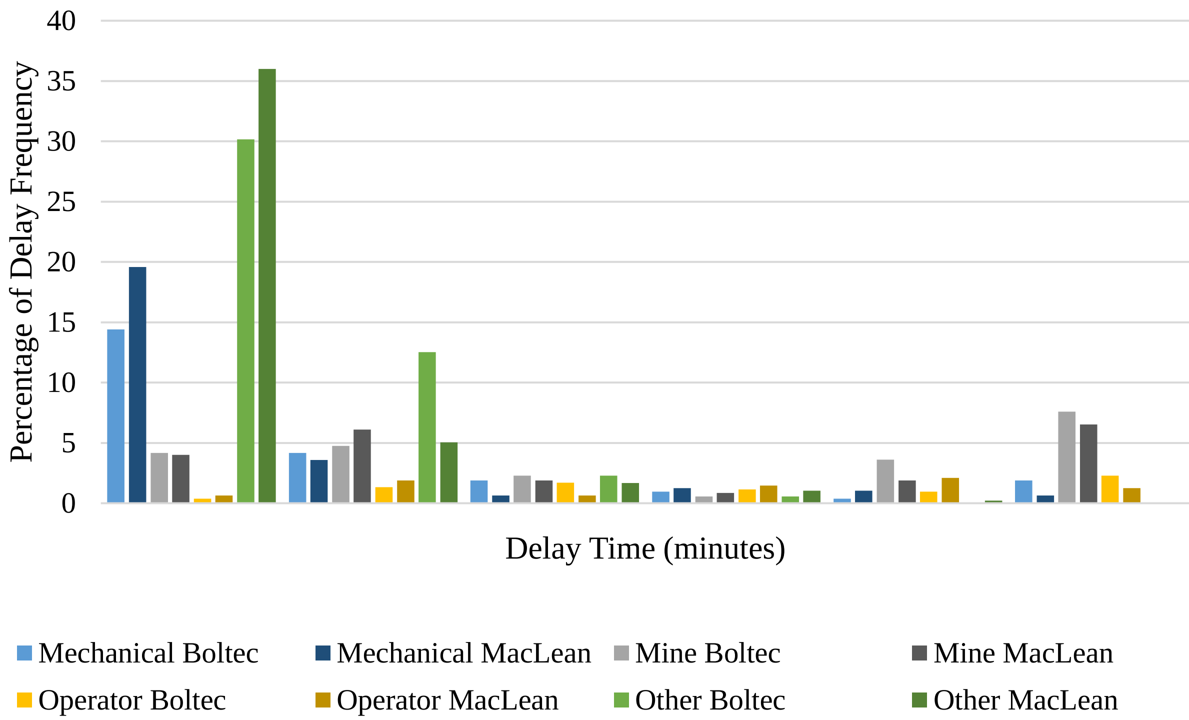



Figure 5.20 Percentage of number of delay types by category and duration

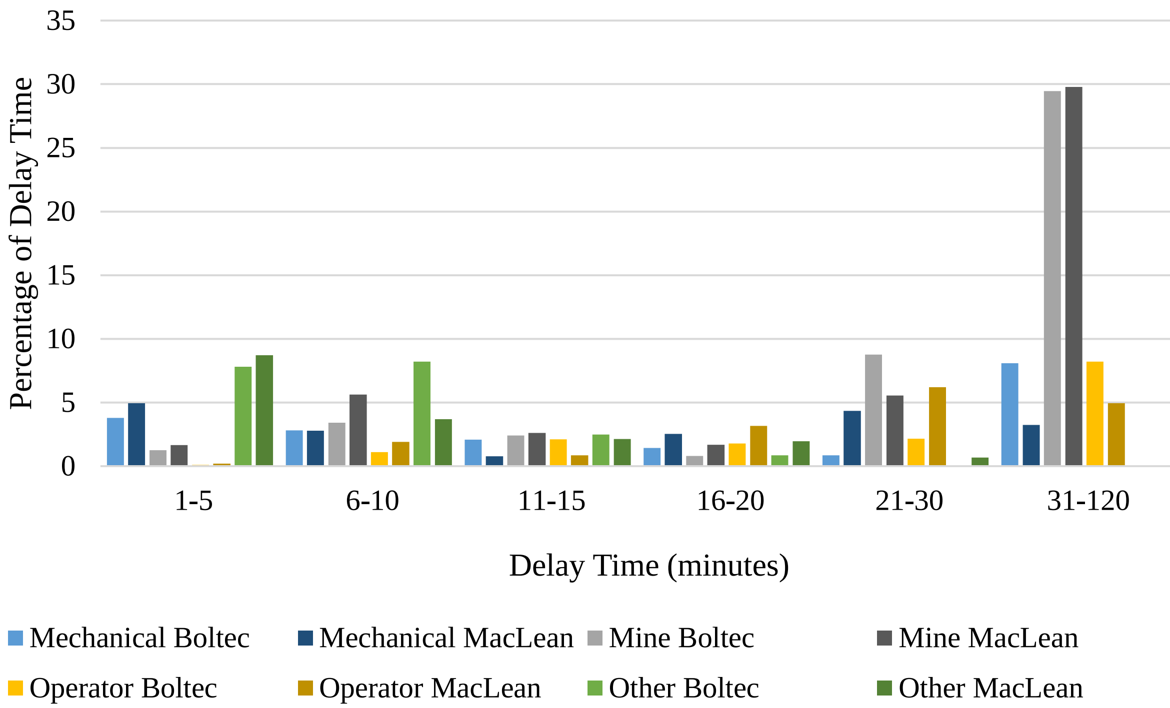



Figure 5.21 Percentage of delay time by category and duration

Mine specific delays consume the most time which is expected since it is found in Stewart et al., 2006 that drill and blast development rates are dominated by mine specific delays. Delay charts are useful for quantifying the observed delay time over the course of a shift, however these charts should be combined with root-cause analysis as shown in Section 5.3 to identify the most frequent and time consuming delays during the bolting process which can be improved. This is expanded upon in Chapter 6. When changes to the process are made, follow-up studies can be made to quantify the change in delay types and delay frequency. Based on delay analysis completed by Eshun & Temeng, 2011, a fishbone analysis of delays observed throughout this work study are shown in Figure 5.22. Further demonstration and discussion of delays is included in Appendix D.

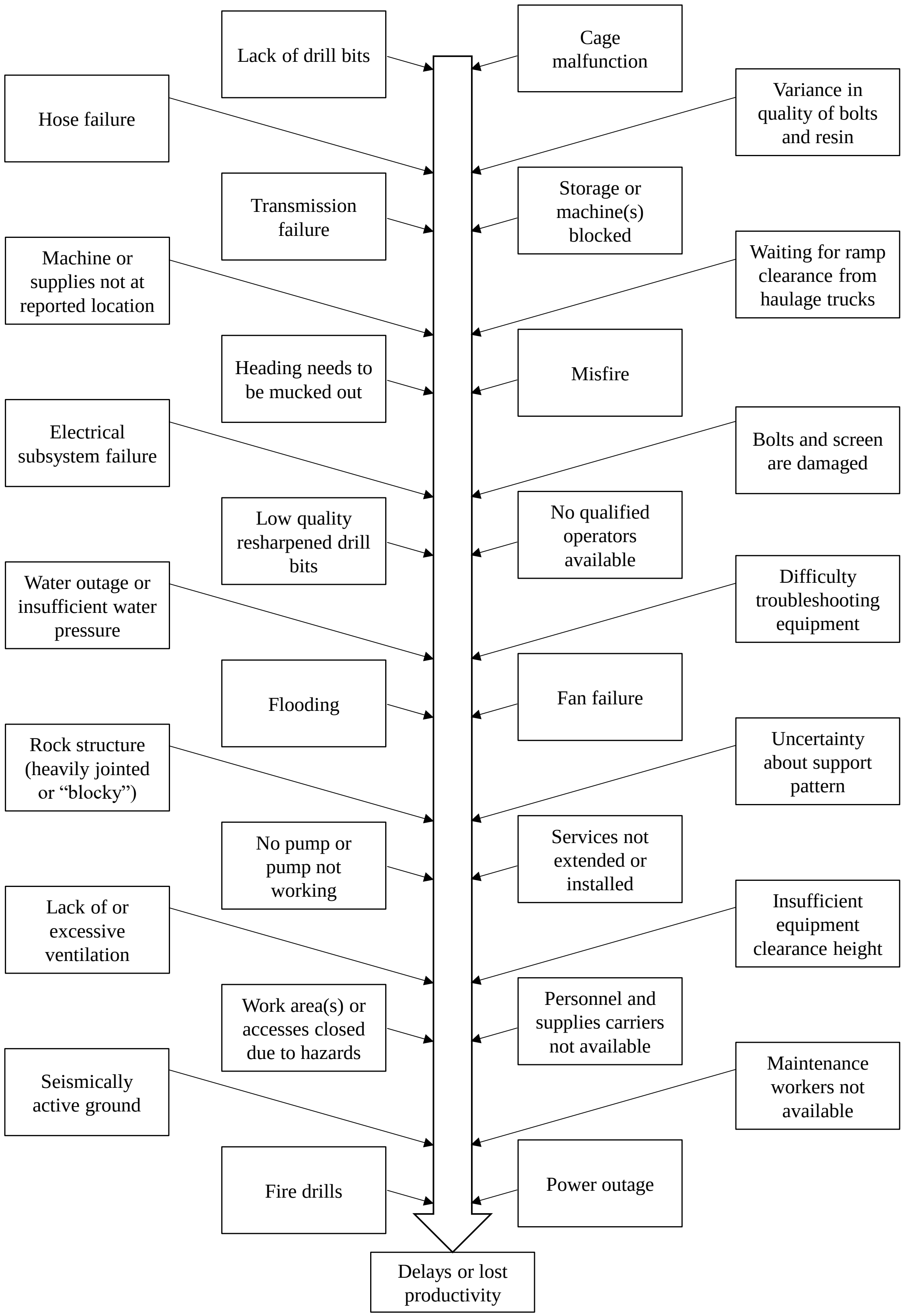



Figure 5.22 Examples of causes of delays or lost productivity observed over the course of the study

## 5.8 Summary

The methodology used to measure productivity in other industries is effective for quantifying productivity as well as qualitatively descriptions of the work environment and factors which affect productivity. Some of these factors can be improved through changes in work practices, other factors cannot be changed such as rock mass properties and rock stress.

Many of the results presented do not address productivity measurement of mining processes alone, however combinations of the analysis and results tools which are verified through productivity questionnaires show the causes of the current state of the mining process and opportunities to improve the process. These tools are also useful for identifying components of the process to be modified and can be used in follow-up studies to measure the improvements and deficiencies of the process.

Similar studies can be completed on other types of mining equipment. In parallel, these analysis tools can be used to measure the relation of productivity between pieces of equipment that are used in the same mining cycle. For example, how bolter and jumbo productivity relate, and which aspects of the development cycle can be improved to increase the productivity of both machines in the same mine area.

The use of video of machine operation can improve the repeatability of the study by multiple observers (Bucholtz et al., 1996) because break points between work tasks can be shown visually, which reduces the uncertainty of the measurement of the process.

Using the methodology shown in Chapter 4, the productivity of bolters was quantified in a variable environment. It is assumed that the productivity of the bolter will change over time as development gets deeper, and the ground conditions and environment in the mine change.

Identifying and reducing delays which exist regardless of changes in the environment can increase the productivity of the bolter. Follow-up studies can be completed to verify that measures have been implemented to increase bolter productivity, and measure the change in bolter productivity in new development areas as the mine becomes deeper.

# Chapter 6

# Discussion About the Effectiveness of the Methodology and Observations About the Results

This chapter is the discussion of the application of the productivity measurement methodology applied to the rock bolting process in three Canadian underground mines, and observations about the bolting process during the study.

## 6.1 Examples of Opportunities to Improve Bolter Productivity

Based on the time study data, maintenance record analysis and responses to questionnaires and delay time analysis, examples of opportunities to increase the productivity of the bolters are:

- Improve communication about machine status, location and support pattern to be installed,
- Optimize logistics and loading of supplies,
- Increase the availability and number of personnel transport vehicles,
- Have operators carry spare hoses on the machines, and have the operators qualified to replace broken hydraulic hoses,
- Use mechanical or hydro scalers to decrease scaling time and increase scaling quality,
- Have ongoing quality assurance and quality control for Split Sets, resin and drill bits to reduce variable drilling and Split Set installation times,
- Reduce the time that bolter operators spend to clear headings, install ventilation tube, cut blasted screen and extend services,

- Improved blasting practices to reduce heading irregularity and improve development quality,
- Optimize maintenance schedules based on bolter electrical and diesel hours,
- Modify the bolter to guard hoses at the base of the boom from falling rock,
- Assignment of equipment with more degrees of freedom to bolt irregular rounds (such as a Boltec or Jumbo).

Further discussion and demonstration about reducing supportive work time, and increasing face time is in Appendix D and Chapter 6. A detailed productivity report was submitted to the mine staff. These reports were found to be useful for understanding bolter productivity and for implementing changes to improve the bolting process.

The methodology shown in Chapter 4 was effective for measuring the productivity of the bolters and answering the research questions. The methodology can be verified by analyzing long term mine production data.

## 6.2 Meeting Study Objectives and Improving the Study Methodology

Based on feedback from the participating mines' ground control departments and management, the study was considered to be capable of meeting the study objectives, however some aspects of the study can be improved (see: Table 6.1).

Table 6.1 How the objectives of the study were met and ways in which the study can be improved

| Work Study Objectives and Sub-Objectives | Ways in Which the Study Could be Improved to Meet Objectives |
| --- | --- |
| **Quantify factors that compose shift time (ST), workplace time (TT) and total time (TT)**<br>• Document abnormal cycle times ✓<br>• Measure productivity of bolters in a deep mine ✓<br>• Compare mechanized and semi-mechanized bolters operating in similar conditions ✓ | • Increased duration of study<br>• Use of production data to estimate face time<br>• Improved maintenance record analysis which could be enhanced by using improved record quality which is intended for analysis<br>• Measurement of mine maintenance practices<br>• Detailed statistical analysis of data<br>• Use of equipment digital records or instrumentation of equipment to obtain long term data |
| **Identify opportunities to improve productivity of the bolters**<br>• Identify root causes of bolter productivity rates ✓<br>• Identify mine specific and equipment specific delays ✓ | • Improved quantification of root causes of delays and proposed solutions<br>• Implementation of corrective actions to improve bolter productivity and quantification of the results<br>• Increased duration of the study to identify uncommon delays |
| **Quantify productivity for different bolting systems and different rock mass conditions – partially met** | • Investigation into how RMR affects the bolting time<br>• Use of scanning technology to quantify overbreak, underbreak and RMR<br>• The use of drilling analysis (such as penetration rate, percussion pressure, hammer frequency etc.) and how these parameters affect bolting rate<br>• Quantify how rock stress affects the bolting cycle<br>• Incorporate near-field seismic activity measured by sensors to quantify how it affects the bolting cycle |

To supplement the study analysis, additional data could be collected to enhance the results:

- Measurement while drilling (MWD) data to improve the control chart analysis and characterize the rock mass (Rostami et al., 2015) and measure hole squeezing which contributes to longer drilling and bolting cycle time,
- Detailed analysis of the Boltec Rig Control System (RCS) data logger, although machine operators believe that this data may contain inaccuracies due to sensor failures, or it can easily be misinterpreted (for example – XYZ positioning of the drill during scaling could be interpreted as bolting time),
- Detailed analysis of mine production and maintenance records,
- Quantification of drift quality in terms of overbreak and underbreak, and how this affects the bolting cycle,
- Completion of follow-up studies once corrective actions have taken place to measure the effectiveness of the implementation of process control,
- Measurement of the interrelation between different development mining processes.

## 6.3 Study Methodology Precision and Accuracy

There were many potential sources of error in the study. The categorization of shift time activities is shown in Appendix B, however these activities may be categorized differently by different observers. Studies could be completed to measure the differences in study results with different observers in the field or using videos of the bolting process. This type of analysis could quantify the amount of observer error to be expected in mining equipment studies.

Due to the time resolution at which the bolting process was measured, the observed bolting times are precise to +/- 1 minute. Precision of the results of future studies could be improved by using an improved time resolution by logging data digitally. Analysis of long term video obtained during the study could also improve the precision of the study, however due to the number of work cycles logged, it is not necessary to study the bolting process at that level of detail.

### 6.2.1 Observer Effect

The case studies for this thesis were carried out by the author. The establishment of break points and classification of time were subjective. It would be of value to compare results obtained by multiple observers. In forestry, a study was conducted by Spinelli et al. in 2013 where twelve researchers measured the same repetitive work cycles performed by a forestry machine. It was found that observer-induced variability was not significant provided that the work elements are broken down into meaningful steps that are easy to recognize and record. Appendix B.1 contains flow diagrams indicating break points for the bolting process, although it is recommended that new observers watch video of the bolter operation to clarify the break points between work activities.

In the author's opinion, the study was not significantly affected by the observer effect as machine operators were working towards specific productivity targets associated with the bolting task and supported an external study of bolting practice. Also, consistent results were obtained regardless of operator, and it seemed as through the workers did not significantly change their work rate when observers were present.

Spinelli et al. (2013) stated that to achieve high accuracy and reliability, studies should be carried out over the course of multiple hours, however the authors mention that Pehkonen (1973) found that measuring accuracy declines after two hours due to observer fatigue. In mines, observers are not able to leave the workplace over the course of a shift for safety and practical reasons.

Therefore, it may be possible to reduce observer fatigue by having two or more observers rotate during the course of a shift.

### 6.2.2 Air Temperature

The study results were collected during the months of May – September. Air temperatures were at a record or near-record high on the surface during the majority of data collection at Mine B. Surface temperatures exceeded 30°C, and Mine B did not have access to a refrigeration system for cooling purposes so heat was managed through ventilation flow and work-rest protocols as required. While the underground temperatures were high due to surface inlet temperature, rock temperature, heat generated from machines, autocompression and recirculation in the ventilation system, the workers seemed to be acclimatized to working in high temperatures. The MacLean bolter was observed to be sensitive to overheating in this environment, but this did not seem to contribute to significant delays during the bolting process.

It has been found in forestry that cold temperatures may affect observer fatigue (Spinelli et al., 2013). Likewise, it can be assumed that high temperatures affect observer fatigue in mining. Further research would need to be completed to quantify the amount of variability in work study results and productivity of workers/equipment due to high temperatures in mines.

### 6.2.3 Methodology Improvement

To better quantify the root causes of low productivity of the mining process, the methodology could be expanded:

- Develop a method of integrating long term production and maintenance data to determine long term productivity of mining equipment,

- Standardize production and maintenance records so that the information can be more useful for the purposes of measuring equipment productivity,
- Establish a method of mapping instrumented data and machine digital records to actions of the machine recorded through time study,
- Perform a more detailed statistical analysis of the results,
- Determine which factors affect the productivity of the work cycles such as rock mass conditions, mine layout, equipment age and maintenance strategy
- Implementation of process improvements, and measurement of the results

A robust methodology can be developed for bolters, and extended to include similar equipment such as jumbo drills, production drills and ANFO loaders. Spatial data such as slope and distance could be taken into account to extend the methodology to include personnel carriers, haulage trucks and LHDs. The methodology could be refined further by taking into account the relation between each of the pieces of equipment used in the development and production cycles of the mine to quantify the interaction of each of the processes.

Similar studies should be completed to analyze the mine’s maintenance and logistics procedures, and how it affects equipment productivity.

## 6.4 Observations About Mechanized Bolting

Based on the observations over the course of the study, comments on the mechanization of the bolting process are shown in Table 6.2 below based on the comments made by Nong, 2011.

Table 6.2 Comments on the improvements introduced by mechanization of the bolting process at Mine C

| **Rationale for mechanization of the bolting process** | **Comments** |
|---|---|
| Improved Efficiencies | • Not observed, however applying corrective actions could improve the mechanized bolting process efficiency beyond the efficiency of the semi-mechanized bolter |
| Productivity | • No productivity increase observed |
| Safety | • Mechanized bolters allowed the operators to safely install bolts into sandfill without a shotcrete layer<br>• Safety data was not collected |
| Attract Women in Mining | • Inconclusive, no female operators participated in the study |
| Low Operating Cost | • Inconclusive, financial information was not obtained<br>• The capital cost of mechanized bolters is significantly higher than semi-mechanized equipment |
| Increased production | • The mechanized bolter allowed one pass of bolts in sandfill rather than two passes which could improve the mine development rate in sandfill |

The study suggested that mechanized bolting did not seem to provide the anticipated productivity advantages over the semi-mechanized process at Mine C, although there were some benefits were identified in the area of safety and production. Part of this is associated with the challenging conditions encountered in a deep operating mine. In some cases, a change to the mine design is required to maximize mechanized equipment productivity (Webber et al., 2010).

An audit of the Boltec performance and methods to improve the equipment performance should be conducted by the mine, its suppliers, and third party experts to achieve maximum output from the mechanized equipment.

## 6.5 Opportunities to Achieve Improved Bolter Productivity

Opportunities to improve bolter productivity were identified through quantitative and qualitative observations and through literature review. This section describes and illustrates observations made and ways to potentially improve the bolting process. It should be noted that changes to a process can have unintended negative consequences, particularly in a variable mining environment. The changes recommended in this section should be analyzed in detail by the mine's staff before implementation.

A positive skew on a cycle time distribution indicates that there is a mechanical issue which should be investigated (Nakajima, 1988). The large tail on the bolt installation distribution for the Boltec is due to intermittent slow drive times, slow Swellex pumping times, alignment issues, and intermittent electrical and feed pressure issues. Often, the cause(s) of these issues are unknown, however there are likely combinations of software and hardware issues that contribute to frequent intermittent problems with the Boltec. By systematically determining the root cause and correcting these issues or redesigning bolter components, the majority of long bolt installation times can be eliminated and the Boltec bolting speed can be significantly improved. It would be expected that if the majority of intermittent issues are corrected, the Boltec and MacLean would have similar bolt installation time distributions where the tail on the distribution is mainly due to installing bolts in difficult ground conditions rather than mechanical and electrical problems.

### 6.5.1 Quality Control of Supplies and Materials Handling

It is estimated that bolts are transported 8-10 times from off-loading the supplies in a warehouse on surface to reaching the heading or stope where bolts are to be installed (Herron, 1983). There are likely more materials handling steps in deep mines compared to shallow mines, as bolts are transported a longer distance. This can affect the quality of bolts since longer transportation times can result in corrosion and damage to the bolts, screen and resin which can contribute to loss of productivity and reduce the effectiveness of the bolt. It was also observed that on occasion, welds on the galvanized screen were corroded in the storage; it is unclear whether this is a manufacturing defect or if it is due to the screen sitting for too long in storages (see: Appendix B).

An audit of supplies logistics can indicate when bolts and screen become damaged along the bolter supplies transportation chain. Materials handling and logistics are often not studied due to the lack of appropriate data for quantitative analysis, however logistics can be analyzed qualitatively to measure the impact on the mine's operations (Pareja, 2000). Machine operators suggested that remote loading of the bolters, or tele-operation of transportation of supplies would improve the efficiency and quality of the mine's logistics.

MacLean operators manually load supplies onto the bolter, and Boltec operators transport supplies to the heading prior to tramming the machine in for bolting. Boltec operators then "gear" their drift by carrying supplies and letting the supplies rest on the drift walls (see: Appendix B). Gearing time could be reduced through optimizing the storage layout, this was proven to be successful through the reduce bolter gearing time by half and allow two bolters to be loaded simultaneously (Watson et al., 2013). Mine C has an optimized storage layout where bins are placed on bunks to reduce the distance at which the MacLean operators had to carry bolts. Mine A has many smaller storage areas dispersed throughout the mine which complicates logistics, and resin often expires. The interaction between logistics equipment, strategy, storage layout, location, and how this affects the bolting process is complex, but an integrated approach could be taken to study these relations to optimize the process using computer-assisted tools (Pareja, 2000).

Resin used for rebar and cone bolt applications was observed to be an important component of successful bolt installation. Some of the issues encountered during the course of the study are listed as follows:

- Variation in resin set times.
- Availability of proper resin supply.
- Adequate resin expiry dates.
- Transportation of resin to the installation site.

The lower $R^2$ for Split Set installation is due to the variation in local ground conditions which results in variable Split Set drive times. Also, what is considered to be acceptable Split Set installation varies from mine to mine as shown in Figure 6.1 which affects Split Set drive times. The majority of Split Set drive time is the last few inches of installation; not completely inserting Split Sets significantly decreases drive times.

Figure 6.1 Left: Split Set installations at Mine A, not all Split Set plates are in contact with the screen; right: Mine C Split Set installations, most plates are in contact with the screen

Transporting personnel to the work face was often challenging due to the mine layout, and the availability of vehicles. Machine operators suggested that having more small personal transportation vehicles rather than using larger vehicles would significantly increase face time since they could travel directly to their workplace rather than waiting for other workers to be dropped off.

To reduce the cost of drill bits at Mine C, bolter operators are issued a limited number of new and re-sharpened drill bits for each shift. Unusual wear of the re-sharpened drill bits was often observed after operators drilled fewer than three holes (see: Figure 6.2), and difficulties installing Split Sets was observed when re-sharpened bits were used even through the bits passed a bit gauge test. Operators did not have Split Set bolt gauges which could indicate whether long Split Set drive times and failed Split Set installations were due to a variance in the diameter of the Split Sets or due to issues with drill bits. Long Split Set drive times also contributed to Split Set rings falling off during installation which reduces the bolt's effectiveness (see: Figure 6.2). If Split Sets could not be completely inserted, operators would often use the drill steel to drive in the Split Sets which also contributed to damage to the Split Set ring. The cause of poor drill bit quality and long Split Set installation times could be investigated to decrease the number of failed bolt installations and decrease bolting cycle time.

Figure 6.2 Left: Unusual bit wear on re-sharpened drill bit after drilling two holes, the drill bit passes the bit gauge test; Right: Split Set ring has fallen off a bolt due to long drive times during installation

## 6.5.2 Root Cause Analysis

Delays are often the result of a combination of two or more factors since the mining environment is variable and productivity relies on multiple factors. To meet the study objectives, an analysis of delay times are quantified in section 5.8 and potential root causes of delays are analyzed using the techniques described in Chapter 4.

Observed factors which can affect the productivity of the bolter are shown in Figure 6.3. Some of these factors can be controlled, while others are uncontrolled. Issues such as overbreak are partially controlled by rock mass quality and rock stress, particularly in deep mines. Issues with drift quality can be minimized despite natural variation. Each component of root causes of bolter productivity should be systematically reviewed, and the components which contribute the most to productivity losses can be identified and corrected.

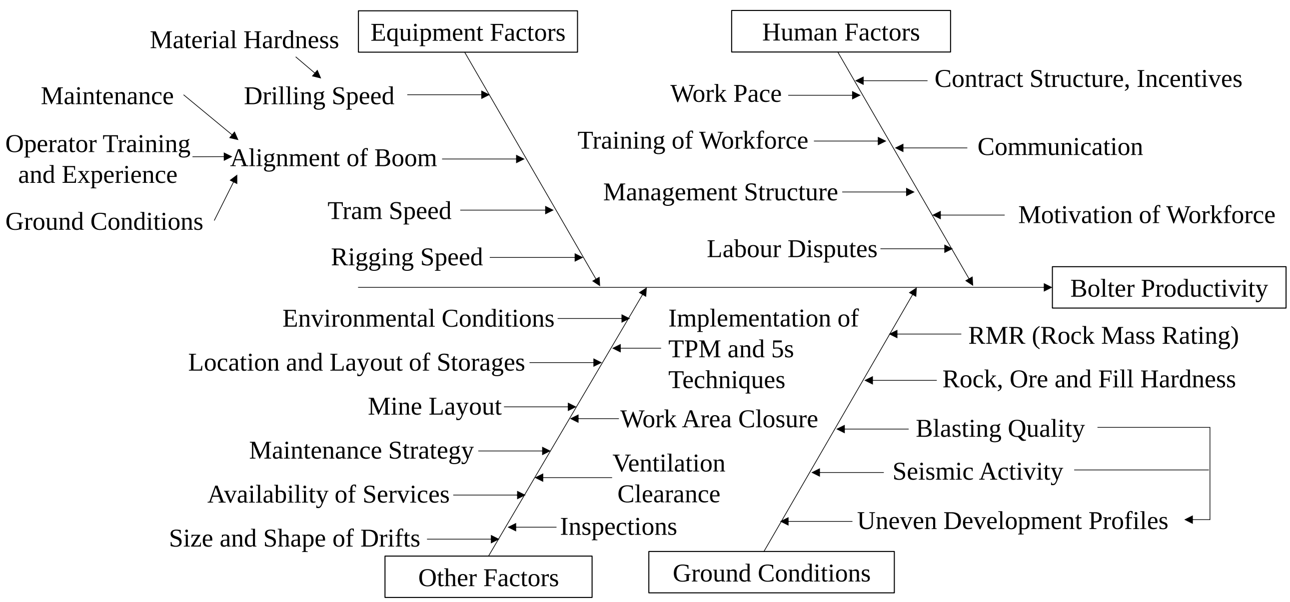



Figure 6.3 Observed factors which contribute to bolter productivity

Many productivity factors are difficult to measure or quantify (for example: worker fatigue due to high temperature and humidity). Mines can use delay analysis to identify which delays can be avoided and complete follow-up studies to confirm whether changes to the bolt installation process contributes to higher equipment productivity. Improved integration of data with varying quality such as maintenance, operational, and logistics data could be fused to improve the understanding of root causes of asset performance, and increase mining efficiency by avoiding equipment failure (Carter et al., 2000; Sehic, 2002; Gustafson et al., 2008; Gustafson et al., 2012)

## 6.5.3 Drift Size and Quality

To meet industry demand for higher productivity, larger equipment is used for operation which results in an increase in rockmass stress and increases the ground support requirements (Thakur, 2007). To excavate larger drifts, larger and more sophisticated equipment is used which requires more complex infrastructure and higher skilled maintenance personnel (Thakur, 2007). In additions, Canadian mining regulations require that drifts are at least 1.5 m wider than any vehicle in operation (Pareja, 2000). In tramming mode, the Boltec MC is 17” taller than the MacLean bolter, and the cabin does not have a retractable roof like many of the jumbos used in development drilling. The tramming time of the Boltec was increased because the roof would drag on ventilation ducts (see: Figure 6.4), and the operators had to be cautious to avoid damaging the ventilation system. This problem could be eliminated by installing the ventilation ducts closer to the top of the drift.

Figure 6.4 Left: Ventilation tube clearance during tramming; Right: Steel ducts damaged by tramming equipment with insufficient clearance

It is typical in Canada for each worker to perform one component of the development cycle rather than complete multiple components of the development cycle which affect one-another which can lead to a diminished pride in the work performed and poor drifting quality (Peloquin, 2007). Poor drifting quality can lead to overbreak and underbreak and damaged rock surrounding excavations which results in re-work and which directly reduces the drifting efficiency (Smith, 2004). At mines where drifting quality is not a priority, workers tend to charge the face with more explosives than necessary to achieve maximum advancement per round (Smith, 2004). Some issues with loading observed during this study are captured in Appendix D. One associated factor associated with misfired holes was the distinction between loading and B-line hook up, where the hook up component was completed by a separate crew managing the blast firing preparation of all pre-loading rounds. It was common for the "lifters"[11] to not be fired since the successful blasting of those holes is more sensitive to the jumbo drill angle and are prone to water intake.

Since the Boltec has more degrees of freedom, it is often used to bolt irregular rounds where the machine must bolt around corners. Since the drilling and loading of irregular rounds is more complex, it was often observed that there were misfires in irregular rounds which significantly affected the productivity of the Boltec. Examples of underbreak which prevented the Boltec operator from entering a heading or which contributed to delays in the bolting cycle are shown in Appendix D.

In particular, the bolting cycle is greatly affected because overbreak and damage to the rock surrounding the drift increases the amount of scaling that needs to be done, and the number of

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[11] The holes at the bottom of the face

bolts to be installed per round (Smith, 2004). It is suggested by Smith (2004) and Peloquin (2007) that quality of drifting would increase if it was taken into account when calculating the workers' incentive pay.

## 6.5.4 Maintenance Strategy

At the mines studied, all bolters are scheduled for preventative maintenance every month for four to seven days depending on maintenance crew schedules. Bolter operators noted that often, when equipment is released from the workshop, some preventative maintenance is not complete, and has to be completed at the face. It was observed during field studies that recently released equipment was prone to intermittent failures at the face.

A large portion of equipment downtime at the face was observed to be due to reactive maintenance. Often, the equipment is difficult to access when it is operating in remote parts of the mine. Therefore, it is often the case that a large portion of equipment downtime at the face due to machine failure is spent waiting for maintenance workers to arrive to resolve what are often simple problems such as hose failure. Based on maintenance records analysis, equipment failure for both bolters is dominated by hose failures. This is partly due to the fact that hoses are exposed to falling rock during the bolting process. Installation of improved hose guards could decrease the number of hose failures. Maintenance personnel were observed to typically be excluded from the incentive system process at the mines participating in this study. Some mines do operate with overall mine production based incentive systems, but these have to be carefully applied in the context of service type support roles such as maintenance. Training equipment operators to perform simple reactive maintenance such as hose replacement and feed chain adjustments, and gearing equipment with machine components which often fail would reduce downtime at the face.

## 6.5.4.1 Equipment Design on Productivity

At Canadian mines, it is common practice for operators to scale with the bolter drill (Peloquin, 2007), and this was observed at all three mines. In addition, equipment booms are under unsupported rock and sandfill. Due to these mining practices, loose rock and sandfill and dirty water from drilling is falling on the bolter booms during scaling and bolting. The bolter booms get clogged up with dirt which contributes to hose and component wear and failure. Operators at Mine C suggested that using a scaling machine in poor ground would reduce the number of hose failures and misalignment of the bolters. This problem is worsened by poor perimeter blasting.

Typically, bolting in Sweden is completed through shotcrete so there is no loose rock which falls on the boom during the bolting process (see: Figure 6.5).

Figure 6.5 Left: Boltec operating in rock rounds in Canada where loose rock can fall through screen or from the face onto the boom; Right: Boltec in operation in Sweden (Gustafson et al., 2014) where bolts and screen are installed through scaled and shotcreted ground, rock does not fall on the boom

Due to the design of the Boltec, it is more prone to misalignment from rocks and sandfill falling on the boom. Furthermore, the Boltec is prone to misalignment during typical operation in good ground and 2$^{nd}$ pass bolting particularly when drilling through obstructions. Due to this issue with misalignment, bolts often fall out of the carousel during the bolt indexing procedure (see: Appendix D.2).

Alignment issues are uncommon on the MacLean due to its robust design; the MacLean bolter has roll bars to protect the boom from falling rock, and many of the hoses are located under the boom to prevent hose damage during bolting and scaling.

The Boltec could be made more robust by reinforcing and guarding the boom from falling rock. Both machines could be more reliable if more hose guards were put in place provided that this does not significantly affect the machine’s maintainability. Boltec operators avoid fully extending the boom since the machine has a tendency to tip forward when the carousel is fully loaded with bolts. Therefore, if the Boltec boom is reinforced, the position of the front jacks on the machine should be moved forward to prevent this problem. It was observed that when the Boltec booms were extended, there was excessive “play” of the bolting and screen handling arms. This contributed to lower face time productivity and dropped screens during screen handling. Stiffening the boom could prevent this issue and improve bolting and screening cycle time, and make the Botlec more user-friendly since compensating for “play” in the boom was frustrating for the operators and required a high level of skill. The screen handling arm intermittently loses grip of the screen, this is often observed when hydraulic oil is leaking from the screen handling arm.

The Boltec utilizes a “slide” system where one feed chain is used for the drilling and bolt installation procedure rather than a pivot system used by the MacLean bolter which uses two feed chains to accomplish the same tasks. This slide system is effective for reducing the number of components on the boom, but when the operator switches between the drilling and bolting tool, the boom often shifts which misaligns the bolting tool relative to the drill hole. It takes a high level of operator skill to re-align the bolting tool with the drill hole. A more rigid system would allow the operators to use the Boltec to its full extent without having to make adjustments to the boom during bolt installation.

Bolts are installed in the face in long term development headings and in the lower wall in all headings for safety purposes (see: Figure 6.6).

Figure 6.6 Left: face bolting contributes to cycle time Right: lower wall bolt installation contributes to increased cycle time

Boltec operators had difficulty installing face bolts since they could not see if the bolt had been installed. A camera that would allow the operators to see the base of the bolt during indexing and the end of the boom during face bolting would increase the productivity of the installation cycle and reduce the number of failed bolt installations.

There was difficulty with lower wall bolt installations since it is easy to damage the Boltec's hydraulic hoses located under the boom. Due to this issue, operators would often install the lower wall bolts at a downward angle. This occasionally caused the bolt plates to slide up the bolt, and interfere with the bolt grip and drilling assembly unless the plates are held in place with zip ties which takes up face time. Operators said that the Boltec was not well suited for lower wall bolt installation.

### 6.5.4.2 Equipment Maintainability

Equipment doesn't perform to its full potential during the break-in period. While the Boltec has been used at Mine C for many years, failures and difficulty maintaining the equipment due to poor quality control, inherent machine design and its interaction with the mining environment, and lack of documented debugging procedures prevent the machine from performing in an optimal state. Therefore the Boltec is likely still in the burn-in period of the bathtub curve (see: Figure 6.7).

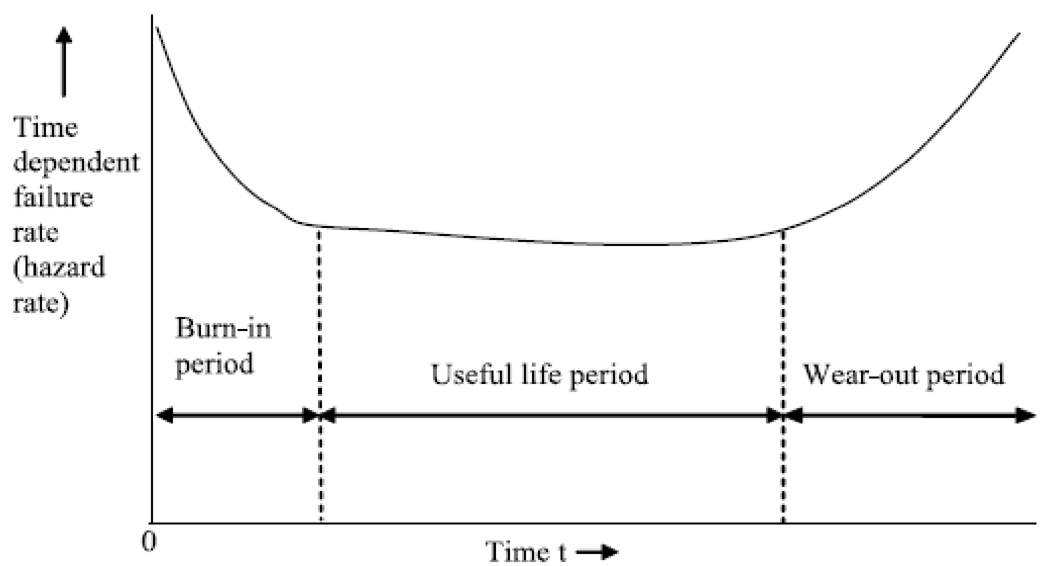


Figure 6.7 The bathtub curve (Kapur, 1982) where the Boltec is likely in the Burn-in period, and the MacLean is in the Useful life period or the Wear-out period

Due to the complexity of the Boltec, operators and mechanics found that it was difficult to troubleshoot, and the Boltec had many intermittent issues. Improved condition monitoring, instrumentation and training could assist workers with maintaining the Boltec which would allow it to perform at its full potential. As a result, maintenance workers often could not correct issues that caused bolting speed loss or intermittent cycle time disruptions.

It also often took two or three people to remove hoses from the Boltec due to how closely the hoses are wrapped, and how close the hose fittings are on the boom (see: Figure 6.8). One or two operators or mechanics can easily remove hoses from the MacLean since the hoses are more accessible. An analysis would need to be completed to make conclusions about the maintainability of each bolter, however it was observed that maintenance workers often had difficulty troubleshooting and repairing the Boltec. In productivity questionnaires, machine operators often responded that a guard to protect hoses which is easy to remove would decrease maintenance time at the face.

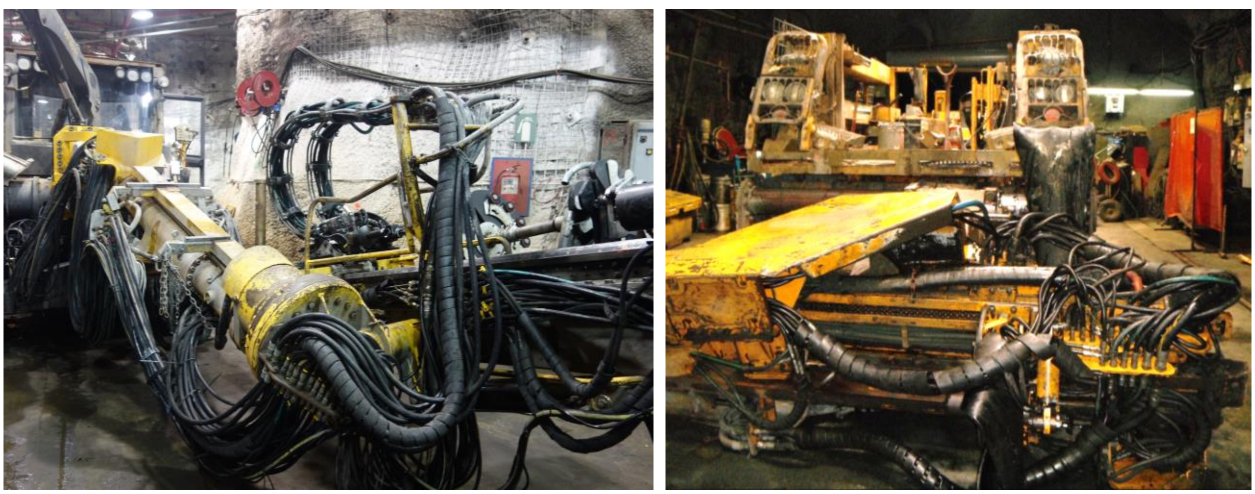

Figure 6.8 Left: Boltec in the workshop at Mine C; Right: MacLean bolter in the workshop at Mine A

The MacLean bolter has been in operation in Canadian mines for over two decades; through support from the equipment supplier and the experience of the equipment operators and maintenance personnel, there were no major issues observed when workers were troubleshooting and repairing the MacLean bolter. This is due to the workers' tacit knowledge developed over the course of years of working with the MacLean bolter.

A total quality management program involving the mine and supplier could be implemented to improve the maintainability of the Boltec. Also, mechanics could be trained as equipment operators (or vice-versa) to reduce the amount of waiting time to troubleshoot equipment.

Compiling an updated troubleshooting guide could help reduce the time required to diagnose and repair the bolters.

### 6.5.5 Reduction of Supportive Work

Based on the results shown in Chapter 5, it is expected that there would be a linear increase in productive work cycles if supportive work at the face was reduced. Some supportive work is unavoidable, but it was observed that large reductions in supportive work time could be achieved by reducing screen handling and scaling time.

Operators would often exit the bolter scissor deck or operating cab to place lower wall screens. Installing a screen handling arm on the MacLean bolter and improving the Boltec screen handling arm could reduce screen installation time.

The volume scaled out could be reduced through improved perimeter blasting, and a mechanical scaler or hydroscaler could be used to remove loose rock prior to bolting. This would also significantly reduce the number of machine failures caused by falling rock.

Mine C bolter operators had to extend services (ventilation ducts, water, compressed air) and install pumps on occasion due to a shortage of support workers. This significantly reduced the time available to bolt over the course of their shift.

## 6.6 Worker Technique and Training

Based on the results from Chapter 5, there was not a significant difference in performance among different equipment operators. There was a difference among workers on the strategy used to troubleshoot issues and their approach to completing supportive work. At the time of the study, there was typically one dedicated Boltec operator per shift at Mine C, and multiple MacLean operators per shift at all mines. Techniques used to operate and troubleshoot the equipment varied more among Boltec operators than among MacLean operators. Boltec operators are often not aware of how others operate the equipment and cope with delays.

By improving Boltec operator training and compiling knowledge learned by operators through experience, the bolting process can be improved, and the duration of delays can be reduced.

## 6.7 Other Observations

By applying the methodology presented in Chapter 5, many opportunities to improve the semi-mechanized and mechanized bolting process were identified. Many production studies in mining are completed with digital data, however this type of data often doesn't provide insight into the root cause of equipment downtime. It is recommended that mines audit their development, production and maintenance processes on a regular basis to find ways to improve the process, and measure the results of changes that are implemented.

Redpath Mining conducted similar studies and was able to achieve rapid development primarily through improvement of the bolting cycle and controlled perimeter blasting (Hubert, 2015). An interesting conclusion from that study is that it was found that modified Jumbos outperformed bolters. This suggests that Canadian mines should consider using Jumbos for bolting rather than using bolters which is a common practice in deep mines in Australia.

Similar studies to the ones presented in this thesis can be conducted in deep mines to improve the drifting cycle. The cost of a productivity case study is relatively low compared to the potential gains that could be achieved by measuring and improving the drifting process, particularly at mines that don't have a continuous improvement plan.

Publication of the methodology and results of such studies is beneficial for the mining sector to avoid duplication of work internally at mining companies, and improve processes at all mines at the lowest possible costs. Such studies have served to improve processes in other industries where firms are in direct competition, such as manufacturing. Since mines are not in direct competition with each other, conducting such studies and publishing the results would not affect the viability of an operation. The forestry industry has published hundreds of papers on their processes in variable environments, and this research knowledge has served to improve their industry and allow management to make informed decisions about equipment selection and maintenance for new and existing operations.

# Chapter 7

# Future Work and Conclusions

## 7.1 Summary of Findings

Based on the results from the study, the productivity of bolters was quantified and compared in a relevant way by using methods developed in the Forestry Industry. Additionally, many opportunities to improve bolter productivity were identified. The primary contribution of this thesis is the development of the methodology to compare mining equipment in different environments, and the results of a large dataset as a baseline for comparing bolter productivity.

The time study indicated that a large portion of the operator's shift time is not dedicated to the primary work task of installing rock bolts. By reducing numerous controllable delays, the overall productivity of the ground support installation process can be improved. Many of the controllable delays can be reduced through improved communication and reporting of the status of equipment, working conditions, maintenance workers, and supplies. MacLean bolters could be geared at the face to remove the need for the operator to tram the MacLean to the storage, then back to work areas. Similarly, on the Boltec, the elimination of the need for workers to use forklifts to transfer bolting supplies between different areas of the mine would reduce Logistics time over the course of the shift.

Quality control of supplies such as Split Set diameter, and re-sharpened drill bits can be improved to reduce the chances of failed work cycles.

It was also observed that excessive overbreak contributed to the need to extra support to be installed, more scaling, and slower work cycles due to difficulty with aligning the boom in irregular rounds. Improved drilling and blasting practices would reduce the amount of extra work and re-work that is caused by poor drift quality.

An analysis of recorded maintenance at the face and mine maintenance records reveals that hydraulic hose failure is the most common cause of lost production at the face and maintenance in the workshop for both types of bolters. Improved hose protection and hose design could prevent this type of maintenance. As well, improved design could facilitate more rapid hose replacement particularly on the more sophisticated equipment.

It was observed that in similar conditions, the Boltec does not install Splitsets as rapidly as the MacLean. A primary reason for this is that due to mis-alignment of the Boltec boom, and lack of operator line of sight during the indexing portion of bolting, the operators would put the Boltec boom in a vertical position to install wall bolts. Reducing this component of cycle time through the use of a camera to view the indexing procedure and improved equipment design and maintenance would improve Boltec productivity.

Canadian mines could become more competitive by quantifying their processes, comparing results, and adopting best practices to achieve faster drift advancement rates.

In the future, this study methodology can be used, expanded upon and improved to achieve the amount of process performance knowledge which has been achieved in the forestry industry. This would help mines understand the impacts of different factors on long term equipment performance.

## 7.2 Future Work

It would be beneficial for the mining industry to develop databases of work studies completed on mining equipment in a standardized way to anticipate how mining processes will perform in the future. With enough studies, external factors (such as rock hardness) that affect process performance could be quantified statistically for improved understanding of the factors that affect processes. In the future, this dataset will be analyzed with statistical software to analyze the amount of variation in the dataset.

By using methods similar to the forestry industry, a standardized work methodology could be developed and expanded upon to measure and compare mining equipment. By performing statistical analysis, external variables such as rock type, work methods, machine-specific features and mine layouts could be accounted for when comparing similar processes in different conditions. Improved data collection procedures would enhance the ability to compare different types of equipment that perform similar tasks. Then, the sources of variation due to work site conditions can be isolated to facilitate comparison of processes.

Time study data could also be used to simulate the mining process, and predict the advancement rate of an operation. Improvements to the processes being studied could be implemented, and quantified to assure that the equipment is performing in an optimized state.

In the future, publications on equipment productivity should clearly define the methods used to collect and categorize data, as well as relevant information such as the duration of the study, and the number of work cycles observed.

## 7.3 Conclusions

Similar to forestry, a large body of work could be assembled to help provide decision support for mines to extract resources in the most productive way. Graphs can be generated to quantify the effects of external factors on machine productivity such as rock hardness and bolt type. Meta-analysis studies could be completed to predict equipment performance within a reasonable amount of error to support procurement decisions. The role of work studies in the mining could be expanded upon and published more frequently to facilitate the understanding and improvement of mechanized processes.

Long term digital records (when available) can supplement manually collected time study data to draw conclusions about long term equipment productivity, how different pieces of equipment interact with each other, and draw conclusions about long term equipment performance and maintenance requirements.

If the mining company chooses to implement changes to the bolting process, then follow-up studies should be completed on regular intervals to quantify the changes to the bolting process.

Work studies conducted in a standardized way at different mines on equipment operating in different conditions can be conducted to compare the effects of external variation of the equipment output.

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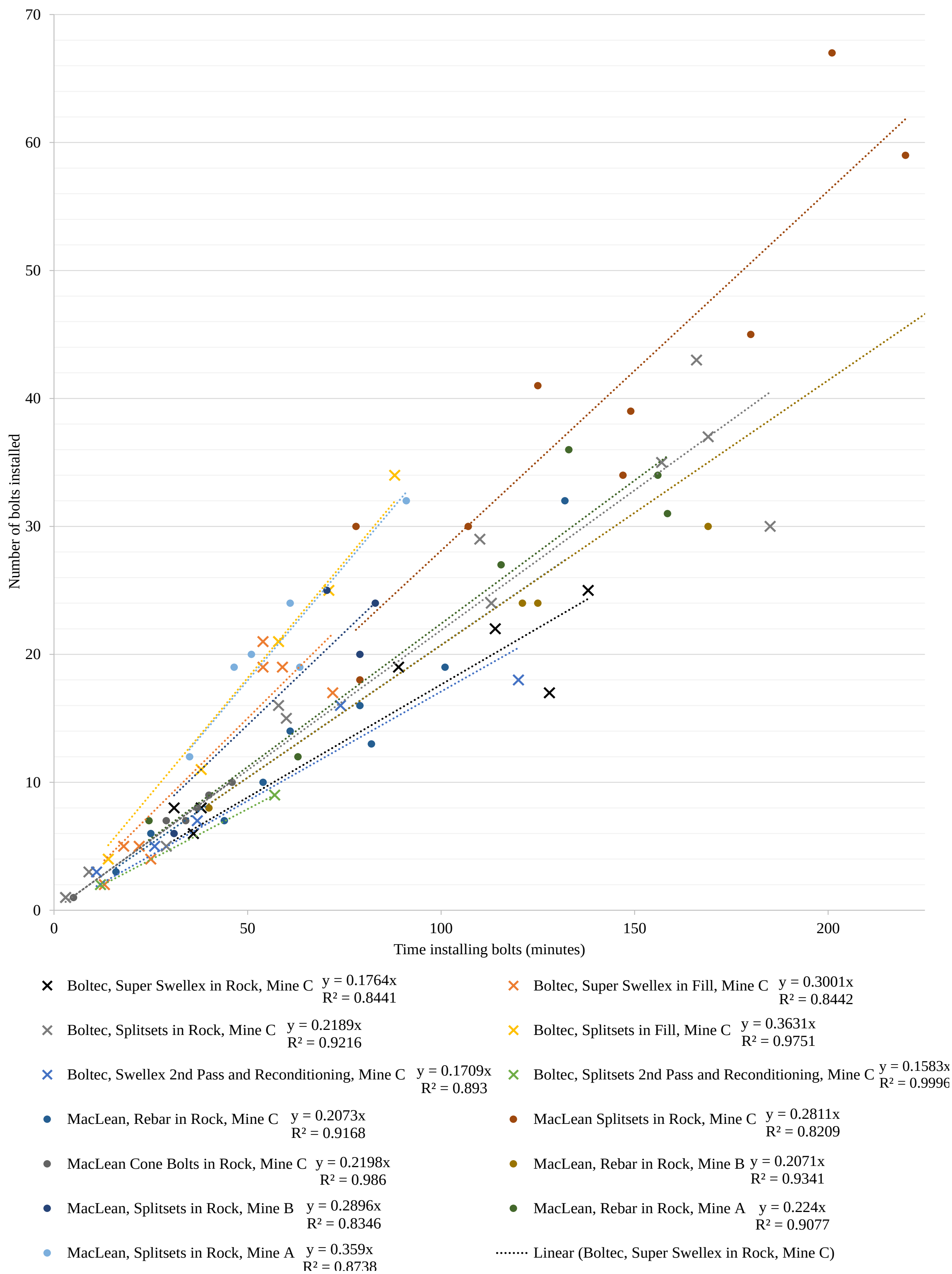
# Appendix A

Observed shift time consumption for MacLean bolter at Mine C

| Shift # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bolter # | 1 | 2 | 3 | 4 | 3 | 4 | 3 | 3 | 1 | 1 | 4 | 2 | | |
| Mine Area | A | B (ramp) | 7910 | A | 8150+ (ramp) | 7280, 7910 | 7910 | A | 8110 | 8110 | 8070 | 7680 | | |
| Operator ID | Cr-A | Cr-B | Cr-C | Cr-D | Cr-D | Cr-E | Cr-F | Cr-G | Cr-B | Cr-H | Cr-I | Cr-J | | |
| Operator Experience | High | High | High | High | High | High | Med | Med | High | High | High | High | Average | σ |
| Shift Time (minutes) | 584 | 562 | 555 | 581 | 554 | 591 | 549 | 440 | 572 | 534 | 643 | 588 | 562.8 | 45.6 |
| Face Time (minutes) | 398 | 368 | 425 | 430 | 254 | 357 | 301 | 355 | 336 | 353 | 395 | 420 | 366.0 | 50.3 |
| Productive Bolt Installation Cycles (N) | 67 | 42 | 16 | 51 | 21 | 42 | 39 | 30 | 54 | 48 | 46 | 69 | 43.8 | 15.4 |
| Productive Bolt Installation Cycle Time (minutes) | 201 | 178 | 79 | 202 | 119 | 196 | 149 | 78 | 179 | 196 | 220 | 274 | 172.6 | 55.2 |
| Unproductive Bolt Installation Cycles (N) | 1 | 0 | 3 | 2 | 0 | 0 | 3 | 0 | 3 | 2 | 3 | 0 | 1.4 | 1.3 |
| Unproductive Bolt Installation Cycle Time (minutes) | 1 | 0 | 19 | 2 | 0 | 0 | 3 | 0 | 1 | 5 | 13 | 0 | 3.7 | 5.8 |
| Bolt Installation Cycles With Atypical Work Element(s) (N) | 6 | 3 | 4 | 5 | 6 | 10 | 12 | 3 | 5 | 6 | 9 | 10 | 6.6 | 2.8 |
| Rebar Installed (N) | 0 | 32 | 16 | 14 | 13 | 7 | 0 | 0 | 6 | 3 | 19 | 10 | 10.0 | 9.1 |
| Rebar Cycle Time (minutes) | 0 | 132 | 79 | 61 | 82 | 44 | 0 | 0 | 25 | 16 | 101 | 54 | 49.5 | 41.5 |
| Cone Bolts Installed (N) | 0 | 10 | 0 | 7 | 8 | 1 | 0 | 0 | 7 | 0 | 9 | 0 | 3.5 | 4.1 |
| Cone Bolt Cycle Time (minutes) | 0 | 46 | 0 | 34 | 37 | 5 | 0 | 0 | 29 | 0 | 40 | 0 | 15.9 | 18.4 |
| Splitsets Installed (N) | 67 | 0 | 0 | 30 | 0 | 34 | 39 | 30 | 41 | 45 | 18 | 59 | 30.3 | 21.4 |
| Splitset Cycle Time (minutes) | 201 | 0 | 0 | 107 | 0 | 147 | 149 | 78 | 125 | 180 | 79 | 220 | 107.2 | 74.5 |
| Screen Installed (N) | 10 | 9 | 4 | 10 | 5 | 8 | 6 | 4 | 11 | 5 | 8 | 12 | 7.7 | 2.7 |
| Screen Installation Time (minutes) | 14 | 28 | 6 | 18 | 13 | 15 | 13 | 5 | 18 | 13 | 24 | 38 | 17.1 | 8.8 |
| Scaling Time (minutes) | 7 | 4 | 20 | 15 | 37 | 0 | 4 | 0 | 1 | 2 | 17 | 7 | 9.5 | 10.5 |
| Cutting and pushing blasted face screen (minutes) | 14 | 17 | 23 | 0 | 15 | 18 | 0 | 0 | 1 | 6 | 2 | 0 | 8.0 | 8.3 |
| Bolter Transportation Time (minutes) | 16 | 92 | 20 | 9 | 24 | 75 | 35 | 13 | 39 | 9 | 3 | 23 | 29.8 | 26.2 |
| Gear bolter in storage (minutes) | 68 | 46 | 0 | 0 | 46 | 34 | 30 | 26 | 70 | 0 | 0 | 20 | 28.3 | 24.6 |
| Other supportive work time (minutes) | 39 | 52 | 79 | 54 | 25 | 38 | 18 | 23 | 11 | 69 | 42 | 29 | 39.9 | 19.7 |
| Small Delays (drill/panel reset/low oil reset) (N) | 15 | 2 | 4 | 13 | 0 | 19 | 15 | 8 | 4 | 12 | 5 | 2 | 8.3 | 6.0 |
| Broken striking bars, drill steel, bits and splitset hammers (N) | 6 | 4 | 6 | 6 | 3 | 4 | 4 | 6 | 5 | 7 | 4 | 6 | 5.1 | 1.2 |
| Number of Maintenance Delays > 5 minutes(N) | 5 | 1 | 2 | 4 | 3 | 1 | 3 | 1 | 2 | 4 | 3 | 2 | 2.6 | 1.3 |
| Maintenance Time (minutes) | 44 | 9 | 130 | 136 | 24 | 19 | 123 | 12 | 50 | 82 | 148 | 38 | 67.9 | 50.7 |
| Logistics Delays (minutes) | 0 | 0 | 26 | 0 | 0 | 0 | 19 | 100 | 0 | 0 | 5 | 3 | 12.8 | 27.6 |
| Personnel Transport Time (minutes) | 91 | 112 | 120 | 92 | 117 | 84 | 100 | 107 | 82 | 94 | 100 | 78 | 98.1 | 13.2 |
| Scheduled Break Time (minutes) | 77 | 10 | 52 | 55 | 104 | 82 | 58 | 76 | 50 | 42 | 78 | 35 | 59.9 | 24.0 |
| Unscheduled Standby and Break Time (minutes) | 13 | 4 | 0 | 0 | 30 | 30 | 0 | 0 | 0 | 21 | 4 | 37 | 11.6 | 13.5 |
| Irregular round | No | No | No | No | Yes | No | No | No | No | Yes | No | No | | |
| Seismic activity (Low, Med, High) | Med | Med | High | Low | Med | Med | Med | Med | Low | High | High | Low | | |




Detailed correlation between cycle time per shift and number of bolts installed for each bolt type and ground type

Four MacLean bolters were observed in operation over the course of twelve 10.5 hour shifts. Ten operators were shadowed, eight of whom were highly experienced and two who were moderately experienced. Ten days of observation occurred in typical development rounds and two days of observation in irregular rounds.

Typical rounds do not have any major abnormalities and the bolter can be driven straight into the heading. No significant amount of time is spent repositioning the bolter and boom when aligning to drill the next hole. Irregular rounds are typically around sharp turns such as intersections. To estimate the long term productivity of the bolter, the amount of irregular rounds should be estimated from the mine development layouts. Extra time is spent to reposition the machine which affects cycle times in irregular rounds.

Typical headings are 16-18ft (5-5.5m) in span and height and are blasted in 8-12ft (2.5-3.5m) rounds. Larger excavations such as ventilation drifts are 22ft (6.5m) in span and height and rounds are 8-12ft deep.

22ft x 22ft, 8ft deep unbolted heading

Typically, 80-120 bolts are installed per round. Operators are contracted to install 60 bolts per shift. In areas that require dynamic support, enhanced support is installed which consists of alternating rows of rebar and cone bolts in the back, and FS-46 Split Sets in the walls.

There was no observed significant difference in bolter productivity difference between small excavations and larger excavations.

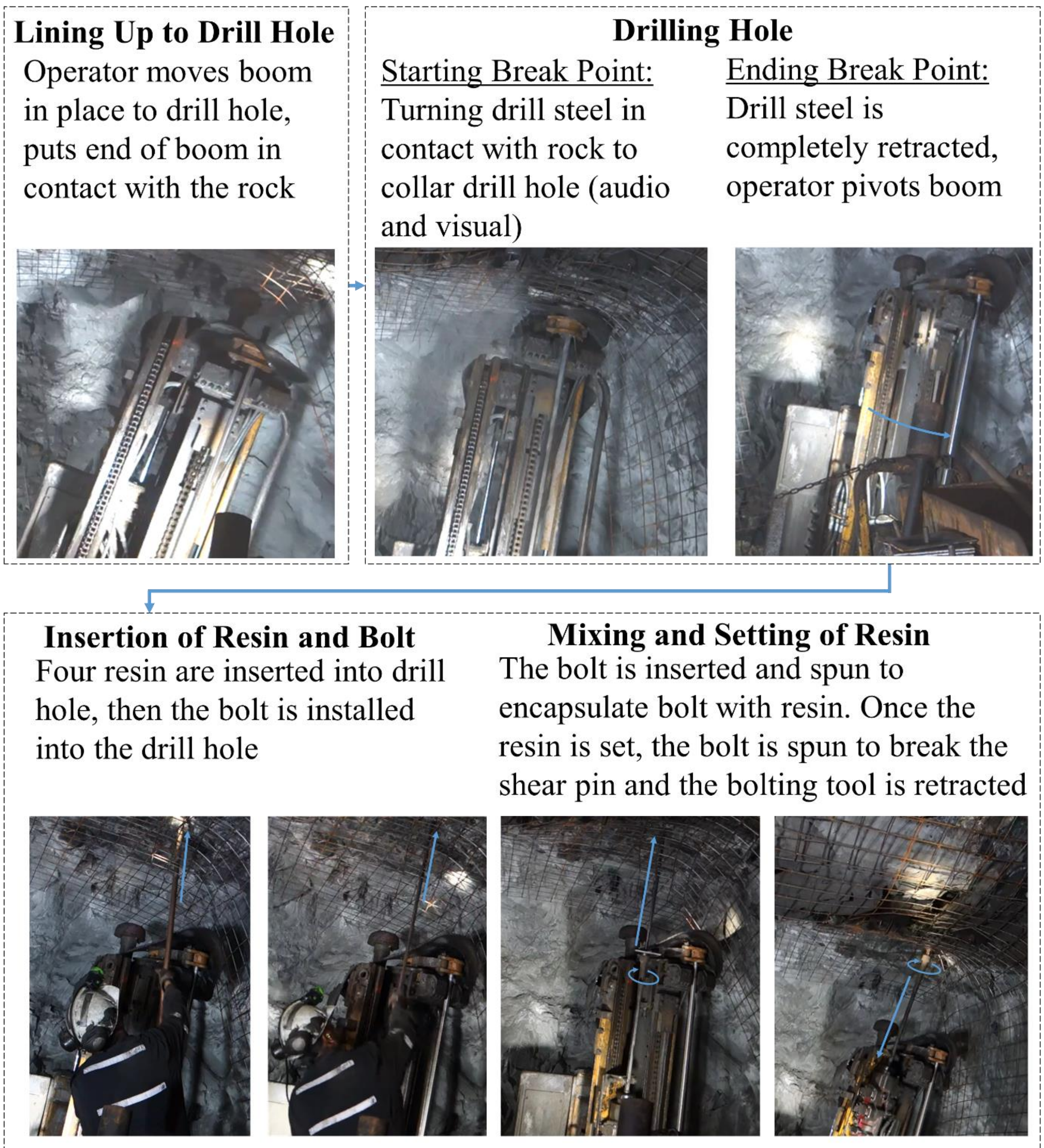
Bolters were in operation in different development levels at depths 2300m to 2500m.
The *RMR*[12] of the rock was measured in-situ with a compass while operators rig the bolters at the face. The average measured RMR was 65, ranging from 60-70. The RMR should be measured for the purposes of comparing and predicting equipment performance at different mines since

[12] Rock Mass Rating (Bieniawski, 1989)

RMR affects drilling rate and Splitset drive times which is a large portion of bolt installation cycle time.

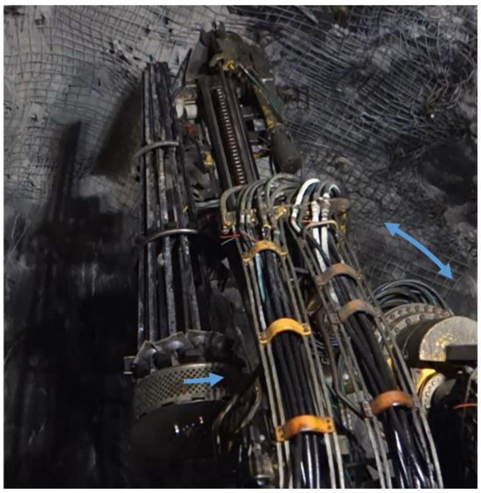
# Appendix B.1

Through higher time resolution data collection and/or video analysis, the sub-elements of work elements measured could be recorded to a greater accuracy. The work elements and break points for rebar and Swellex installation for a MacLean and Boltec bolters are shown in the figures below:



**Lining Up to Drill Hole and Indexing Next Bolt**

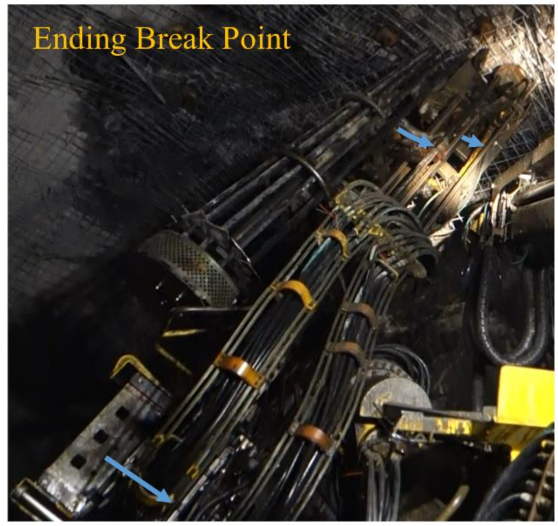
Operator moves boom in indexing position (if necessary), aligns the next bolt from the carousel, moves the boom in place to drill hole, puts end of boom in contact with the rock



**Drilling Hole**

Starting Break Point: Turning drill steel in contact with rock to collar drill hole (audio and visual)

Ending Break Point: Drill steel is completely retracted, operator slides boom into bolting mode

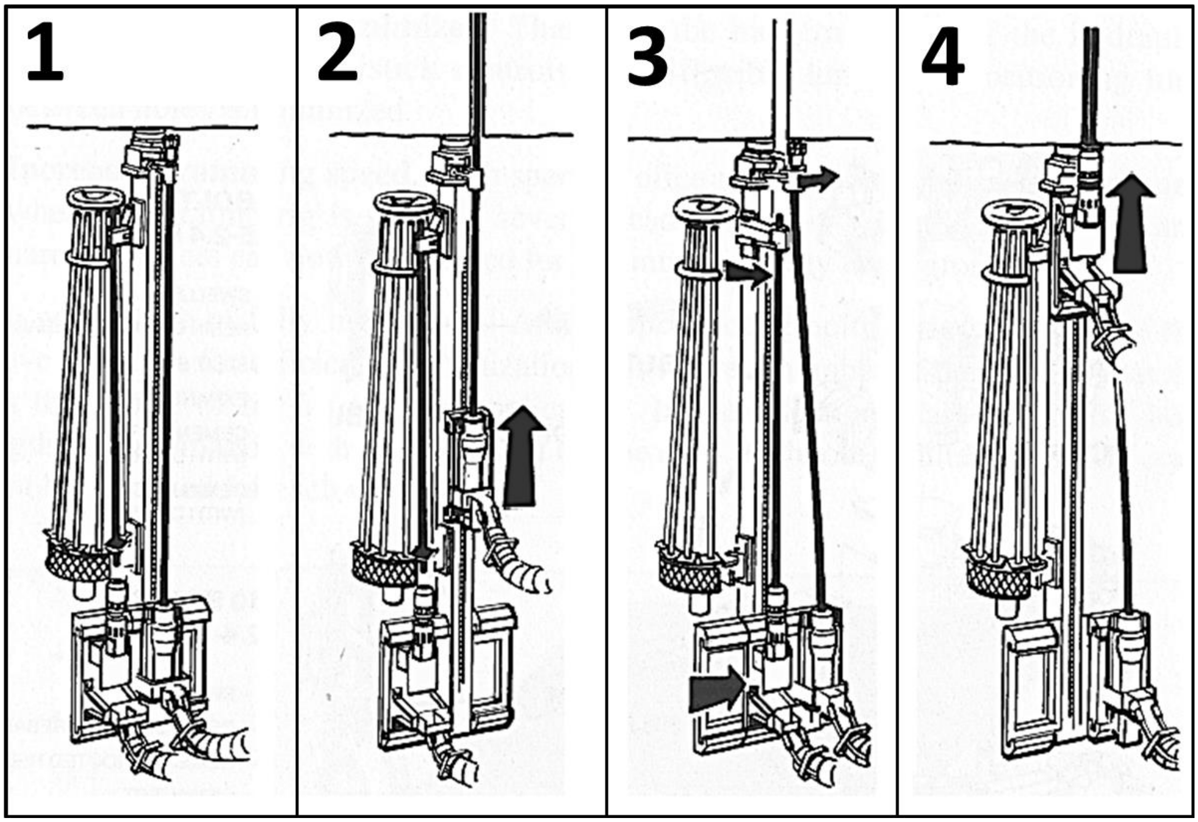



**Insertion of Swellex**

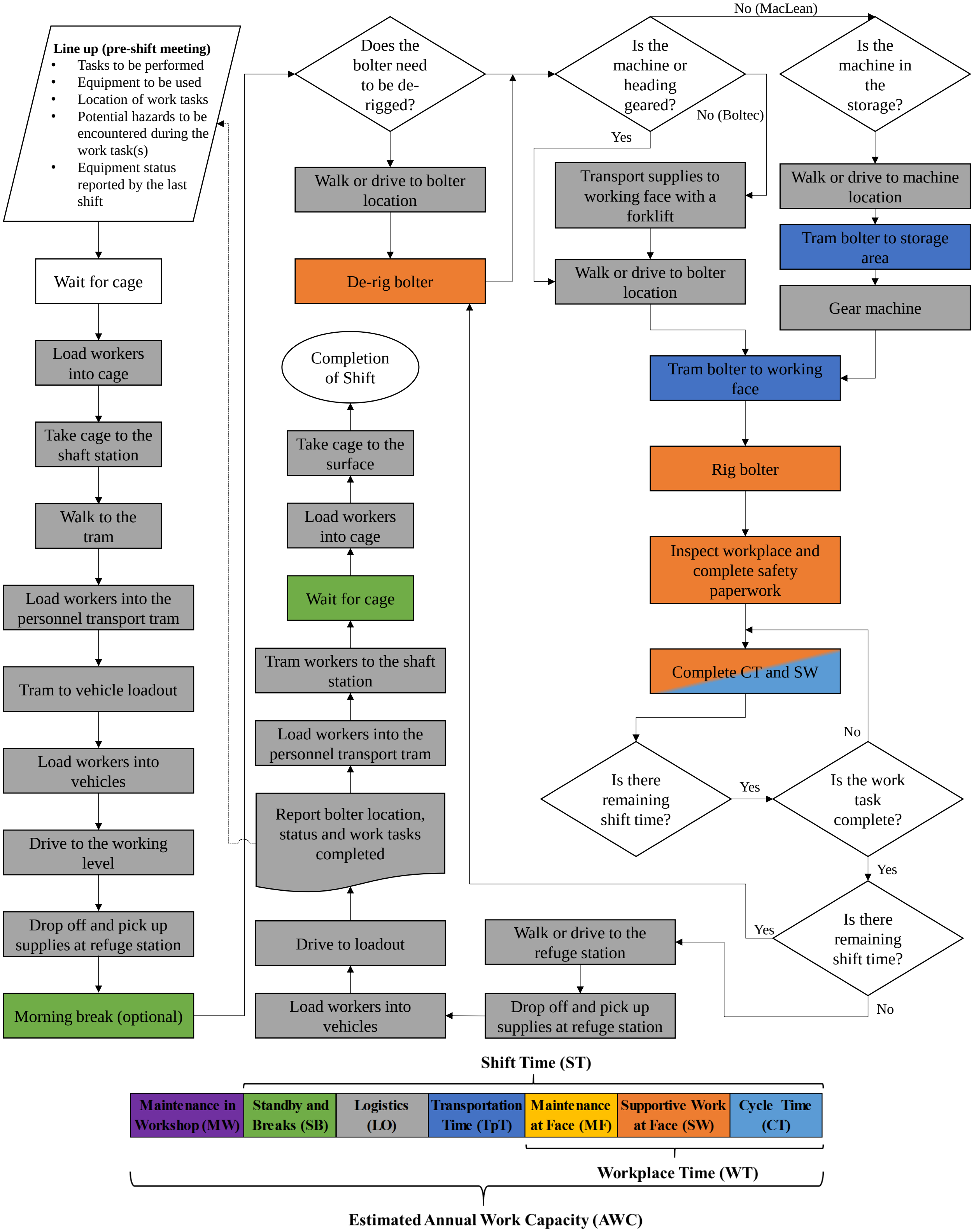
Swellex is inserted into drill hole


**Pumping of Swellex**

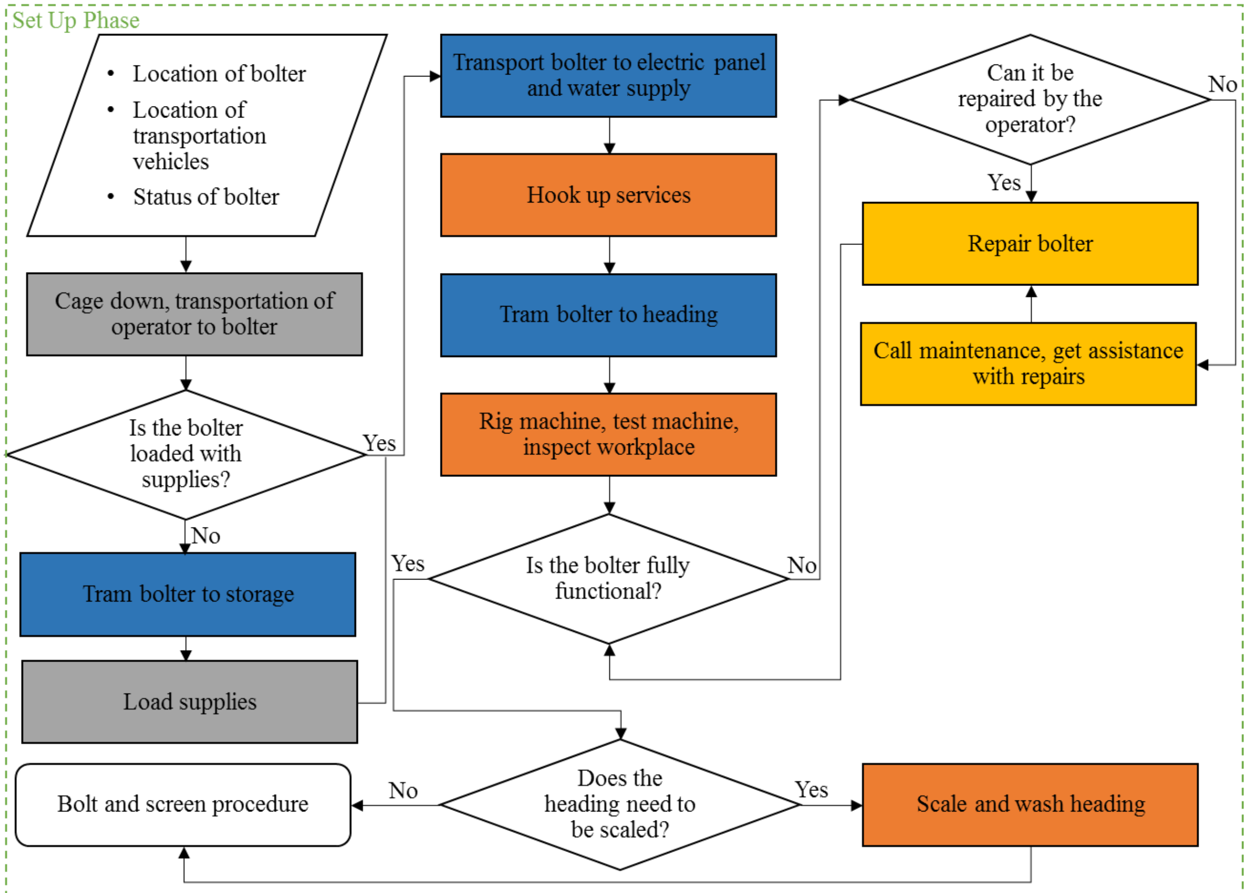
Water is pumped into the Swellex bolt until the bolt reaches the appropriate pressure. Then the operator retracts the Swellex pump valve and indexes the next bolt




Swellex installation with a mechanized bolter (Stillborg, 1994)

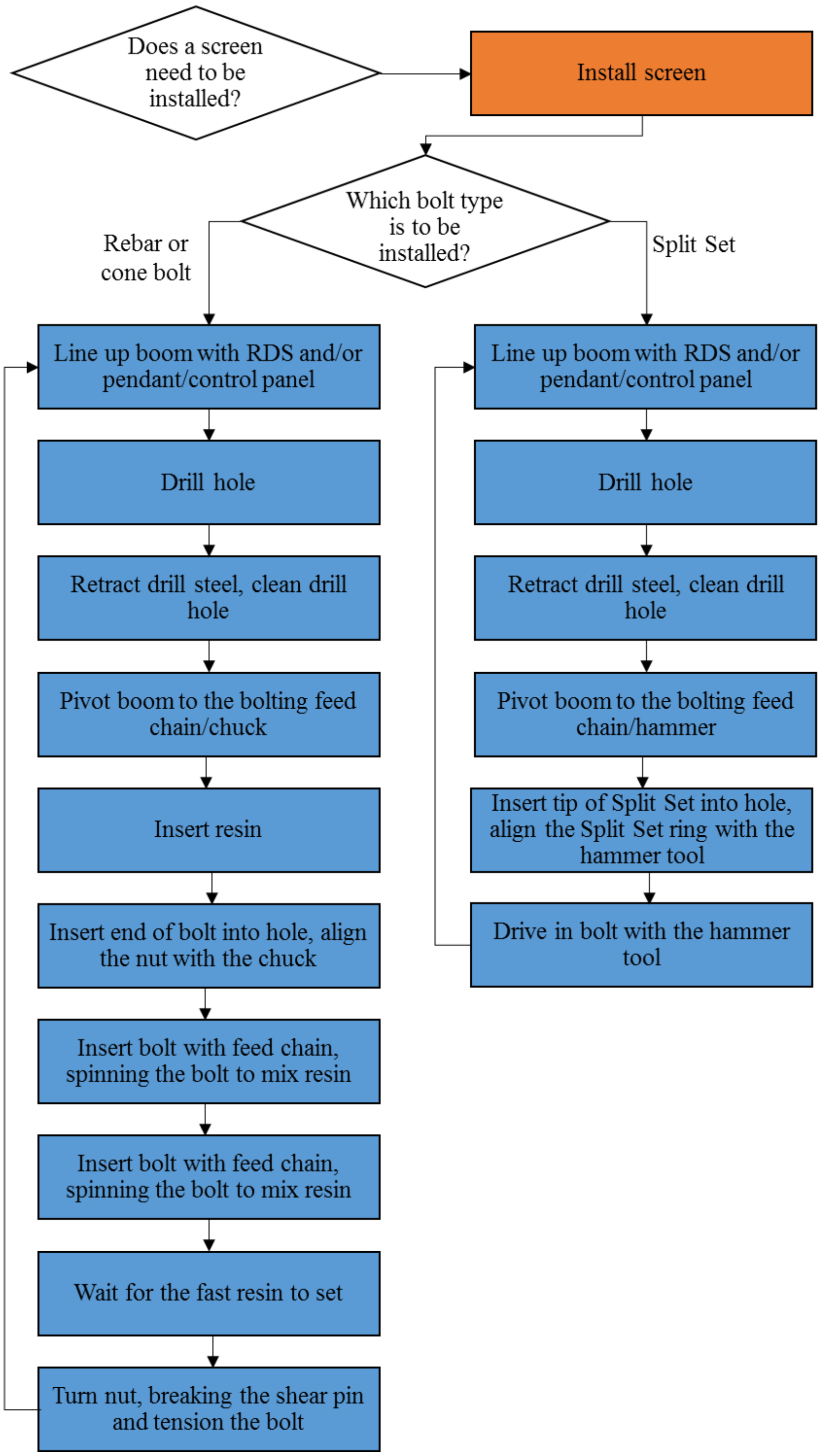



Simplified components of shift time without maintenance or mine-specific delays

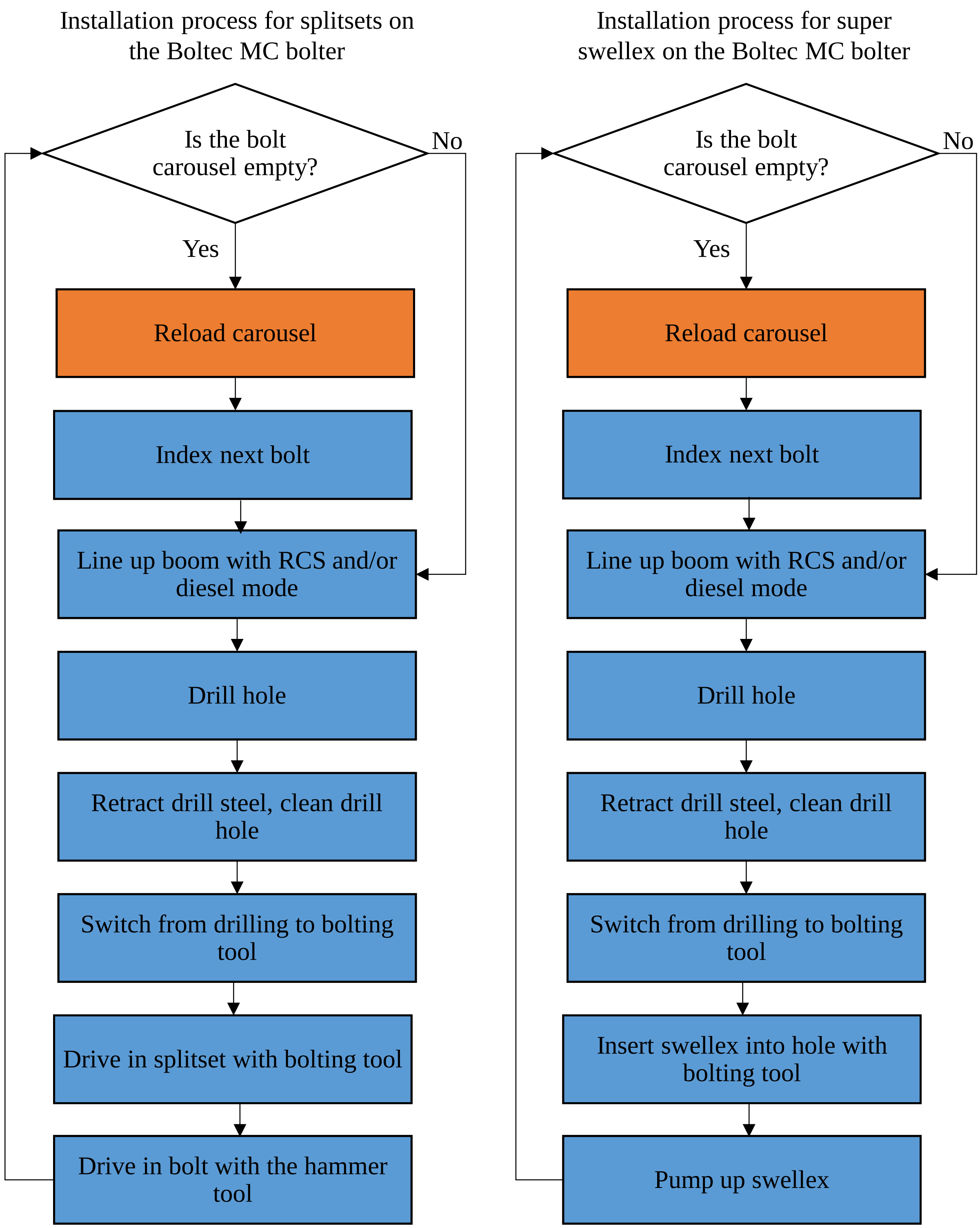



Process flow diagram for the set up phase of bolting on the MacLean

The bolting and screening process diagram divided into work elements is shown in the following figure.

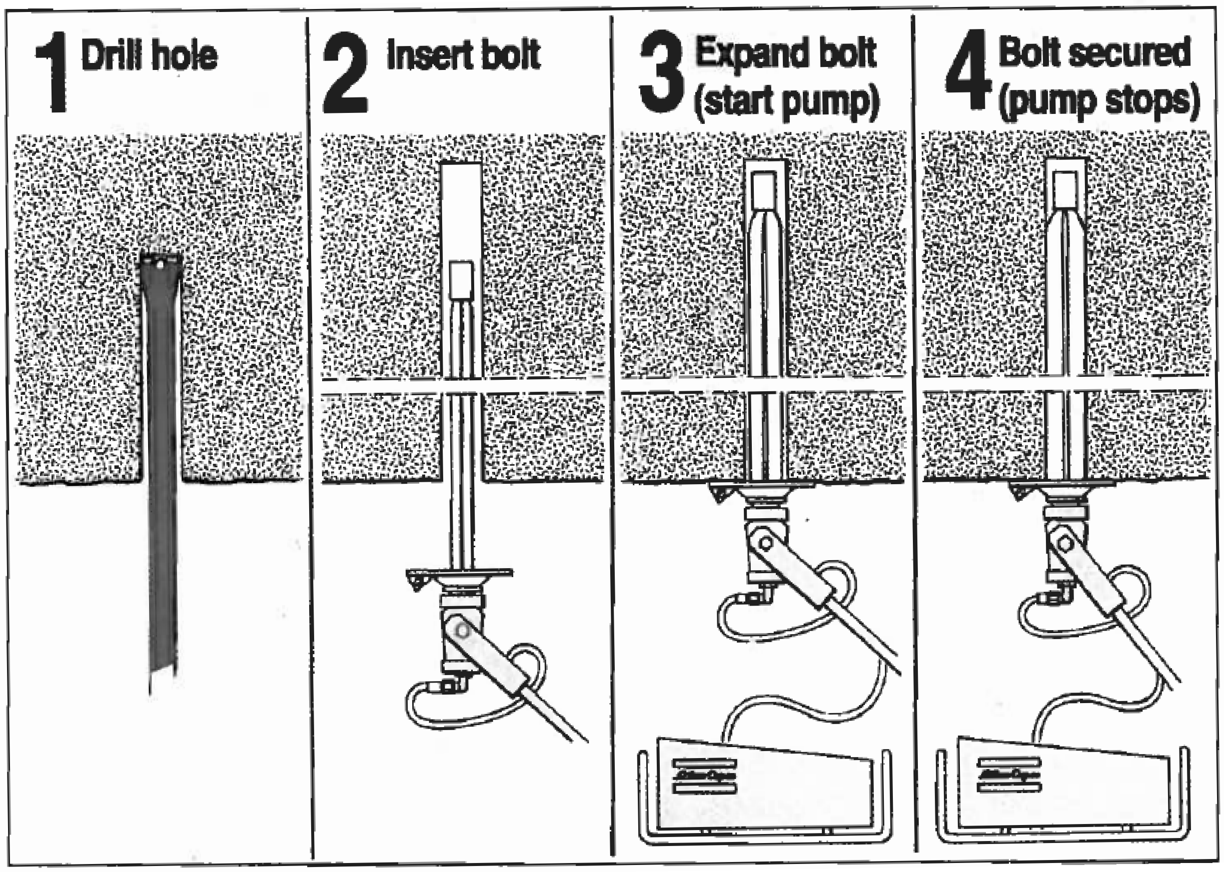



Bolt installation procedure for MacLean bolter




Bolt installation procedure for Boltec MC bolter

The de-rigging and shutdown procedure is similar to the set up procedure except the processes take place in the opposite order.




Swellex installation process (Atlas Copco, 2003)


Concept for integrating OEE, cycle time, production and development rates using control charts to detect equipment process variation that affects the mine's output

# Appendix B.2

## Materials handling


a) Boltec supplies storage on the 2340 m level b) Transportation of Boltec supplies with forklift c) Storage bins next to Boltec d) Operator “gearing” heading by leaning bolts and screen on drift walls

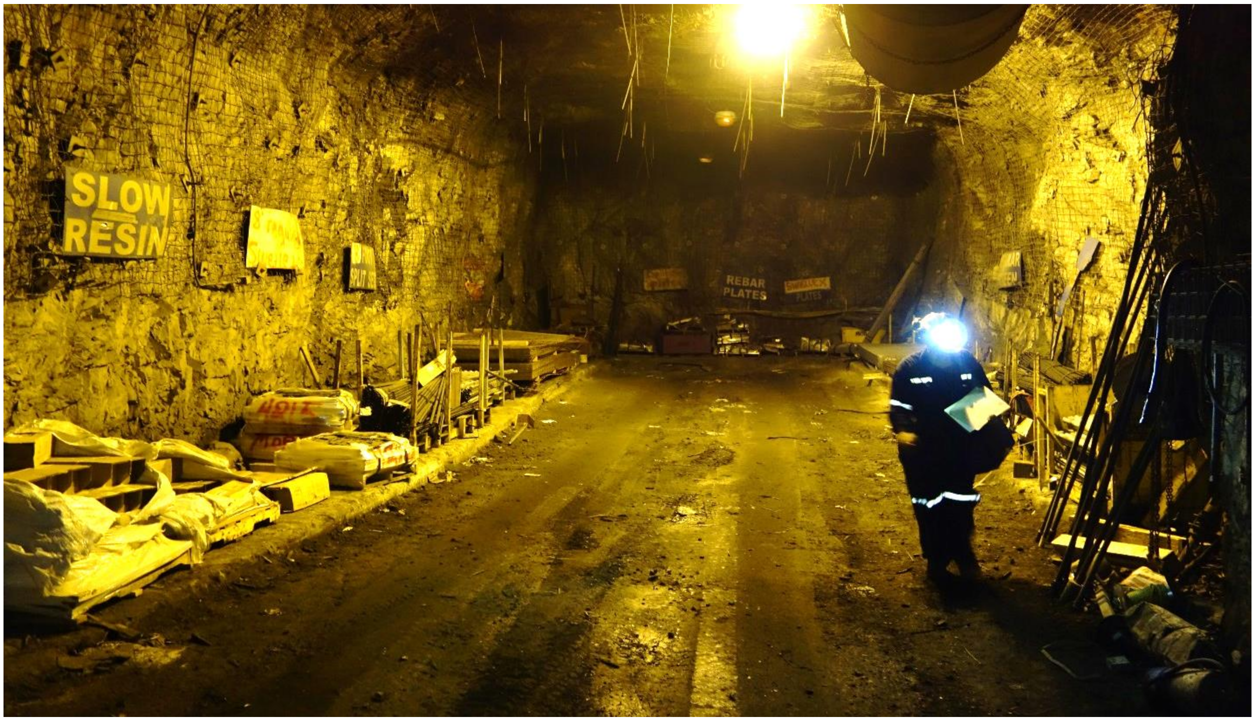

a) Operator gearing MacLean in storage on the 2430 m level b) Bolts, plates and #0 gauge squares on the deck of the bolter c) Tramming geared bolter into heading d) Bolts to be installed against front guard rail

Corroded welds which can affect the screen's retaining capacity

Storage Layout


Bolter supplies storages at Mine A

At Mine A, operators often said that supplies were missing, disorganized, expired or corroded. Since many of the storages were too small to fit a bolter inside, operators had to carry supplies from the storage to the machine which adds to the bolter gearing time.




Storage at Mine B

The storage at Mine B is efficient in layout and is in a central location. Operators complained that other workers park remote equipment in the bolter storage which requires a remote control to remove. This was observed twice during the course of the study.

MacLean storage at Mine C

For example, the bolter storage at this mine is centralized which contributed to lower transportation and gearing times of the bolter as well as a reduction in operator fatigue from gearing since operators can align the bolter with storage bins and place supplies onto the deck of the bolter using fewer work elements than other storage configurations.


Boltec supplies storage at Mine C

The Boltec storage is located next to the main access drift on the level. Operators said that the storage was often disorganized that that the supplies are damaged on occasion. A more central storage location and effective layout could reduce supplies transportation time and the amount of damaged supplies.

# Appendix C

Examples of delays, causes of delays and identified non-value adding processes which could be addressed by the mine management and shift supervisors:

Work practices which contributed to higher levels of productivity compared to other mines are described in the productivity report.

Storage Layout:

For example, the bolter storage at this mine is centralized which contributed to lower transportation and gearing times of the bolter as well as a reduction in operator fatigue from gearing since operators can align the bolter with storage bins and place supplies onto the deck of the bolter using fewer work elements than other storage configurations.

There were a variety of observed storage layouts. Examples of other storage layouts are shown on the following page:

Examples of unproductive work cycles are:

- The bolt is significantly damaged during installation,
- Bogged drill steel,
- The bolt is not completely inserted and is bent back.

Other supportive work time includes:

- Clearing and spray painting bootlegs,
- Clearing dust,
- Rigging and de-rigging the bolter,

- Unboxing and organizing supplies,
- Cleaning the machine and the workplace.

Splitset installation is more variable since the installation time depends on multiple factors such as:

- Driving tool feed pressure,
- Rock structure (joints, slips, roughness) and loose rock in the drill hole,
- Variability in Split Set size and drill bit size,
- Closure of drill holes in highly stressed ground.

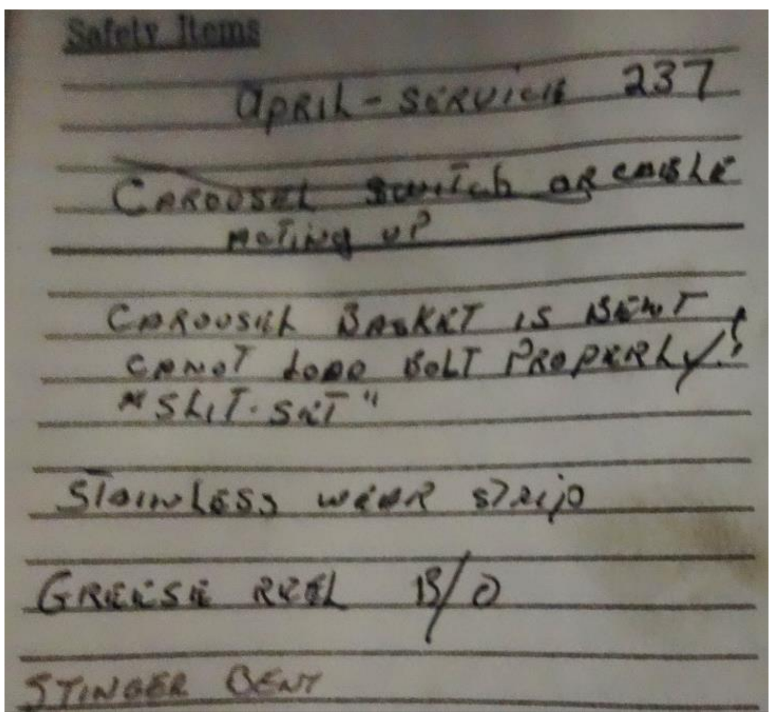
During the installation of resin/rebar and cone bolts, the operator clears the drill holes manually prior to bolt insertion.

Detailed delay description and analysis.

The most time consuming type of equipment failure at the face is hose failure. Operators were not permitted to make and replace hoses, so mechanics would be called to repair hoses. Operators would specify the hose type and length over the radio. The majority of hose failures at the face are non-wrapped hoses located on the base of the drilling tool and are damaged by falling rock during scaling and typical bolt installations near the face.

Damaged hoses on base of drilling tool (drilling tool is pointed downward)

Maintenance Record Samples



Safety Items

April - SERVICE 237

CAROUSEL SWITCH OR CABLE ACTING UP

CAROUSEL BASKET IS BENT CANOT LOAD BOLT PROPERLY ✓ "SLIT SET"

STAINLESS WEAR STRIP

GREASE REEL 13/0

STINGER BENT

Example of handwritten maintenance records for the Boltec at Mine C

| Date | Shift | Hour Meter | Work Performed | LP Code | Hours Down |
|---|---|---|---|---|---|
| 20-Jun | 13 | 1608 | t/s swellex system not making pressure deadheaded pump and it made over 300 bar deadheaded and swellex head could not make pressure took direction valves apart did not see any isues but they are dumping the water to ground ordered two new valves | AV | 6 |
| 20-Jun | 12 | 1603 | replaced teflon wear strip in bolting tool saddle,----- did pre-inspection<br>replaced teflon wear strip in bolting tool saddle | MM | 1 |
| 19-Jun | 13 | | | AV | 0 |
| 19-Jun | 12 | 1600 | installed hose | AV | 2 |
| 18-Jun | 13 | 1597.6 | Repaired b\o and leaking hoses on screen handler boom. | AV | 0 |
| 10-Jun | 13 | | | AV | 0 |
| 10-Jun | 12 | 1590 | Check out carousel issue. Manual box and cable were b/o. Replaced box and cable. Re-wrapped hoses and tested system. All good to use. | AV | 5 |
| 08-Jun | 12 | 1589.2 | located hydraulic oil leak and tightened fitting, and tightened up waterpump belt | AV | 0 |
| 06-Jun | 13 | | | AV | 0 |
| 06-Jun | 12 | | | AV | 0 |
| 05-Jun | 20 | | | AV | 0 |
| 05-Jun | 13 | 1588.2 | completed repairs from service and greased booms | MP | 10.5 |
| 05-Jun | 12 | 1588.3 | with Copco -----. Lost time to move equipment 2 hrs. Reinstalled fender and tool box. Welded bolt tool bracket and bolt stop on rear gripper. Tested grease reel/ pump and it works good. Ran on diesel and unit is building 9 bar of air which is the max setting it should have so it's ok. Noticed centralizer bracket is coming off, found broken bolt into feed rail. Removed centralizer assy to fix threads, replaced b/o hoses. wrapped 3 sections of hose.<br>with Copco ------. Lost time to move equipment 2 hrs. Reinstalled fender and tool box. Welded bolt tool bracket and bolt stop on rear gripper. Tested grease reel/ pump and it works good. Ran on diesel and unit is building 9 bar of air which is the max setting it should have so it's ok. Noticed centralizer bracket is coming off, found broken bolt into feed rail. | MP | 10.5 |
| 04-Jun | 20 | | | MP | 3 |
| 04-Jun | 13 | 1586.3 | continue on repairs,checked chain tention pressure.pressure was at 900 psi set pressure to 750 psi(50 bar) as per manual.intalled heli coils for rear deck slippers and installed missing slippers adjusted slippers | MP | 10.5 |
| 04-Jun | 12 | 1586.3 | Removed tool box and front left fender. Removed old grease reel, prepped new grease reel. Installed new grease reel. | MP | 10.5 |
| 03-Jun | 20 | | | MP | 3 |
| 03-Jun | 13 | 1586.3 | continued on repairs moved equipment around shop ,replaced rear water misters and filter,repaired leak at cent,and started replacing bad hoses and repairing leaks | MP | 10.5 |
| 03-Jun | 12 | 1586.2 | Feed beam cracked where front pully is mounted moved pully to other side and moved stinger bracket back one hole,Installed new pulley. greased pyulley. Washed A/C condensor. Installed new teflon strips on cradle and drill shelf. Replaced b/o delay drilling light. R&R grippers.<br>Feed beam cracked where front pully is mounted moved pully to other side and moved stinger bracket back one hole,Installed new pulley. greased pyulley. Washed A/C condensor. Installed new teflon strips on cradle and drill shelf. Replaced b/o delay drilling light. | MP | 10.5 |
| 02-Jun | 20 | | | MP | 3 |
| 02-Jun | 13 | 1586.3 | continued on repairs,replaced rear tail light replaced swellex pump,moved star wheel carosel tube back,T,s front pully loose found feed beam cracked.moved equipmnet out off shop to get bolter under crain. | MP | 10.5 |
| 02-Jun | 12 | 1586.2 | Performed 12 week service | MP | 10.5 |
| 01-Jun | 20 | | | MP | 3 |
| 01-Jun | 13 | | | MP | 10.5 |
| 01-Jun | 12 | | | MP | 10.5 |

Example of Boltec maintenance records from Mine C, logged on a computer

# Appendix D.1

## Mining conditions contributing to decreased bolter productivity

**ANFO Loading:** Each hole is completely loaded with ANFO which results in overbreak, and damaged rock surrounding the excavation

Figure D-1 Typical face loaded with ANFO at Mine A


Figure D-2 Mine A misfires and underbreak: a) heading not cleared out, underbreak b) four missed holes c) three missed holes, d) 2.5ft floor heave that needs to be blasted before bolting

Figure D-3 Left: Overbreak and irregular drift size in sandfill round; Right: Operator removes underbroken sandfill from corners of a drift prior to bolting

Figure D-4 Left: Rock ejected from lower wall during bolting; Right: Rock is ejected from the upper corner of a drift during a strainburst

Figure D-5 Left: Wedge failure in a drift; Right: Installed bolts after wedge failure reconditioning

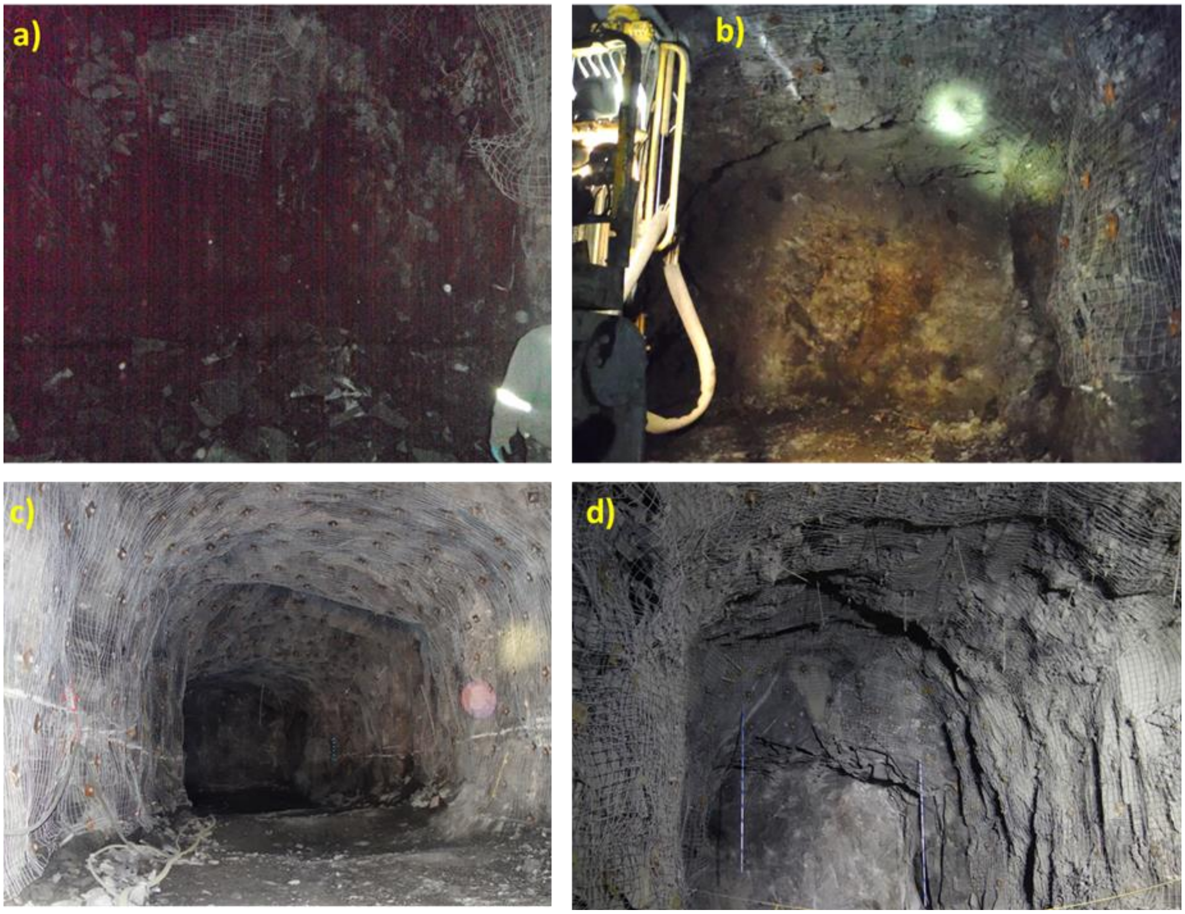
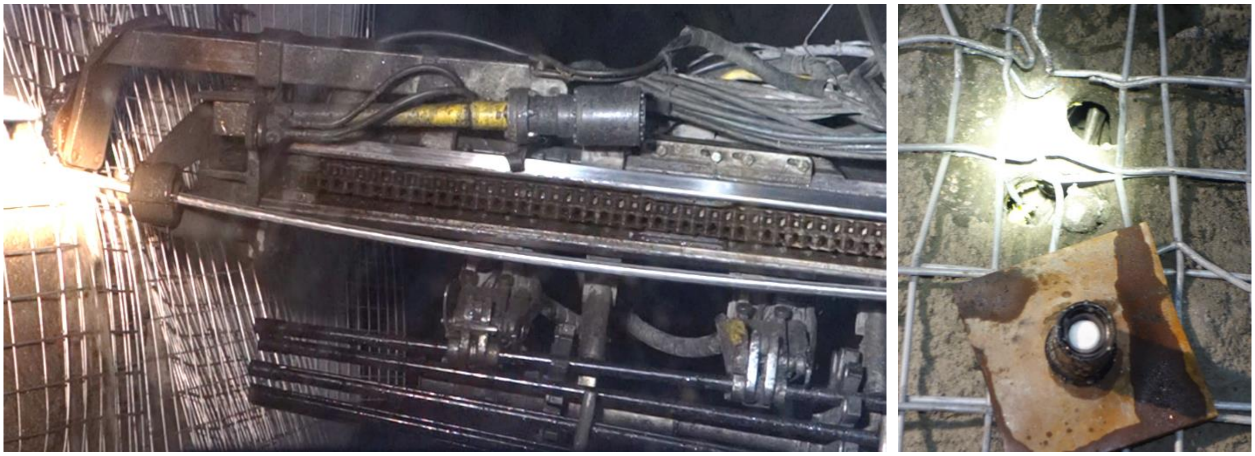



Figure D-6 a) Large loose pile from scaling out damaged ground due to blasting which had to be removed with a LHD prior resuming the bolting procedure b) Overbroken heading at Mine B c) & d) Irregular drift shapes and sizes at Mine C which contribute to an increase in the number of bolts installed per round

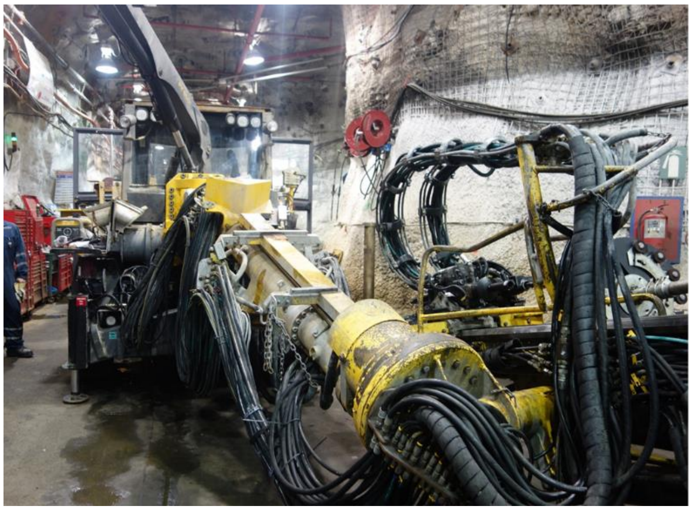
# Appendix D.2



Left: Drill steel bends during 2nd pass bolt installation resulting in misalignment of the boom; Right: Obstructions in drill hole which contribute to drill bit wear and misalignment of the boom during drilling and bolting

Left: operator installs screen manually, Middle: screen handling from bin Right: screen is dropped from the screen handling arm

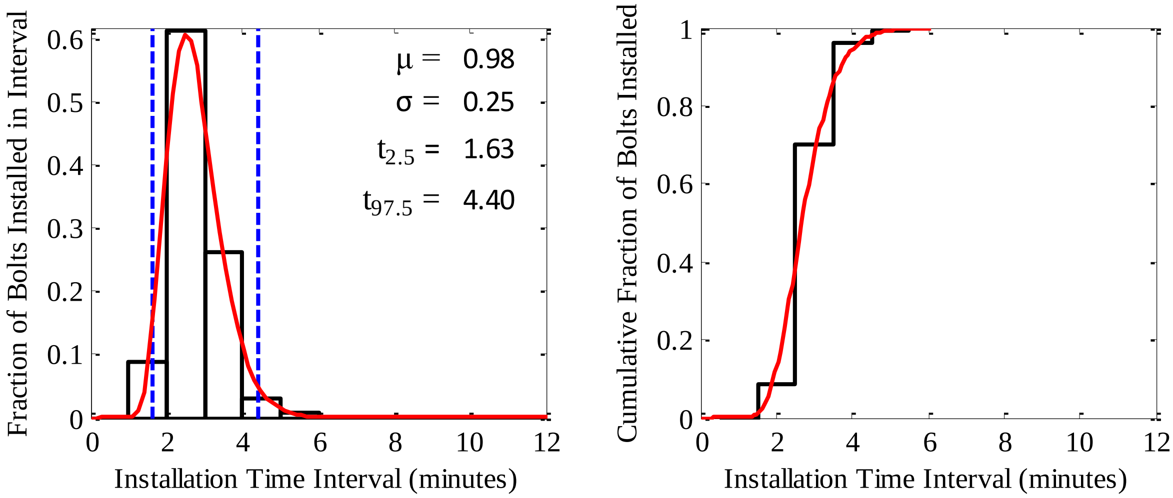

Left: face bolting contributes to cycle time Right: lower wall bolt installation contributes to increased cycle time



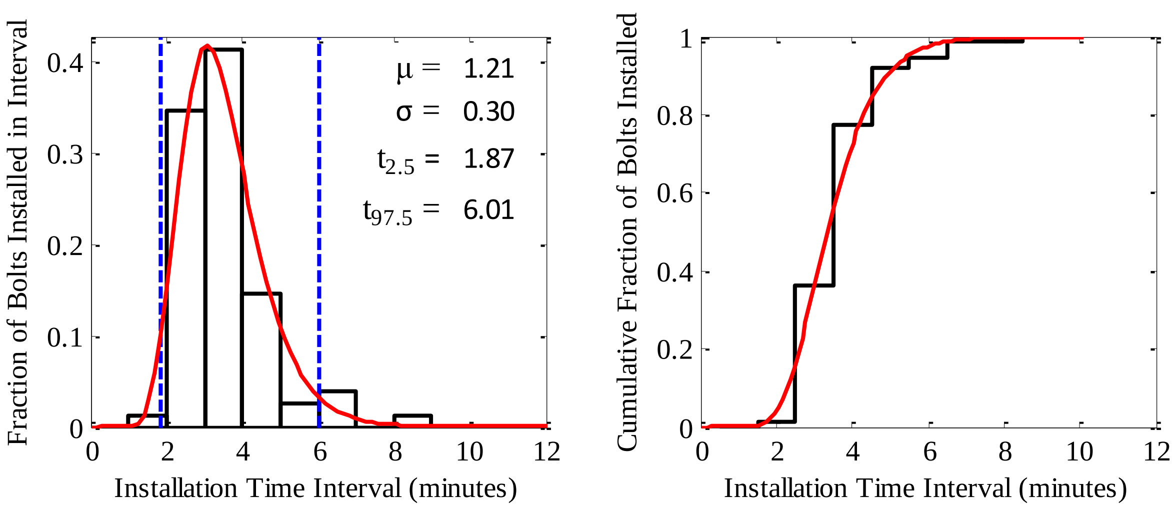

Left: Boltec MC in the Mine C workshop; Right: Hose failure

# Appendix E

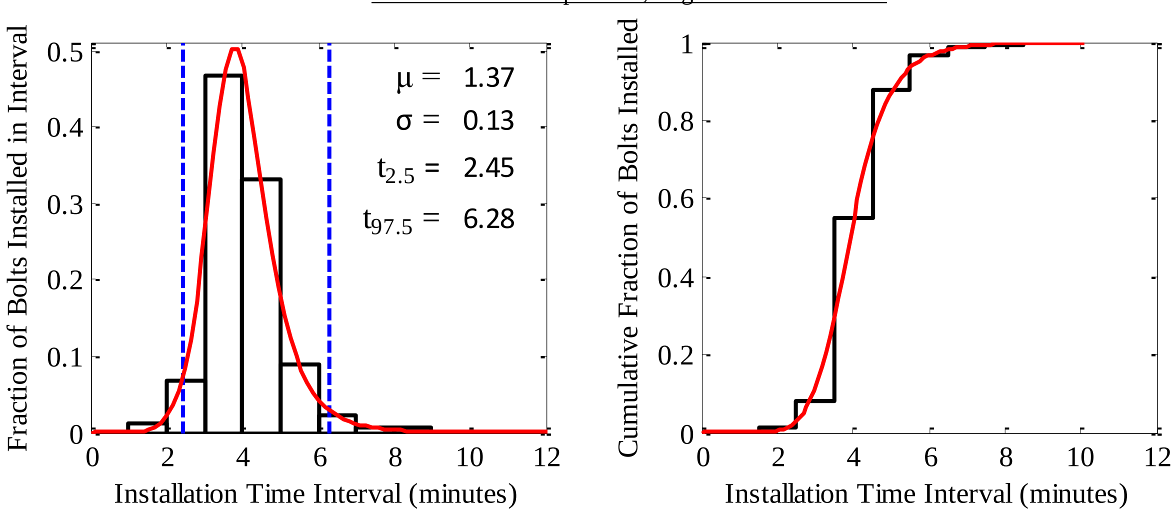
## Detailed Bolt Installation Cycle Time Charts and Probability Distributions



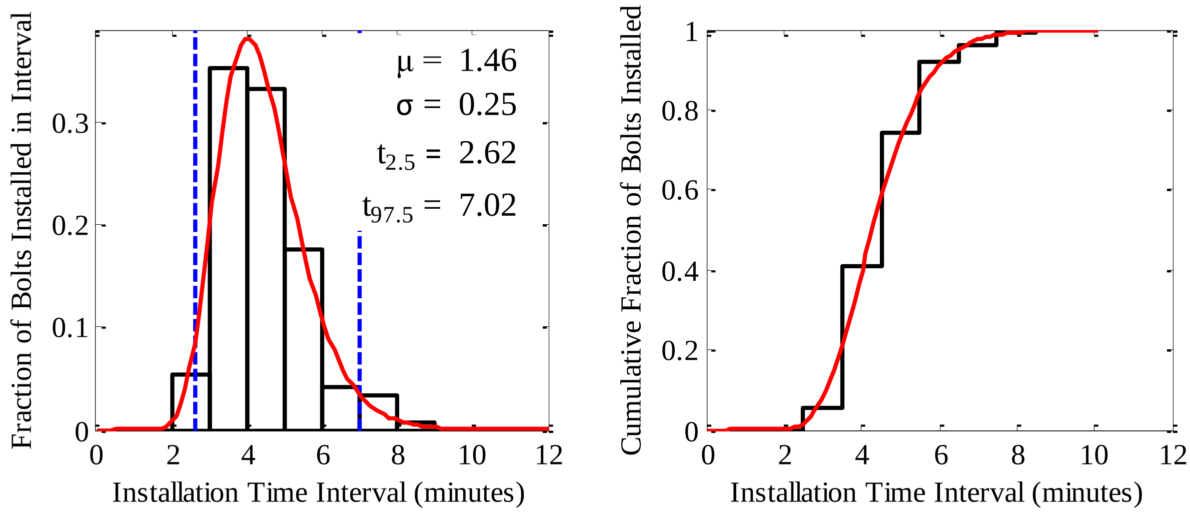

Mine A MacLean Split Sets, Lognormal Distribution



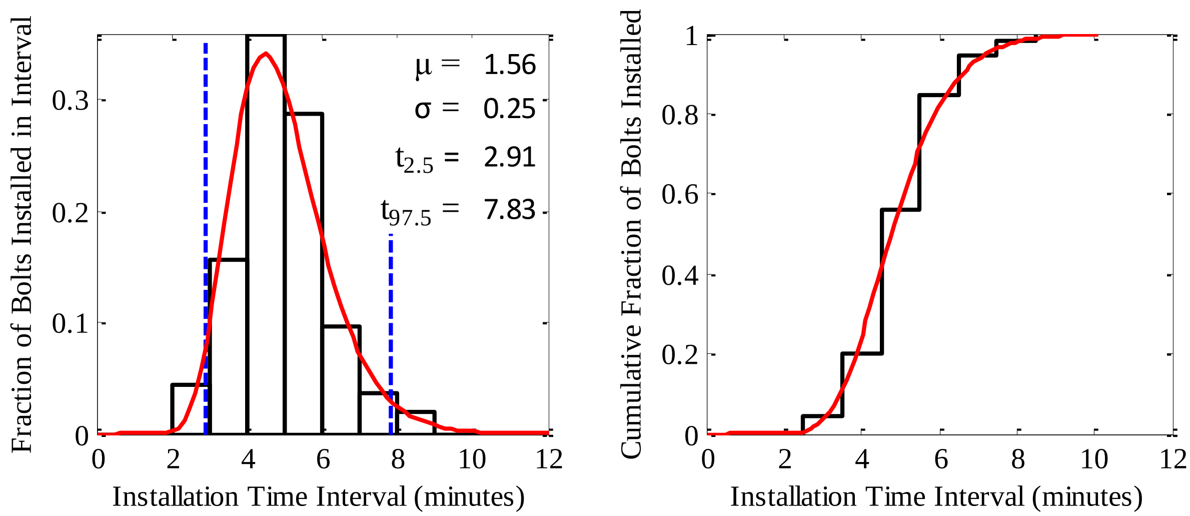

Mine B MacLean Split Sets, Lognormal Distribution



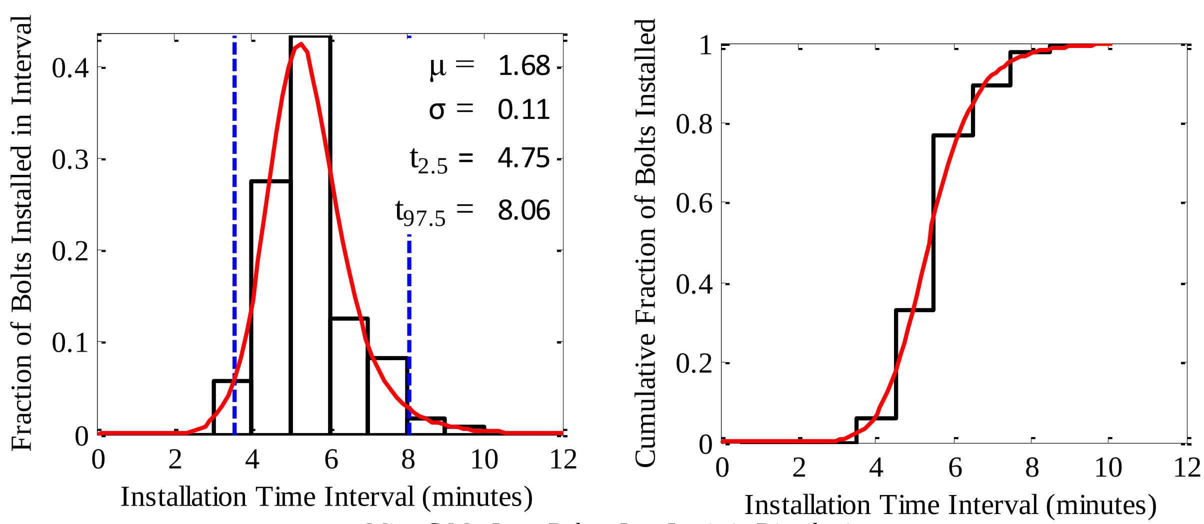

Mine C MacLean Split Sets, Log-Logistic Distribution



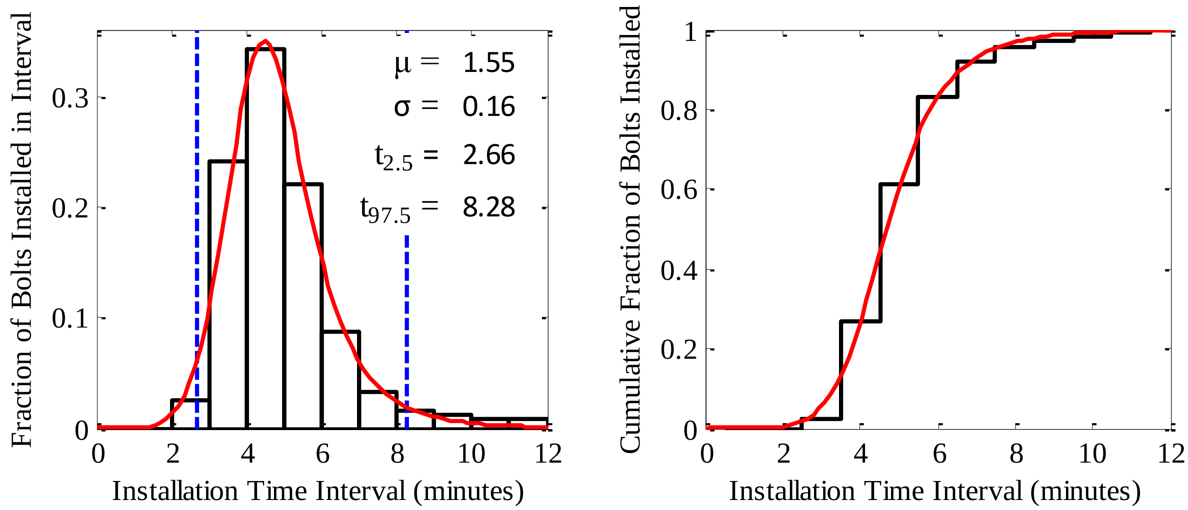

Mine A MacLean Rebar, Lognormal Distribution



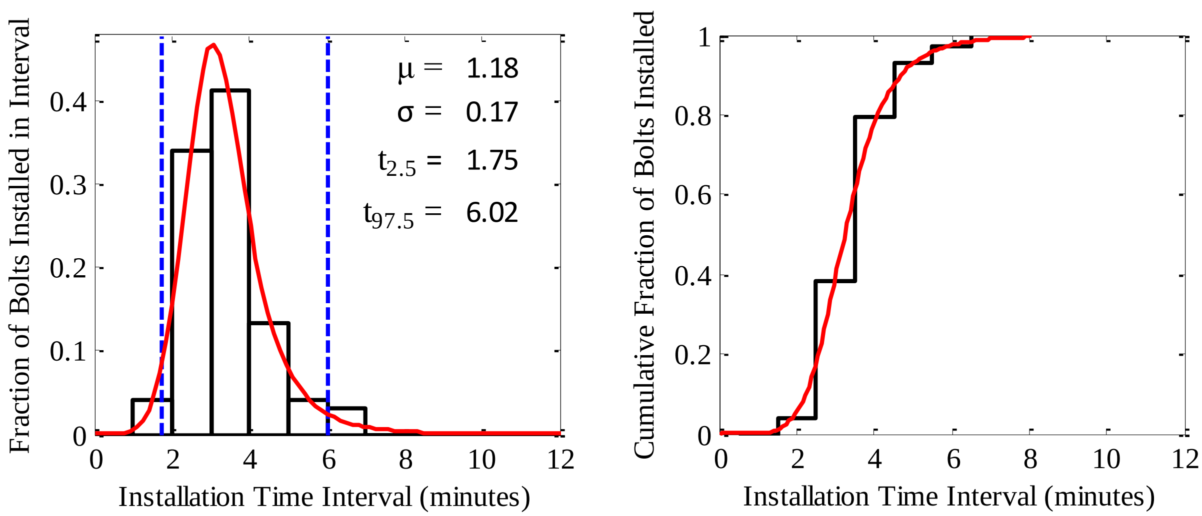

Mine B MacLean Rebar, Lognormal Distribution



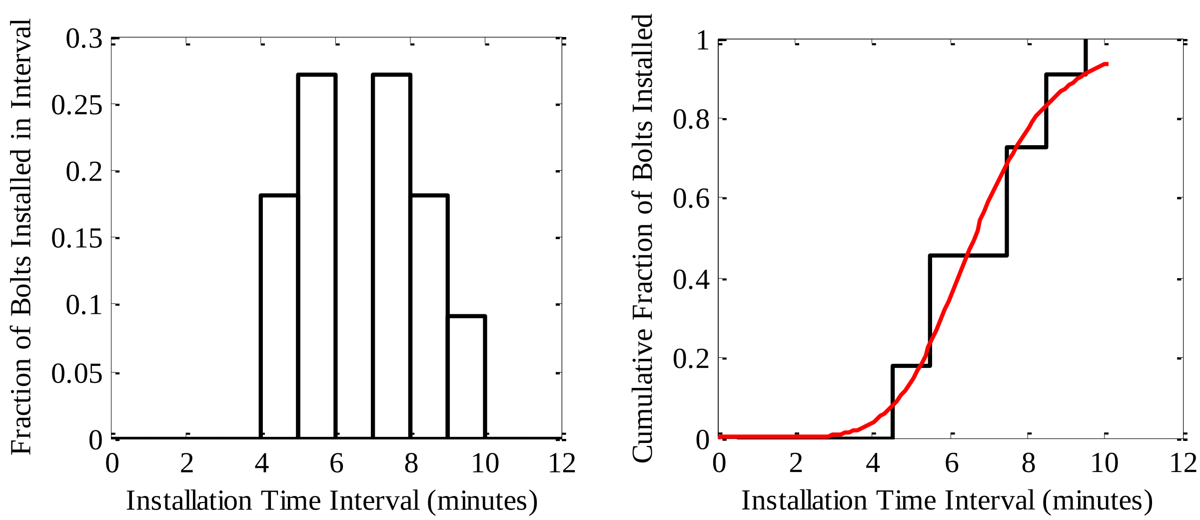

Mine C MacLean Rebar, Log-Logistic Distribution



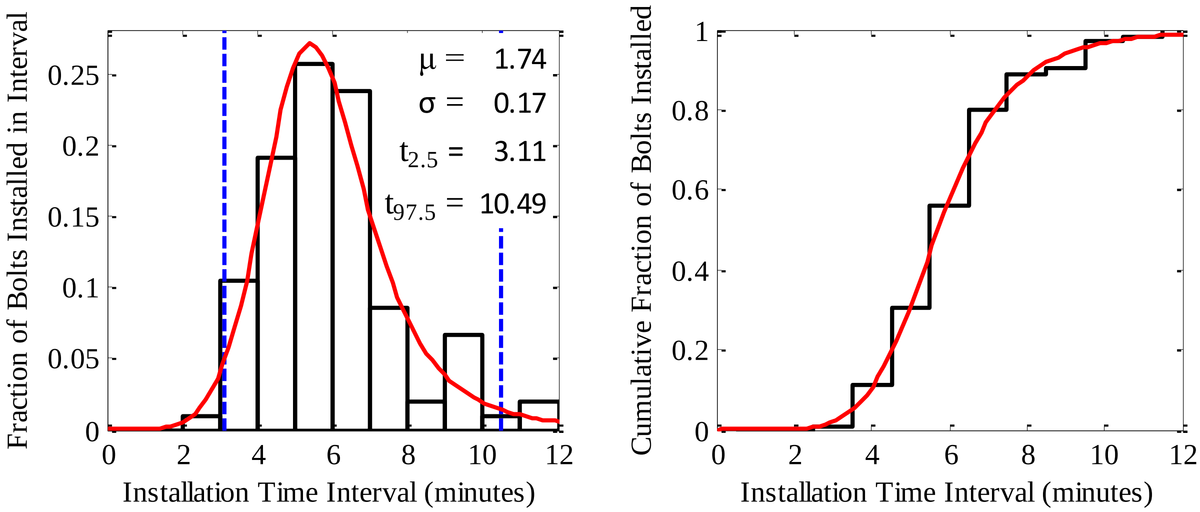

Mine C Boltec Split Sets in Rock, Log-Logistic Distribution



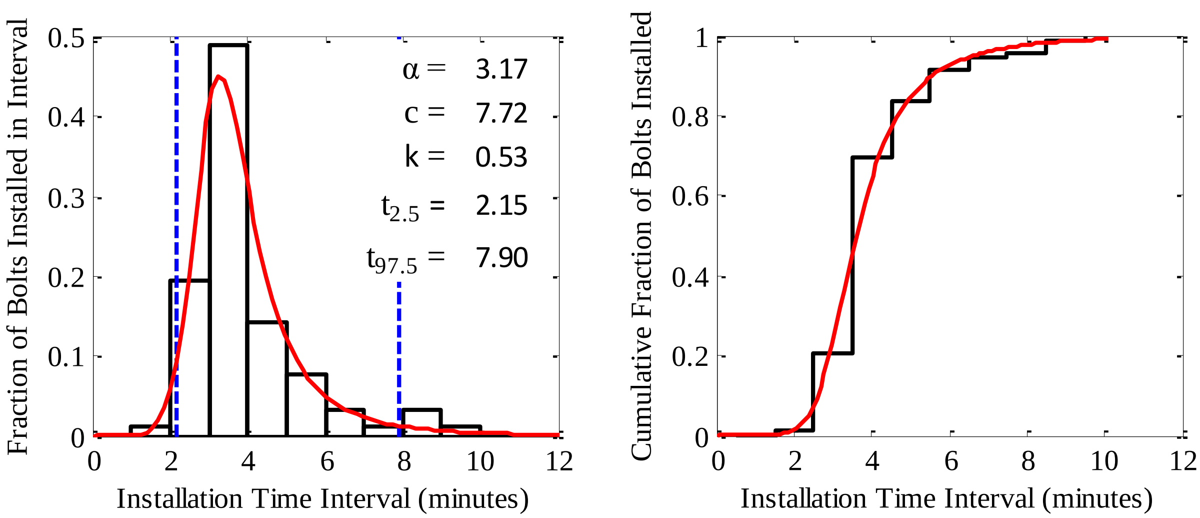

Mine C Boltec Split Sets in Fill, Log-Logistic Distribution



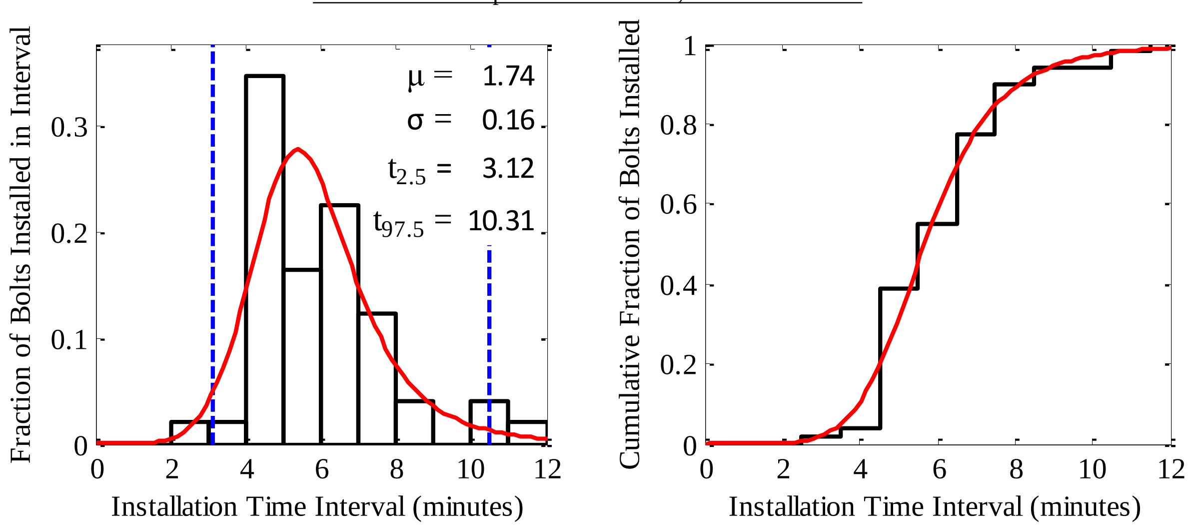

Mine C Boltec Split Sets 2nd Pass, Insufficient data for statistical analysis



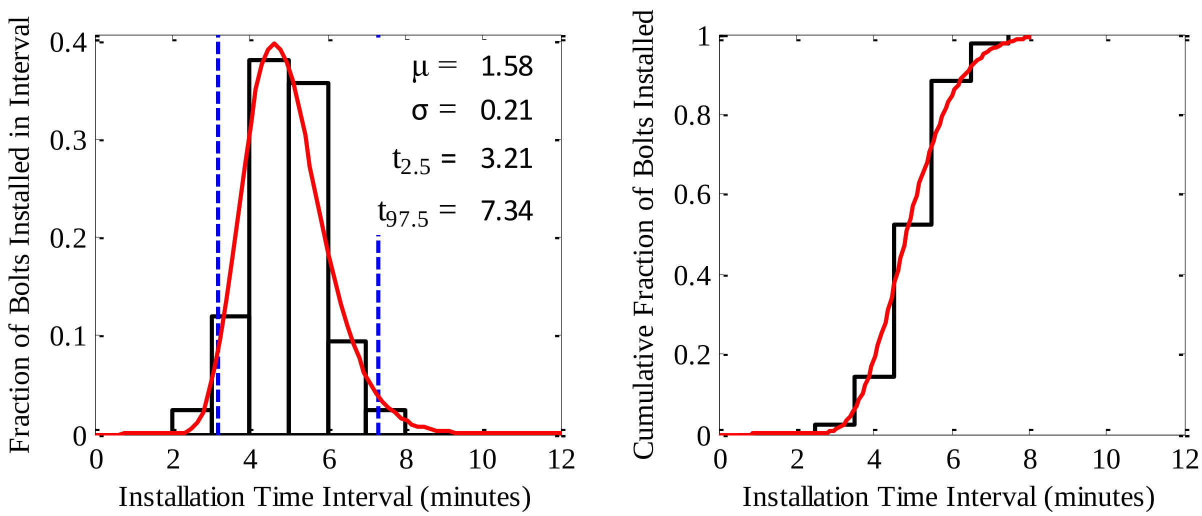

Mine C Boltec Super Swellex in Rock, Log-Logistic Distribution



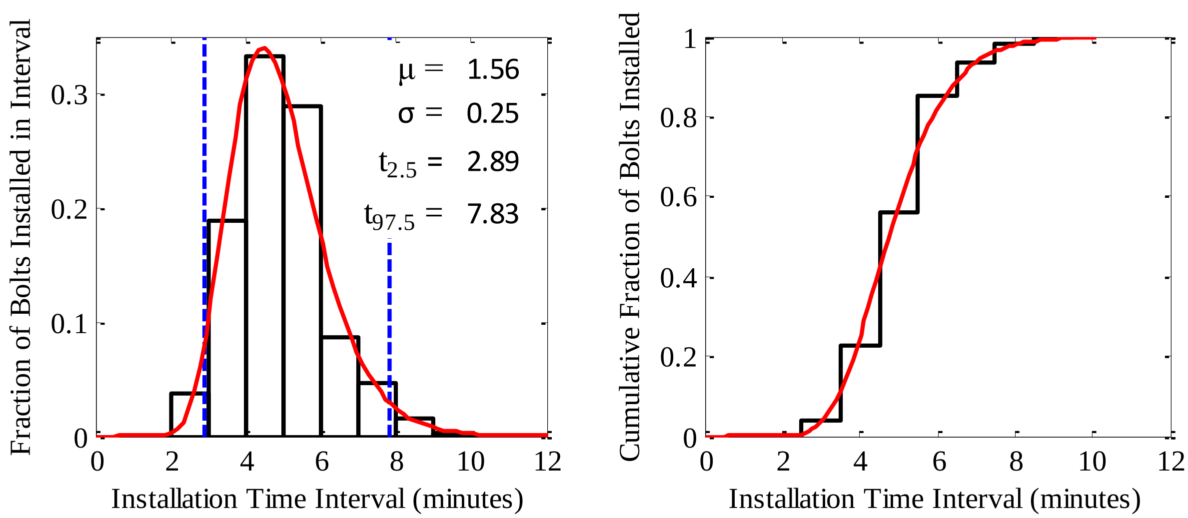

Mine C Boltec Super Swellex in Fill, Burr Distribution



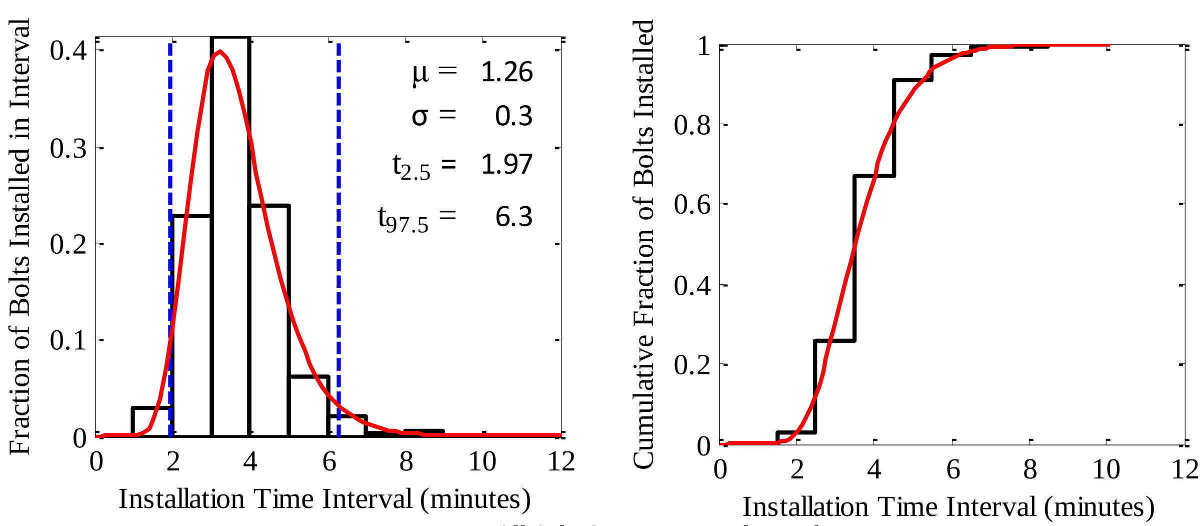

Mine C Boltec Super Swellex 2nd Pass, Log-Logistic Distribution



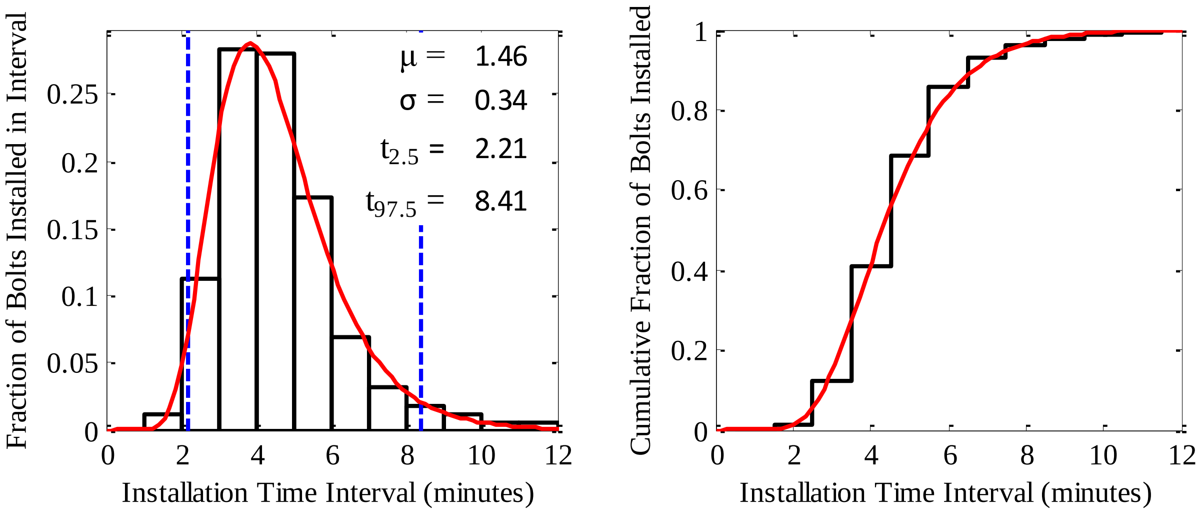

Mine C MacLean Modified Cone Bolts, Lognormal Distribution



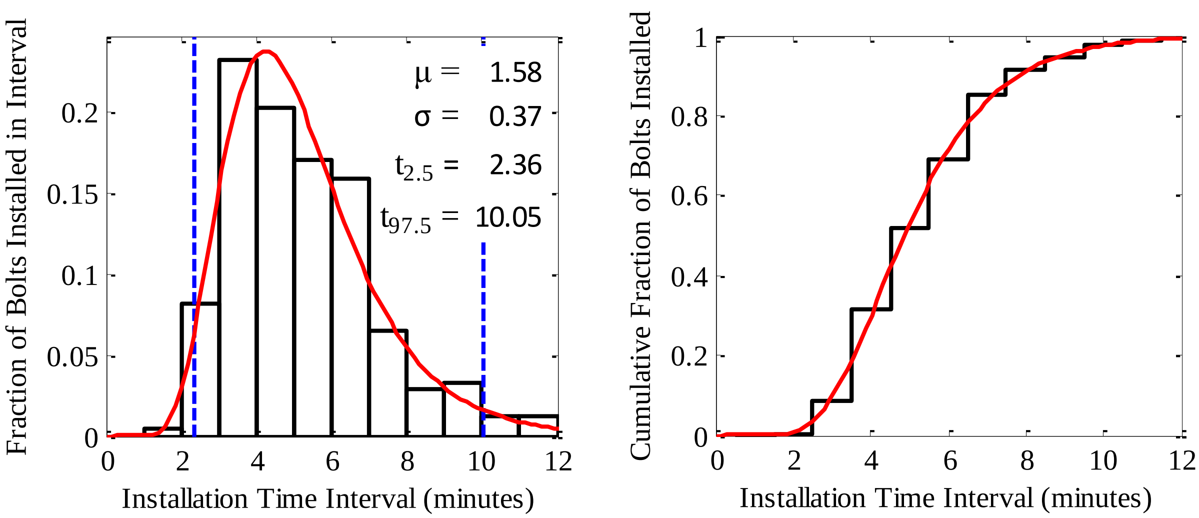

MacLean All Rebar, Lognormal Distribution



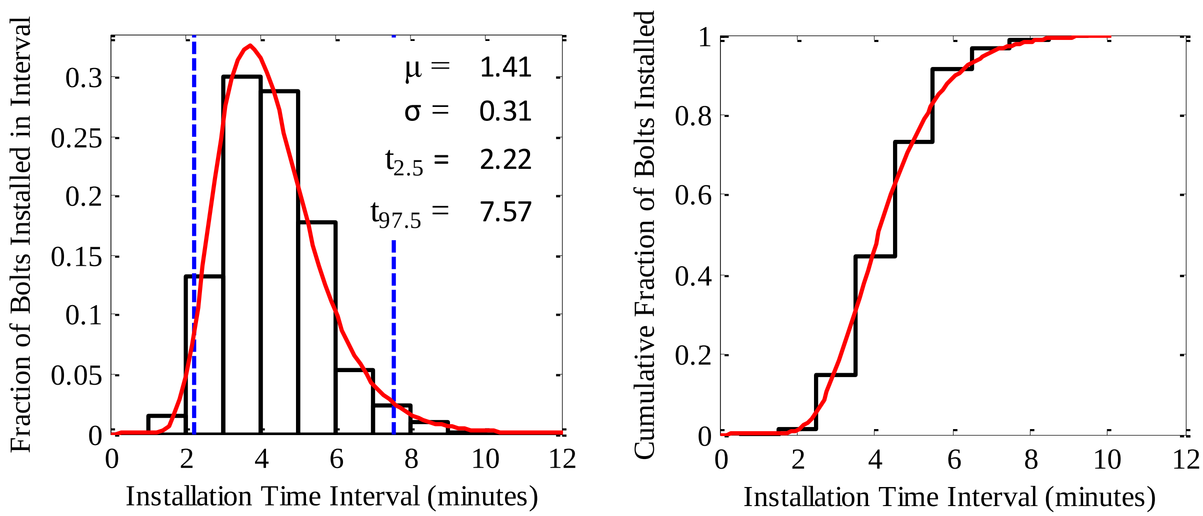

MacLean All Split Sets, Lognormal Distribution



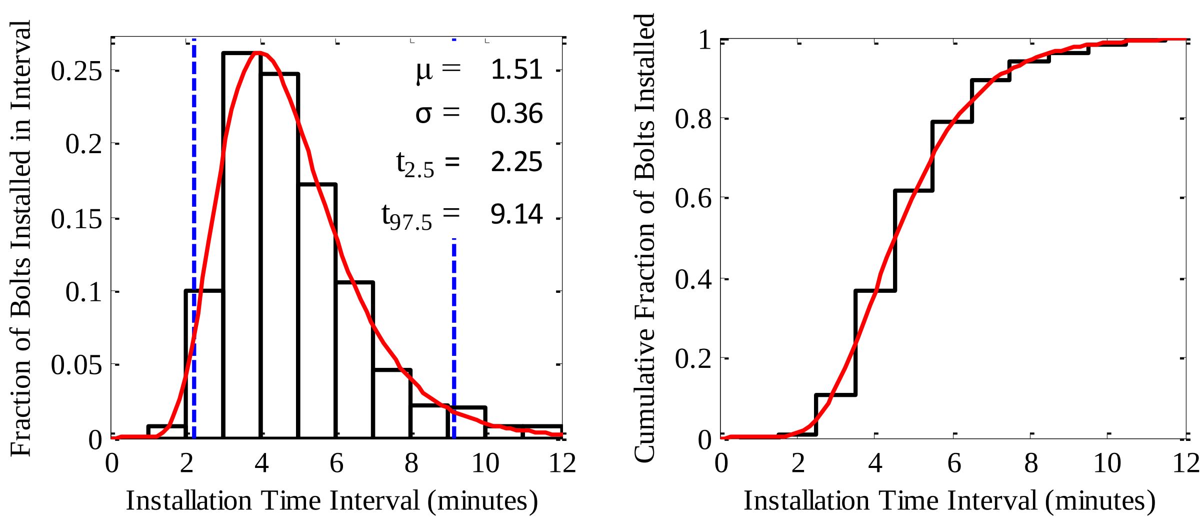

Mine C Boltec all Split Sets, Lognormal Distribution



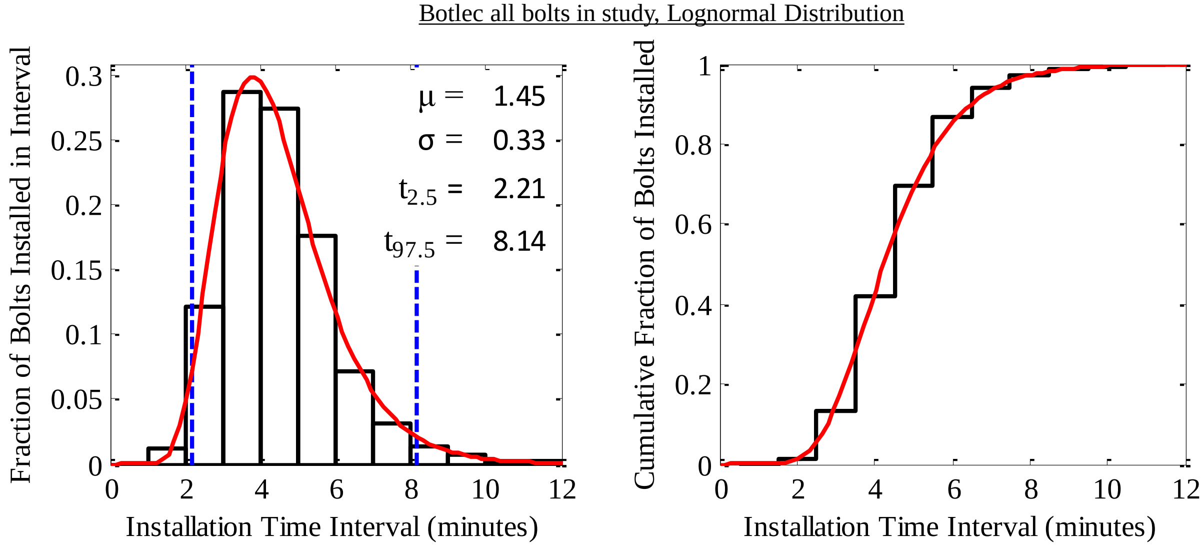

Mine C Botlec Super Swellex, Lognormal Distribution




MacLean all bolts in study, Lognormal Distribution




Botlec all bolts in study, Lognormal Distribution




All bolts in study, lognormal distribution

# Appendix F

Process measurement in mining and tunneling is completed for many reasons including:

1. Documenting equipment operation processes and improvements for future use such as:
   - Specifying procedures for the collection, analysis and evaluation of measured data through pilot studies (Freivalds & Niebel, 2013);
   - Contributing to a mining database to exchange equipment performance data among different operations (Moser & Oberndorver, 1996);
   - Identifying methods to improve processes, and the results of process control (Hall & Harper, 2005; Oggeri & Ova, 2004; Song et al., 2015a);
   - Obtaining historical data of process performance for new mines in similar conditions (Oggeri & Ova, 2004);
   - Measurement of process interaction within the drill and blast cycle (Skawina, 2013);
   - Benchmarking equipment and generate probability distributions for mining processes for the purpose of maintenance and schedule optimization (Tomlingson, 2009; Hall & Harper, 2005; Song et al., 2015a; Song et al., 2015b);
   - Obtaining data for the purposes of performance modelling and modelling of mining systems (Einstein, 1996);
   - Quantifying uncertainties and variability of processes, and understand the cause of variation (Kennedy, 2005);
   - Measurement of the quality and cause of quality loss of the excavation process (Peloquin, 2007);

- Model how processes are affected by geological conditions and uncertainty (Oggeri & Ova, 2004);
- Identifying best practices for machine operation (Robertson et al., 2003), since best practices are often undocumented and communicated verbally or through demonstration based on workers' tacit knowledge (Sanda, 2011a;
- Measuring work to modify financial incentives ("bonus") systems (Freivalds & Niebel, 2013).

2. Analysis of equipment design and maintenance through:
    - Analyzing which equipment subsystems can be improved through design or modification to maintenance strategy (Barabady & Kumar, 2008);
    - Maintenance analysis and optimization (Vagenas et al., 1997; Tomlingson, 2009);
    - Analyzing the root causes of equipment failure (Hall, 1997).
3. Improving health and safety by:
    - Identifying and quantifying hazards and risks during the work process such as physical hazards, dust and noise exposure (Oggeri & Ova, 2004; Peterson & Alcorn, 2007);
    - Obtaining information for the purposes of operator training or to model a physical system for the purposes of developing virtual reality training (Horberry et al., 2010; Tichon & Burgess-Limerick, 2011);
    - Measuring the physical activities that workers perform and their energy expenditure for the purposes of identifying the level of refrigeration required to work safely and productively (Maté et al, 2007; Kenny et al., 2012);

- Measurement of vibration to investigate the cause of musculoskeletal disorders caused by vibration exposure in the workplace (Leduc et al., 2011);
- Investigation of the cause of workplace accidents (Anderson & Prosser, 2007);
- Evaluation of ground conditions while drilling (Bahrampour et al., 2013; Naeimipour et al., 2014; Rostami et al., 2015).

Therefore, to complete the studies listed above and to allow similar processes to be compared at different mines, a standardized measurement methodology would improve the researcher's ability to compare processes.