The comparison of automatic and manual loading in an underground mining environment

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Preface

I would like to first write a few words of gratitude to the people who helped in writing this thesis. I would first like to thank my supervisor Dr. Anna Gustafson for her guidance and help, as well as my opponent Anna Tranell for some excellent critique of my work. I would also like to thank Mikael Andersson, Deniz Pehriz and Arne Renström at Boliden Minerals for their support.

I also want to give my sincerest thanks to my parents and relatives for their never ending encouragement and support, without which this thesis let alone my engineering degree would never have been possible. Finally, I would like to thank my friends and fellow students at LTU who has made these past four years absolutely awesome and helped me strive on to greater things. Couldn’t have made it without you guys…
Abstract

Mine automation has been in development since the 1980s and began to be implemented in the 1990s with the biggest drivers being safety, reduced maintenance and increased productivity. Automation is used in many different mining methods performing a variety of tasks. However, very few studies have been conducted regarding the performance of automatic vehicles in real world mines, neither has much research been done when comparing automated and manual loading.

The purpose of this thesis is twofold. First it is to identify and produce metrics that can be used to compare automatic and manual loading in an underground mining environment. A literary study is presented as a basis for these metrics where the development history is chronicled and the mechanics by which an automated system controls an automatic vehicle is explained. Also included is a description of different mining methods and the part that automation plays in them.

Secondly, the goal is to use these metrics in a real world case study of automated loading in an actual operational mine. The Garpenberg mine, owned by Boliden Minerals, is an underground metal mine located in Dalarna, Sweden, and mining has been done there since the 1200s. Load-Haul-Dump (LHD) machines are used to load and haul ore ether using automation or tele operation. For this study information is extracted from Bolidens internal databases to calculate the metrics which are then used to analyze the performance and reliability of automated loaders, and also to compare manual and automatic loading.

There are mainly three types of metrics that are relevant to automatic and manual loading, these being time related metrics, production related metrics and reliability related metrics.

Since the LHDs dealt with in this thesis are operated both manually and automatically the main use of the time related metrics is to find the relationship between modes of operation in regards to engine hours spent in action, the amount and character of downtime that occurred during the analyzed time span, and the utilization of automatic LHDs during the workday. The most straightforward comparison between manual and automatic loading is the production, i.e. the tonnage of loaded material per unit time. In this thesis production will be analyzed per hour and per loading activity (which run between 3 and 4 hours). Lastly automated and manual loading will be compared on the basis of availability and maintenance, the reason being that LHDs are driven in different ways depending on the mode of operation.

The results show that automatic loading consists of between 14 and 29% of production time while contributing to between 17 and 28% of downtime. No clear connection can be seen between downtime and the relationship of automatic to manual loading, as the difference is not bigger than 10% either way. Manual loading constitutes between 2500 and 3250 engine hours, while time spent during automatic loading constitutes between 420 and 1095 engine hours. The majority of all downtime is not specific to either mode of operation, although automatic specific stops constitutes up to 50% of total downtime for two of the LHDs studied. The distribution of loading activities is similar for both manual and automatic loading, with the number of concurrent activities dipping during lunch breaks and stopping entirely during shift changes. Manual loading peaks around 1000 concurrent jobs while automatic peaks at just fewer than 200.
Regarding production the results show that manual loading is more effective in the short term, as three out of four LHDs has had a higher tonnage loaded per hour. However, when looking at the tonnage loaded per activity, automatic loading catches up to manual loading and produces more tonnage in the long term, with three out of four LHDs getting this higher production.

One interesting result can be found in regards to fuel economy, as one of the LHDs show a reduced consumption of fuel while at the same time having had the largest percentage of time spent in automatic mode. No clear connection can be seen with the rest of the LHDs however, as they show no clear connection between time spent in either mode of operation and the amount of fuel consumed.

Automatic loading proved to have slightly higher availability than manual loading. In all cases however, the difference in no more than 10% and both modes of operation is above 90% availability. The higher availability of automatic loading is attributed to the fact that manual loading constitutes much more time than automatic loading, and thus there has been more time for breakdowns and production stops to occur for manual loading. The relationship of preventive and corrective maintenance is the same for all four LHDs irrespective of amount of time spent in either operating mode. Preventive maintenance jobs accounts for more than 90% of the number maintenance actions for all LHDs.

When analyzing what kinds of production stops are the most prevalent, there are differences between manual and automatic loading. For manual loading the most common stops are those that have to do with external circumstances in the mine such as blocked access and fallen boulders, and those to do with minor breakdowns of the LHD. For automatic loading the most common stops are those to do with the automatic system and the equipment used to operate the automated LHD, followed by those caused by external circumstances, similarly to manual loading. Automatic loading has proportionally fewer stops than manual loading in all categories except those unique to automation, which is in turn the biggest category of all production stops.

The conclusions that can be drawn from these results are that automatic loading can outperform manual loading in the long term, but that continuous uninterrupted loading activates are important to achieve this. Automatic and manual loading show comparable reliability when it comes to maintenance and repairs (serious breakdowns are very rare). Availability and the relationship of preventive and corrective maintenance are similar between both modes of operation. The analysis of production stops show that the biggest problem with automatic loading is the automatic systems and the specialized equipments inability to handle the underground environment. Problems with recorded routes and falsely tripped safety systems are the most common stops.
Recommendations to Boliden Minerals regarding the automatic system consist of improving remote troubleshooting and streamlining of problem solving dealing with automation software and hardware. Steps should also be taken towards tailoring the underground environment to better suit automation.

Suggestions to further research consist of deeper studies of all the metrics presented in this thesis to better analyze the role of automation in the global mining industry. Another avenue of study is the combination of the findings in this thesis with the actual environment and layout in the Garpenberg mine to better understand the connection between operating environment and the reliability and productivity of the automatic system.
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1 Introduction

Automation has been developed in cooperation with the mining industry since the 1980s and is today implemented in a variety of mining methods both above and below ground, mainly with loading and hauling of ore and rock via the use of automated Load-Haul-Dump machines (LHDs) and dumper trucks [1][2]. Although automated systems have reached a certain sophistication and reliability, there is still room for improvement and research. One important field of investigation is the comparison between manual and automated loading and hauling, as well as the identification of problems and their solutions. Mine automation has recently begun to be implemented in actual mining endeavors around the globe and thus there have been few studies conducted regarding the actual performance of these systems in real world mine production conditions. Comparisons of automatic and manual loading have previously been done from the perspectives of production and maintenance [3], as well as reliability [4]. Comparisons have also been made based on technical and operational issues [5]. Research have been done on the character of problems with automatic mining systems and their related failure modes [6], as well as the impact that the operating environment has on such systems [7]. Tests have previously been made on the applications of automation in drilling, loading and charging of bore holes [8] and longwall coal mining [9].

1.1 Statement of the problem

Boliden Minerals has since 2011 implemented and used a system for automated loading of ore in the Garpenberg underground mine. The company is looking for means to analyze and compare automated loading to conventional manual loading to plan further investments in mine development. However, as mentioned earlier there have been few studies on the performance of automatic mining systems and the comparison between manual and automatic loading. Therefore there are no standardized metrics by which automatic systems can be evaluated. To make analysis and comparison possible these metrics must be produced based on relevant factors.

1.2 Objectives

The aim of this study is to present metrics that can be used to compare manual and automatic loading of ore in an underground mining environment and then implement them in a real life case study of the Garpenberg underground mine. The purpose of these metrics is also to assist in further research to find avenues for improvement in automated loading systems.

1.3 Scope and limitations

This thesis will include a literary study of automatic and tele operated loading systems for use underground. It also performs a general analysis of the system in use in the Garpenberg underground mine with the aim of producing metrics that can be used to quantify the productivity and reliability of the system. These metrics will also be used to identify possible improvements and provide a comparison between automatic and manual loading. Although the goal of this thesis is to apply the metrics in a case study of the Garpenberg mine, the metrics themselves are not limited to that specific mine and can be used in any other scenario, as long as it is limited to the automatic and manual loading of material underground.
However, as it was known from the start of the development procedure that the metrics were to be applied to Garpenberg, they may not give a complete picture when applied elsewhere, as there may be additional factors at play in other scenarios that is not present in the Garpenberg mine. The metrics may therefore need slight modification when applied in these scenarios.

The thesis will be limited to four LHD loaders of the same model, designated Roy, Roger, Rolf and Rudolf, that are currently used for automatic loading. The timespan for the data analyzed is the whole of 2015 with the exception of the loader designated Rolf, which entered service in 2016. For this machine data will therefore be taken from the data that is available, which span from January to September 2016.
2 Methodology

As a basis for the construction of metrics, a literary study was conducted that included the following:

- Underground mining methods with emphasis on sublevel stoping, in order to gain familiarity with mining procedures and the relevant method for this thesis.
- Loading and hauling of material underground as well as the workings of LHD-machines
- The function and development of automation describing its history and the different ways an automatic vehicle interprets and interacts with its environment. A description of modern commercial automatic systems and their providers is also included.
- The special equipment needed for remote and automatic operation of LHDs, regarding both the surrounding infrastructure and the onboard equipment of the machine, as well as the different ways an operator can control an automatic vehicle.

The information gathered from this study was then analyzed to form a coherent overview of the strengths and weaknesses of automation, the differences between manual and automatic loading, and identifying the factors that has the biggest impact on the performance of automated vehicles and systems. Firsthand experience was also gained via a weeklong visit to the Garpenberg underground mine. Data was collected from two of Bolidens internal databases: Gantt, which deal with production, and Maximo, which deals with maintenance. Times were reported in these databases with the format Year,Month,Day,hh:mm:ss. This data was directly imported to Microsoft Excel for processing. All data was tagged in such a way as to be separable based on mode of operation and LHD loader id, as visualized in figure 1.
This data was then used in the creations of metrics meant for the analysis and comparison of manual and automatic loading. Calculations such as means, percentages and sums were performed using the functions present in the Excel software. The results were then evaluated to identify differences and commonalities between manual and automatic loading. Recommendations were drawn from these results and also from general observations obtained during the process of writing the thesis.

### 2.1 Terminology

Certain terminology is used to describe the metrics dealt with in this thesis that may need clarification. What follows is a list of terms used, see table 1.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Engine hours</td>
<td>The reported number of hours that a LHD has been in action during the relevant time frame.</td>
</tr>
<tr>
<td>Downtime</td>
<td>The reported amount of time that LHD has been out of action when it otherwise would have been active during the relevant time frame. This is irrelevant to the cause of the standstill.</td>
</tr>
<tr>
<td>Production stops</td>
<td>The reported causes for all downtime that has occurred. This is any form of problem that causes the LHD to halt the work it was planned to perform.</td>
</tr>
<tr>
<td>Metric</td>
<td>Always refers to the quantification of factors relevant to the effectiveness, reliability and comparison of automatic and manual loading of material underground.</td>
</tr>
</tbody>
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Table 1, Terminology
3 Theory

3.1 Mining methods

There are many different methods for mineral extraction in use today. Each one works best under certain circumstances. There are two main categories in mining, above ground methods which mainly include open pit mining, and underground methods such as sublevel caving, shrinkage and sublevel stoping, and cut and fill [10]. Nearly all mining today involves the usage of explosives to break up the rock, which can then be loaded and hauled away for processing.

The mining method used in the Garpenberg mine is a variant of Sublevel stoping, the so called open ended method. Loading is performed in-stope.

3.1.1 Sublevel Stoping

Sub level stoping is an underground mining method that is unsupported, meaning that no support structures are built to hold up the overhanging rock after blasting. It is best suited for vertical orebodies, since gravity is an important factor when making the blasted ore available for loading. This method is best suited for orebodies with the following characteristics [11]:

- Steeply dipping orebody, the inclination of the footwall must exceed the angle of repose.
- Stable rock in both the footwall and the hanging wall
- Competent ore and host rock
- The boundaries of the ore body are regular.

There are three variations of sublevel stoping, the blasthole method, the open ended method and vertical crater retreat [10] which all share a similar procedure that can be seen in figure 2 and 3.

![Figure 2. Open ended method. [10]](image1)

![Figure 3. Blasthole method. [10]](image2)
The mining procedure starts with the driving of a haulage level, from where the blasted ore will be collected, or mucked, as it’s called in mining jargon. This level consists of a haulage drift where the ore will be transported and draw points which leads into the future stope [10]. These draw points are trough shaped to funnel the ore to access drifts where it can be mucked. One or more sub levels are then driven into the ore above the haulage level. These sublevels will be used to bore holes into the ore which are then filled with explosives, which are detonated and the broken rock is allowed to flow down with the help of gravity into the drift below [11].

This creates a large open cavern, a Stope, that is filled with broken ore which can then be removed from the draw point. It is a relatively cheap, effective mining method that allows for about 75% of all ore to be mined with about 20% dilution, although the cost for developing the orebody prior to mining is rather high [10]. After the ore has been removed the stope is refilled with concrete or some other fitting material which will then be the bottom of the next stope, as more drifts are driven further up in the orebody. The difference between the methods mentioned earlier is mainly the way the boreholes are arranged when drilling the orebody.

3.1.2 The open ended and blasthole methods
In the blasthole method the ore is drilled in a radial pattern around the sublevel drift [10]. These holes are drilled and loaded in sets that allow massive blocks of ore to be blasted. When using the open ended method however, the holes are drilled vertically between the level, allowing for ore to be blasted in sheets rather than blocks [10]. Two vertically aligned drifts are driven into the ore. Holes are then drilled vertically down from the top drift. This results in a tall, rectangular slice of the orebody being blasted. The first step in mining a slice is to blast a vertical chute between the upper and lower drift. The purpose of this is that blasted rock swells, meaning that open space is needed for the ore to flow into to avert clogging of the stope. The main difference between the open ended and the blasthole methods is that the sublevel must be as wide as the stope in order to accommodate the drilling rigs and allow for parallel drilling for the open ended method, while the blasthole method allows for the sublevel to be of much smaller diameter than the orebody [12]. This can be seen in figure 4 and 5 below. There are pros and cons both methods. The open ended method allows for better fragmentation and more broken rock per meter drilled. It also permits reduced drilling and explosives costs, as much as 30% in some African copper mines [12]. This cost reduction may be mitigated when driving the sublevel however, since it needs to be driven out to the width of the stope. The open ended method also results in a larger room being opened that may increase the risks to the drilling personnel [12].
Vertical crater retreat differs from the other two methods in several ways. The staging process is the same with a couple of additions. An undercut is made on the haulage level under the stope. Parallel, big diameter holes, 100-200 mm [12], are drilled from the sub level and into the undercut, as seen in figure 6. These holes are then plugged at the bottom and loaded with high power explosive charges. This allow for horizontal slices being blasted into the bottom of the stope where it can be mucked with remote controlled Load-Haul-Dump machines (LHDs) or by an automated drawpoint system [11]. The loading of these holes are more complicated than those of the other methods, since the depth of the holes must be ascertained, the charges must be positioned right and be of the right power, and they also need to be contained correctly to ensure correct fragmentation [11]. This method does however allow for a rapid production rate, thin slices being blasted and hauled continuously [12].
3.1.4 In-stope mucking
Developing haulage levels is an expensive and time consuming process, which can however be made cheaper by performing in-stope mucking, which means that the ore is loaded in the stope directly by remote controlled LHDs, reducing both costs and development time [11]. With this come bigger risks for the machines however, since they are directly below unsecured rock, and so they always run the risk of being buried due to cave-ins, or being smashed by falling boulders [11].

3.1.5 Safety
In regards to safety sublevel stoping is hard to beat, since stopes are contained, with no access needed for production to be continuous [10]. Instability in the surrounding mine should not be a problem since stable rock is a criteria for using these mining methods to begin with [11]. Of course the risks increase dramatically when loading in the stope itself, although there should be no risks to personnel since the only vehicles that enter the stope are controlled remotely [11]. Costs is still an issue though, since machines don’t take kindly to cave-ins and falling boulders, and large sums may be needed for repairs and maintenance [11].

3.1.6 Unit operations of mining
All forms of mining operations can be split up into fundamental tasks that form a cycle which allows ore to be mined and taken out of the ground. These are called Unit operations of mining and can be split into two categories: Production operations, which are the activities directly connected with the extraction of minerals, and Auxiliary operations which are activities that are not directly involved with production but keep the mine running [10].

Production operations mainly exists of two activities: Excavation/Rock breakage and material handling [10], which in themselves made up of smaller tasks that can differ depending on circumstances and the mining method used. Excavation for instance, may be used when the material being mined is soft enough to be dug directly with diggers [13], while when mining in hard rock explosives or drilling is needed [10]. When mining underground in hard rock, these are the unit operations in general use [10]:

- Drilling of the rock
- Blasting
- Loading of ore
- Hauling of ore to the surface

There are many auxiliary operations as well. These are things like ventilation of blasting fumes and dust, reinforcement of drifts and tunnels using rock bolts, wire mesh and concrete, as well as providing vitalities like water, ventilation, electricity and communication [10]. Sometimes, due to their importance for safety, ventilation and reinforcement are grouped with the primary cycle.

3.1.7 Loading and Hauling
Loading signifies the act of removing extracted ore or rock and placing these in a haulage vehicle or at a place where it can be loaded onto one, while hauling signifies moving of these materials from the front and dumping them at a discharge point, which may be a ore chute, a crusher or a dumpsite [10]. The term Excavation is used when referring to digging in situ materials directly without the need for rock breaking, as when digging coal, soil or other loose
materials, which can then be loaded onto haulage units [11]. There also exist machines designed to combine loading and hauling, such as LHDs or hopper loaders [13]. Both loading and hauling machinery vary tremendously in size to fit circumstances, from bucket machines shorter than a man that operate in small drifts to excavators the size of entire open pit mines [14].

More than 75% of all underground mines utilize LHDs for both large and small fronts [13]. LHDs load the ore from the draw point and dump it into ore chutes or loading buffers on the actual haulage level. From there the ore is transported in various ways using dedicated hauling units [10]. These can be motorized, such as mining trucks, which work well due to their flexibility, availability and cheap implementation [13]. Material can also be moved via conveyor or rail cars, which have high, constant production, but require a lot of effort to implement, since space is finite and dedicated tunnels are needed to house the tracks/conveyor [13]. Vertical transport is an important step in underground mining. Trucks can fulfil this job by using the mines ramps to move material to the surface, again being a flexible choice of transportation, however, the distance traveled uphill becomes very large and the gradient takes a strain on the vehicles [13]. Skips are a viable option, although just like conveyors they require a lot of planning to implement [13].

3.1.8 LHD-machines

LHD machines are a backbone of modern production systems in most underground metal mines, and are used in a variety of mining methods [5]. There are various sizes and models of LHDs but most have a similar design. Figure 7 and 8 show the gamete of the different sizes of LHDs, from small 1 ton capacity machines to bigger ones with capacities of 17 ton. Figure 9 shows the general dimensions of a LHD, which consists of two parts, a front and rear carriage connected in the middle by a hydraulic joint. This joint is what allows the machine to steer [14]. Each carriage stands on two rubber tires. The rear carriage contains the engine, driver’s cabin and hydraulic pumps while the front carriage holds up the bucket. The hydraulics power the booms that hold the bucket, allowing it to load and lift several tons of material and also maneuver the machine through tight tunnels, even when fully loaded. Carrying capacities vary from one to twenty tons or more [15]. Good fragmentation of the muck is desirable since it reduces the wear on the machine and increases productivity by making it easier to fill the bucket [13]. LHDs are powered by diesel or electricity [13][15]. One very important feature is the ability for these machines to be controlled from a distance allowing them to operate inside of stopes, as previously mentioned [13]. This is either done using a control pad worn by the operator in close proximity to the machine, or, as is the focus of this thesis, the machine can be controlled remotely via specialized systems from above or below ground using remote operator’s stations [16].
3.2 Automation and automated systems

The Swedish academy’s dictionary’s definition of automation is “(a)self-moving or self-serving machine or installation”. The main use of automation is to perform cyclic and/or repetitious procedures that save manpower and increase production. It is widespread in agriculture [18] and also in general industry and storage of goods.

Hartman & Mutmansky (2002) presented a good timeline showing the evolution of automated system in the mining industry, which is visualized in figure 10.

The path towards automation in the mining industry began in the 1950 when continuous miners, high power equipment and other labor saving technology were introduced [10].
In the 70s remote control began to be implemented and has since then been a staple in the industry, greatly increasing safety for miners by removing them from the biggest hazards [10]. Research into mine automation started in the 1980 and towards the end of the 90s the first commercial systems emerged. As Ghodrati et al. (2015) puts it: “Mine automation covers everything involved when we try to replace human senses and intelligence with machines, including sensor technology, communication network and devices… automated mining involves the removal of human labor from the active mining operation area and process. The mining industry is in the midst of a transition towards automation.”

Automation and remote control is applicable in many unit operations in underground mining. Loading and hauling is foremost of these [10], although it also has potential in continuous coal mining [9] and loading of blast holes [8].

### 3.2.1 Automation and remote control of LHDs

There are two ways of remote operation of LHDs, Line of sight control and tele remote control. Line of sight remote operation is done via handheld control devices that communicates with the LHD via radio or hardwire [10]. The control pad, shown in figure 12, features a complete set of controls like those found in the driver’s cabin, although it does lack the gauges found in the cabin which indicate rev count, oil pressure, etc. Thus the driver does not have access to any vehicle telemetry. The driver does however have a good view of the surroundings, allowing him to monitor the state of the walls and ceiling, which may give hints when it’s about to cave, see figure 11.

![Figure 11. Remote controlled LHD.](image1.png)

![Figure 12. Handheld control pad.](image2.png)

Tele remote operation is performed from a control station situated in a separate location, either above or below ground or from a mobile station mounted in e.g. a vehicle [5]. Teleoperation is almost always connected with automation, and the system dealers also provide control stations [20][1]. These are fitted with multiple view screens connected to cameras onboard the LHD. They also show vehicle telemetry and a laser scanned view of the drifts geometry [5]. They also sport a complete set of controls as well as seen below in figure 13 and 14.
The station is connected to the LHD via a semi-wireless broadband intranet connection, a WLAN network, which transmits all data exchanged between the operator and the loader [16]. The LHD is connected wirelessly to transmitters installed in the mine. These transmitters are themselves connected to the network using fiber optics [22], see figure 15.

3.2.2 Automation
A disclaimer regarding automation of LHDs should be made. A more correct term would be Semi automation. Currently there exists no system that can automate the loading process in its entirety [10][5][6]. This is because the act of filling the bucket is very difficult to program into an automated system, due to there being very many variables affecting the action, such as the fragmentation of material [23]. The order of work for the LHD is as follows [5], see figure 16:

- The operator at the control station fills the bucket manually at a drawpoint.
- The machine is set on automatic during tramming to the dumpsite.
- The bucket is emptied automatically.
- The machine is set on automatic mode while returning to the loading area.
Figure 16. Semi-automated loading cycle.

3.2.3 Setup of routes and navigation

For an automated system to work the LHD needs to be able to localize itself in its environment. This can be done either with internal or external navigation. External navigation makes use of things in the environment that the LHD can interact with in order to calculate its position. These may be beacon or tags which have reflectors or transmitters [24]. A LHD can use a laser or receiver to ping the location of several of these beacons (at least three are needed) in order to triangulate its position [20]. Another similar method is rail guiding. Rail guiding has been used in industry since the 60s and involves buried wires or painted reflective lines on a factory floor. The principle is the same as for beacons, although the machine simply follows the lines to its destination [25]. These types of navigation do not work well in a mining environment however, mainly because of two reasons:

- Installation costs. The reason for the popularity of this navigation system in industry is because the high installation cost is balanced by its extreme reliability and longevity. This is due to very stable conditions [25]. This is not true of an underground mine. There is always a risk of equipment breakage due to collisions with vehicles, rock falls and cave-ins, and high moisture and dust content in the air. Roads in mines are made of gravel and often turn to mud, burying markings on it. Beacons may also be blocked with mud and dust [20].

- Inflexibility. Once installed these marking are difficult to modify and thus are not suited for mining use. Mining operations, especially loading and hauling, changes continuously as stopes are mined out and machines are transferred between different production areas [20].
Larsson et al. (2005) points out that these methods don’t allow for the same tramming speed as manual driving, reducing production, and the problem of insufficient look ahead when using rail systems. In addition none of these utilize collision detection, which is a problem in a busy mine.

Internal navigation thus seems to be the correct method to use when mining. This type of navigation uses measuring devices carried on the vehicle itself to calculate distance traveled without any outside reference. The two ways of doing this are odometry and inertial navigation [20]. Odometers work by counting revolutions of an axel or wheels which are then used to calculate distance. Inertial navigation uses accelerometers to measure acceleration which can then be derived to give distance travelled [20].

These mechanisms can allow a vehicle to keep track of its position and travel from point A to B. The automated system then needs to be programmed in such a way as to know the path that it is to take before operation can begin. This can be done in the following ways:

- **Dead reckoning**, which combine odometry and/or inertia with set beacons at different points to navigate [24].
- **Learning.** The system records a route driven manually by an operator by laser scanning the topography. The system will then scan it surroundings when operating on its own and compare it to the recording [24].
- **Computerized map.** A simplified map of the mine can be constructed which the system will then follow using odometry/inertia aided by tags on walls and laser scanning [24].

Navigation using computer maps are the most flexible method since changes can be made in the map directly, while a recorded route cannot be changed without rerecording it [24].

### 3.2.4 Developers and providers

There are three main providers of automated mining systems:

- AutoMine®, and AutoMine® Lite from Sandvik Mining [26].
- Minegem from Caterpillar [27].
- Scooptram Automation from Atlas Copco [19].

The general functions of these systems are quite similar:

- They all employ control stations which can be set up at different locations, above or below ground, stationary or mobile.
- Tramming and emptying of bucket is done automatically with the driver reduced to supervising duty.
- Navigation is done using mainly laser scanners with additional input from sensors, accelerometers and odometers.
- All use collision detection systems.
- Data transferring is done via WLAN.
They all use sophisticated computer programs to monitor road conditions and machine health, enhancing tramming and dumping.

3.2.5 Equipment on LHDs and mine
All commercial automatic systems require extra equipment to be installed on the LHD and in the mine environment. These aids both with tele operation and automation [28][19]:

- IR capable cameras and laser scanners are fitted to the front and back which give a front and rear view.
- Sensors for measuring distance, load in bucket, and machine health are fitted.
- WLAN transmitters/receivers and safety perimeter systems are installed in the mine.

3.2.6 Safety systems
All Commercial automated systems use a double redundancy safety system comprising of a perimeter barrier and the scanners mounted in the vehicle [16][2]. Each automated vehicle uses its scanners to detect its surroundings to ensure that it is in the right location. This system also detects obstructions and will stop the vehicle if there is a risk of collision, which safeguard not only the LHD itself but also other mobile equipment and people. To ensure safety, no human presence or equipment is allowed within the LHDs workspace, which is enforced by a perimeter system consisting of laser gates [2][27]. These work by laser beams being bounced between two pylons on opposite sides of a drift. If these lasers are interrupted the safety system is tripped and the automated machine is deadlocked. This also makes sure that the LHD does not leave its designated area [2][16].

3.2.7 Advantages of Automation
The main advantage with automation is the safety and ergonomics of the operator. As both Ghodrati et al.(2015) and Paraszczak et al.(2015) points out, the underground mine is a harsh environment and although the safety has improved during the latter half of the twentieth century, it can still be dangerous. Just about every single publication on automated loading stress this increased safety, and with good cause. Traumatic injury is still a serious, although decreasing, danger in mining. Causes are both those inherent to the underground environment, such as rock falls and cave ins, and those associated with heavy industry, such as falls from heights, accidents with mobile equipment and entrapment [29].

The most serious hazard when stoping is overhanging unsupported rock, which is thankfully avoided almost entirely since LHDs are always controlled remotely then loading. There is still health issues however which is due to various aspects of the underground mine environment such as dust and fumes from newly blasted rock that linger after ventilating and also the exhaust from vehicles and machines [30]. Air quality is an important factor that can be directly harmful, or at least be tiring for personnel. Radon is an odorless radioactive gas that is found in some underground mines, and is the result of the radioactive decay of uranium. It is highly carcinogenic when breathed [31]. Then there is the not so nice combination of darkness and uneven, muddy ground with standing water and loose rocks, and the traffic of heavy machinery with poor visibility. Vehicles usually have enclosed cabins with AC, but in
the case of LHDs, the operator is of course not there when loading, and even within the cabin there is a large amount of vibration, which can be harmful for the back and neck [5].

Practically all of these dangers and hazards can be avoided by moving the operator to a sheltered control room. Having a more pleasant workplace also makes the work less tiring for personnel and allows them to work longer and more efficiently and reduces the risk of human errors [5].

A mayor time sink is traveling and moving when changing shifts and when blasting is performed. With a centralized control station above ground this time loss can be significantly reduced [5]. It also allows for work to continue even when blasting, since there is no danger when stationed above ground. When driving a LHD on site, depending on where in the mine it is situated, the operator needs to travel a fair distance underground, sharing the space with heavy traffic. Limiting the number of vehicles below ground may ease congestion. Automation and tele operation is also a valuable asset to increase production during shift changes and lunch breaks [5].

3.2.8 Problems with automation
The automation of loading and hauling can be very advantageous considering increased safety, efficiency and productivity. However, there are problems with automated systems. Automation may be very reliable in ideal circumstances, but the real world is far from ideal. First of all is the implementation of such systems in already existing mines, since it is no simple task to install and integrate WLAN transmitters, safety systems and control stations. Extra equipment also needs to be installed on the LHD machines that are going to be operated. It may also be necessary to hire specialized drivers or provide training for the regular workforce to control LHDs remotely. A large investment of money is needed for this. It is also very important that this procedure is done correctly in order to reap the benefits believing that a swift upgrade to an LHD will increase revenue will probably do the opposite [5].

Another obstacle for automated systems is the balance between steady operation and safety. Because of the emphasis put on safety for humans and machines, the automated system needs to carefully scan and record the surroundings when preparing a route, and if these parameters change, the machine may decide to halt automation. But since the circumstances in a mine might change suddenly, the consequence is that the system gets somewhat skittish, stopping as soon as it can’t recognize where it is exactly. Examples are protruding rocks, reinforcements and media from tunnel walls, in addition to the mere contents of the bucket, that the scanners and cameras pick up that the system interprets as obstructions, and thus the machine stops [5]. Fumes and dust is also common when loading and may have the same effect [5]. Gustafson et al.(2013) found that of all unscheduled stops, only 3% were attributed to problems with automation. 75% of all stops were caused by circumstances common to all types of loading, such as large boulders blocking the way. The most important aspect of these stops is that they’re rarely severe, and would be solvable if personnel were on site ready to fix them. But that defeats the main reason for implementing automation in the first place.
3.2.9 Solutions
The main solution for solving the problems with automation may be to have automation in mind already when designing a mine [6]. This is because automation has been proven to be very reliable as long as the environment is favorable. Automation is being continuously implemented in heavy industry [35], agriculture [36] and warehouse storage [37], and many of these places have been tailored to them. To increase the reliability of automated systems efforts should therefore be put towards making the mine environment as friendly as possible for automation [5]. Suppression of dust is important, as well as road maintenance [5]. The severity of halts in production could be decreased a lot by implementing self-diagnostics and remote troubleshooting, and also streamlining the reset procedure in case of a false perimeter breach [6][5]. This is because restarting automation is complicated and requires the operator to travel to the work zone in person to check the perimeter or deal with problems.

It is also important to know that completely uninterrupted operation of automated systems is very difficult, if not impossible. It is therefore important that companies do commit to the implementation of automation and invest enough capital and manpower for development. Automation systems is are not of the shelf products, and failing to realize that will generally cause the investment in automation to be wasted [1].

3.2.10 Productivity and Reliability
A big advocacy for automation is the reckoned increase in production and reduced maintenance it is to achieve. This is debatable however, since there has been very few studies of automation in real functional mines. Gustafson et al has published papers analyzing the productivity and maintenance of automated LHDs [3], the impact the mining environment has on automated LHDs [4] and the comparison between manual and automatic loading [4]. The results show that manual loading produced more tons per hour and that automated LHDs did have a greater proportion of production cycle times that were longer than 7 minutes [7]. This may have been due to the bucket being easier to fill manually. According to Paraszczak the production over a longer time span may be higher for automated loading however, although those numbers cannot be verified. This is a possibility though, since bucket filling seems to be easier when done manually, while automated tramming can be done faster. Utilization and the ratio between production and maintenance costs were the same for automated and manual loading [3].

When it comes to maintenance Gustafson et al (2013) showed that automated LHDs had a larger number of maintenance work orders, and that the systems in most need of maintenance differed between automatic and manual operation. For automation the engine and transmission needed most attention while for manual operation it was the chassis and cabin what were problematic. Therefore one may conclude that automated systems can handle navigation better as to not collide with drift walls and the like, but that correct choice and use of gears, in addition to rev count of the engine needs to be optimized.
4 The case study mine

4.1 Garpenberg
The Garpenberg mine is situated in Dalarna County in Sweden, close to Hedemora. Boliden Minerals has been the proprietor of the mine since 1957, but mining has been done at the site since the thirteenth century, making Garpenberg the oldest still operating mine in Sweden. At the beginning of production in 1957 around 300,000 tons of ore was mined each year [32].

Production continued for the rest of the twentieth century with mixed success, but at the end of the 1990s the mine very nearly closed due to bankruptcy. That changed however when four new orebodies were discovered, one of which, Lappberget, was the second largest in the company’s history [32]. This proved to be an excellent incentive for investment, and in 2011 a sum of 3.9 billion Swedish kronor were used for upgrading and expansion [33]. It was at this time that Berglaven, the skip system that today move all mined ore up from the deep was built, and also when the systems that today are used for automation was implemented [33].

4.2 Mining method
The mining method used is the open ended variant of sublevel stoping, which is well suited to the large, vertical and fairly homogeneous orebodies present in the mine. Loading is done directly from the stope using remote controlled LHDs.

The explosives used are two part emulsion bulk slurry, which is mixed on site and pumped into the production holes [34]. The two parts are inert when not mixed which make the handling much safer than older conventional explosives. Each salvo produces between 10,000 and 20,000 tons of crushed ore. Mining is currently done between 500 and 1200 meters below ground. The ore mined is a composite ore which contains lead, copper and zing as well as gold and silver [34].

Loading of ore is done by LHDs controlled remotely by an operator either within line of sight or from a control station. The ore is transported to crushing stations by trucks with a maximum capacity of 33 tons [34]. This service is provided by entrepreneurs who move both ore and waste rock. The crushers are situated on levels 700 and 1087 below the surface. Here the ore is broken into smaller pieces before it is loaded into the main skip that transports it to above ground level. The ore is put into short term storage in order to be refined into concentrate. Enough ore for approximately two days production can be held in storage [34]. The ore is refined on site via flotation. This refining method involves crushing the ore two additional times with water being added. The product of this is a slurry of water and finely mixed ore. The metal particles are then separated from the slurry, leaving behind tailings of mineral sand. The process is called flotation and works by adding certain chemicals to the slurry which adhere to the metal and makes the particles hydrophobic, meaning water repulsing [34]. Gas is then pumped through the vats containing the slurry, which causes the metal to cling to the gas bubbles which then carry it to the surface, practically making a metal infused froth, similar to that of beer, which is then scraped off. This froth can then be concentrated by moisture removal to produce concentrates of Zinc, Lead and Copper. The noble metals, Silver and Gold, are mainly found mixed in these three [34].
This is as far in the chain of refinement goes at the actual mine. The concentrate is shipped off to smelters in northern Sweden, Finland and Norway [34].

4.3 Automation in Garpenberg

The system in use at Garpenberg is Sandviks Automine light™. Automine lite is as its name implies a slimmed down, more flexible version of the Automine system. This flexibility makes it easy to set up new routes, or modify existing ones for the automated LHDs. There is a cost for this simplicity and flexibility, and that is that Automine lite lacks some of the more advanced features of other automatic systems, such as fleet automation [16]. Currently the machines are controlled from control stations at ground level and at depth 760 meters. A mobile station in the form of a van is also used. Filling of the bucket and dumping is done by remote control while traming is automatic. Each LHD is fitted with three IR capable cameras, which provide a view to the front and rear. A camera is also fitted on the boom that holds the bucket.

4.4 Shifts

The mine operates by a two shift system, visualized in figure 17:

![Shifts at the Garpenberg mine](image)

The dayshift starts at 06:00 and ends at 15:00, while the night shift starts at 18:00 and ends at 03:00. This leaves a gap of three hours between each shift when blasting and ventilation is performed. All personnel vacate the mine during blasting hours.
5 Identification of metrics

Based on the study of literature and personal observations, there are several different relevant aspects that can be quantized using metrics. The main ones are those connected to production and those connected to availability and reliability.

5.1 Time related metrics

5.1.1 Time percentage of operating modes

Fitting a LHD for automatic loading does not necessarily limit the machines capabilities for manual operation. Thus, many LHDs perform both tasks to some extent. In these cases it is vital to calculate a percentage of engine hours spent in these two modes in order to do any comparisons. If a significant difference (in production, availability, etc.) is found between two loaders, which correspond to a difference in time spent in the two modes of operation, this can be an indication of a connection between the two.

A comparison can also be made by studying the amount of engine hours spent in each mode of operation and the amount of downtime caused by each mode. By calculating the percentage that each mode contributes to the total time in regards to engine hours and downtime one may see if one mode is more prone to production stops than the other. If let’s say that automated loading contributes 30% of all time spent in action, and simultaneously contributes 50% of downtime, then automatic loading would be overrepresented when it comes to production stops. If Automatic and Manual loading were equally reliable, then the percentages for engine hours and downtime would be similar.

It is important to define what constitutes a significant result in regards to this metric. Because of the broad strokes approach to this, downtime was included regardless of what caused it. It also includes the natural variations in downtime. Due to this inaccuracy, a significant result requires for the difference of percentages to be large and consistent for all four LHDs. Downtime is analyzed in more detail in other metrics, where the cause of any significant result can be found.

The source of data for this metric was Gantt. For loading activities timestamps for start and end was reported, and so to find the time per activity the following calculation was made to find the total time:

\[
\text{End of loading activity} - \text{Beginning of loading activity} = \text{Time per loading activity}
\]
Time per loading activity was then summed for the entire year:

\[
\sum_{2015/01/01}^{2016/12/31} \text{Time per loading activity} = \text{Total engine hours during one year}
\]

This was performed for both operating modes separately and then plotted as percentages of the sum of both modes, as seen in figure 18 and 19 below.

For production stops the time spent out of action per production stop were reported, so these times were simply summed for the entire year.

\[
\sum_{2015/01/01}^{2016/12/31} \text{Downtime per production stop} = \text{Total downtime for one year}
\]

This was done for both automatic and manual loading in a similar manner as for engine hours.

Finally these were visualized in pie charts for all machines where time percentages could be compared.

### 5.1.2 Distribution of engine hours and downtime

In addition to studying the proportion of engine hours to downtime it is also important to know that there are some stops of production that are unique to one or the other mode of operation. It can therefore be important to visualize the relationship of mode specific stops to the total downtime, and also to the total engine hours. This gives a general overview of the differences between automatic and manual loading.

The procedure for producing this metric is similar to the previous one, with the addition of tagging and separating those stops that are specific to either manual or automatic loading. For automation these stops are those that pertain to the automated system software, and the specialized equipment onboard the LHDs and externally in
the mine. Examples of these are problems with recorded routes and wrongly tripped safety systems, problems with scanners and cameras on the LHD and problems with perimeter gates on the loading levels in the mine.

Stops specific to manual operation were those that hinder or make it impossible for an operator to control the LHD. These are things like problems with climate control and ventilation, malfunctioning control pads, and broken parts of the driver’s cabin, seat and controls inside the cabin such as steering, pedals etc.

For this metric the unspecified downtime, automation specific, manual specific and engine hours was plotted for each LHD, separated by mode of operation as seen in figure 20.

![Distribution engine hours/Downtime](image)

**Figure 20. Engine hours, downtime and mode specific downtime**

### 5.1.3 Distribution of loading activities during 24 hours

One of the strengths of automatic loading is that it can operate at times when manual loading is not possible, such as during blasting, lunch breaks or shift changes. Thus it is important to identify when the dips in manual production occur and compensate these with automation and tele operation. It can also be of interest to see how the relationship between modes of operation changes during the workday.

To investigate this it is necessary to visualize how loading activities shift during the workday. This can be done in the following way:

All the data is duplicated and moved down below the last entry in the same workbook, as seen in table 2, creating an activity list double the original length.
When a loading activity starts it is given a value of 1 which logged in a separate column in Excel and when a loading activity ends it is given a value of -1, which is logged in the same column as above but in the lower set of data.

Sort_time and Start_End is of vital importance when plotting the daily loading activities. As can be seen in the table above, it is the beginning time of the activity that is logged for the upper set of data, but the end time in the lower set. Equally so with Start_End, where the upper set is given a value of 1 and the lower set a value of -1.

By sorting the entire list by the Sort_time, from 06:00 onwards, one gets a continuous stream of loading activities beginning and ending.

The final step is to add two other columns designated Ack_auto and Ack_man, which continuously sums all the Sort_time values for manual and automatic loading separately, giving a moment to moment count of the number of loading activities.

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>RESOURCENAME</th>
<th>STARTTIME_org</th>
<th>ENDTIME_org</th>
<th>Sort_time</th>
<th>Start_End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic loading</td>
<td>Roger (517)</td>
<td>2015-01-02 06:00:00</td>
<td>2015-01-02 10:20:12</td>
<td>06:00:00</td>
<td>1</td>
</tr>
<tr>
<td>Automatic loading</td>
<td>Rudolf (517)</td>
<td>2015-01-02 06:03:45</td>
<td>2015-01-02 10:02:34</td>
<td>06:03:45</td>
<td>1</td>
</tr>
<tr>
<td>COPY BELOW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automatic loading</td>
<td>Roger (517)</td>
<td>2015-01-02 06:00:00</td>
<td>2015-01-02 10:20:12</td>
<td>10:20:12</td>
<td>-1</td>
</tr>
<tr>
<td>Automatic loading</td>
<td>Rudolf (517)</td>
<td>2015-01-02 06:03:45</td>
<td>2015-01-02 10:02:34</td>
<td>10:02:34</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 2. Excerpt of the Excel workbook used to analyze the distribution of activities.

The column titles in table 2 have the following meanings:

ACTIVITY: The mode of operation used during the loading activity.
RESOURCENAME: The ID of the loader that performed the loading activity, Roy, Roger, Rolf or Rudolf.
STARTTIME_org: The timestamp for the beginning of the loading activity.
ENDTIME_org: The timestamp for the end of the loading activity.

When plotting, Sort_time forms the x-axis, listing the time of day beginning at 06:00 in the morning, being the start of the day shift. Ack_auto and Ack_man forms the y_axis with the height of the curves being the number of loading activities at that specific time, See figure 21.
5.2 Production related metrics

5.2.1 Tonnage per hour
The most obvious comparison between automated and manual loading is the average tonnage loaded per unit time. This time unit can be varied to give production metrics for both short term and long term, which can be valuable when comparing manual and automatic loading. As Paraszczak et al. (2015) pointed out, the advantages of automatic loading may manifest only when looking at the long term production since manual loading may be able to load ore faster and easier, but automatic loading may be able to operate for a longer time. These two different concepts of a higher production during a shorter time available vs. lower production but more time available is definitely worth studying.

This metric was produced by dividing the total engine hours for one year with the yearly production in tons, in order to get tons per hour. The procedure for getting the total engine hours were the same as used previously:

\[
\text{End of loading activity} - \text{Beginning of loading activity} = \text{Time per loading activity}
\]

\[
\sum_{\text{2015 Jan 1 00:00:00}}^{\text{2016 Jan 1 00:00:00}} \text{Time per loading activity} = \text{Total engine hours during one year}
\]
Gantt has the tonnage loaded per activity, which could simply be summed for the whole year, and then be divided with the total engine time:

\[
\frac{\text{Total production for one year}}{\text{Total engine hours for one year}} = \text{Tonnage per hour}
\]

5.2.2 Tonnage and time per loading activity
In Garpenberg loading is divided into activities which consist of loading from a particular stope. These activities are reported with an amount of time and a tonnage which can give certain information about workflow and production. If there are discrepancies between time and tonnage, such as low tonnage with a large amount of time, that may indicate that the workflow is not optimized.

The procedure here is exactly the same as for tons per hour, but instead of dividing the tonnage with engine hours it is divided by the number of loading activities performed during one year.

\[
\frac{\text{Total production for one year}}{\text{Number of loading activities for one year}} = \text{Tonnage per loading activity}
\]

5.2.3 Fuel economy
With one of the reckoned benefits of automation being more careful driving of the LHDs, with better use of gears and rev count compared to manual operation, it may be of importance to compare the economic driving of LHDs between automatic and manual operation. One way to measure this is to look at fuel economy, since driving in low gear with high revs tend to have adverse effects on a vehicles fuel mileage. The concept of “eco drive” is popular then discussing car traffic on roads [38], and should be applicable to diesel driven LHDs as well.

Data for this metric was taken from Maximo. By simply summing the fuel consumption for one whole year for each machine and comparing this to the total amount of engine hours, separated by mode of operation for each machine, certain conclusions about the economic driving of the LHDs can be made.

5.3 Reliability related metrics
5.3.1 Availability
Availability is an important concept in reliability theory which is used to show a percentage of the time a machine is able to perform its purpose. It is calculated in the following way [39]:

\[
\text{Availability} = \frac{MTTF}{MTTF + MTTR}
\]
Where MTTF is the Mean Time To Fail and MTTR is the Mean Time To Repair [40]. These terms are most commonly associated with maintenance of repairable systems. In this thesis however they will be modified slightly too also accommodate the Mean Time Between Stops (MTBS) and Mean Time Between Boulder (MTBB). These modified terms will be used to calculate the availability in relationship to factors that may impact automatic and manual loading in different ways. For instance, fallen boulders are perceived as being harder to clear using tele operation than doing so manually on site. This may then be disproved if no difference in availability is found.

MTTF, MTBS and MTBB are calculated in an identical way. First the data is filtered so that it is relevant for a particular availability. For MTBS no filtering is done, as every type of stop is relevant. For MTTF only the stops that are attributed to breakdowns are included. For MTBB only stops due to fallen boulders are included. After filtering the data is sorted by the date they occurred, using the timestamps in Gantt that mark the beginning of downtime. In the explanations below the term “time between stops” refers to the way MTTF, MTBS and MTBB is calculated.

To get the time between stops a new column is added to display this, using the following formula.

\[
\text{Starttime of current stop} - \text{End time of previous stop} = \text{Time between stops}
\]

An average is then taken from this column to represent the mean time between stops. Gantt already includes the time out of action, so MTTR is simply the average of the sum of all these times.

Table 3 below shows as an example the availability when looking at all stops of production, which is then used to make column diagrams for all machines and modes of operation. The tables for MTTF and MTBB are similar to Table 3.

<table>
<thead>
<tr>
<th></th>
<th>MTBS</th>
<th>MTTR</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roy auto</td>
<td>113:26:41</td>
<td>6:53:58</td>
<td>94,27%</td>
</tr>
<tr>
<td>Roy man</td>
<td>41:42:41</td>
<td>4:32:22</td>
<td>90,19%</td>
</tr>
<tr>
<td>Roger auto</td>
<td>108:27:24</td>
<td>4:39:52</td>
<td>95,88%</td>
</tr>
<tr>
<td>Roger man</td>
<td>37:17:18</td>
<td>3:24:10</td>
<td>91,64%</td>
</tr>
<tr>
<td>Rolf auto</td>
<td>178:29:36</td>
<td>1:21:44</td>
<td>99,24%</td>
</tr>
<tr>
<td>Rolf man</td>
<td>47:19:31</td>
<td>1:03:33</td>
<td>97,81%</td>
</tr>
<tr>
<td>Rudolf auto</td>
<td>108:01:16</td>
<td>5:39:49</td>
<td>95,02%</td>
</tr>
<tr>
<td>Rudolf man</td>
<td>36:47:25</td>
<td>4:40:37</td>
<td>88,72%</td>
</tr>
</tbody>
</table>

Table 3. Table of availabilities, all stops.
5.3.2 Preventive and corrective maintenance

The two main ways of performing maintenance are Preventive maintenance (PM) and Corrective maintenance (CM) [39]. As the names imply, PM is done to prevent breakdowns by maintenance being scheduled on set times, and so attempts to repair or replace components before they break. While CM is done only after a breakdown has occurred. There are some advantages to both. PM can reduce the severity of breakdowns and also cut down on the wear and tear due to the fact that components in bad condition can in turn affect other components since they cannot perform optimally [40]. Preventive maintenance does however require a lot of time and manpower to perform, thus creating large costs. CM does not produce any costs up until a breakdown occurs, and may be the best option if there is an upper limit to the cost of spare parts for repairs [40].

It is generally accepted that PM is the optimum solution in most cases, and is definitely true when it comes to the underground mining industry [40]. A very difficult situation could arise if a vehicle weighting dozens of tons were stranded far from a workshop due to a severe breakdown, with blocked access creating congestion due to the limited space in underground tunnels. This is particularly true concerning tele operated and automatic vehicles, as the driver and other personnel are not present. The relationship between PM and CM could therefore be an important factor in comparing manual and automatic loading, as a big selling point of automated systems is the optimized use of equipment with reduced wear and tear as a result [19][27][26], something which the literature does not fully support [5].

Maximo contains data on both preventive and corrective maintenance jobs. Each job is given a tag and then the number of these jobs are summed and then displayed as percentages of PM and CM in relation to the total numbers of maintenance jobs, as seen in figure 22 below. It must be stressed that it is the number of maintenance jobs that is the basis for this metric, not the time spent performing maintenance. The reason for this is the lack of data, as no end times for maintenance jobs are reported in Maximo. This is explained further in chapters 7 and 8.

![Distribution PM/CM](image)

Figure 22. Distribution of PMCM
5.3.3 Analysis of production stops

Production stops can occur for a variety of reasons and can vary in severity. An analysis of the quantity and duration of different kinds of stops can be very valuable since it provides a lot of information which availability does not give. Quantifying both the number of stops and their duration can show how well halts of production are dealt with and which type is the most severe. It can also be used to give recommendations regarding improvements to the loading systems. If for instance a certain kind of breakdown is common and it takes a lot of time to fix, it is important to then try and minimize the occurrence of that stop or minimize its impact, while if production halts due to a stop which occur often but takes very little time to fix, it should not be given priority since its impact is comparatively small. This analysis also allow for a detailed comparison between automatic and manual loading.

Gantt has data on stops of production where the time of the incident and its duration is reported, in addition to info on what category of stop it was and commentaries about the stop. A lot of work had to be done to the data concerning stops of production. This was due to there being a plethora of different categories, sub categories and commentaries detailing different stops, and also it appear that during 2015 the reporting system was updated, thus there were two different set of categories in which stops were recorded. Then there were also the issue of reporting errors with the downtime being wrongly reported, resulting in production stops with timestamps of 00:00:00, which would signify a stop taking zero time to fix. Some stops also had large timestamps with no adequate reported cause, such as a miscellaneous stop accounting for a hundred hours of downtime.

To solve these problems and make analysis possible the following changes were done to the data:

- Elimination of zero values. All stops with timestamps of 00:00:00 were removed
- Elimination of stops with timestamps larger than 40 hours. After consulting Boliden, stops causing this much downtime was either deemed as reporting errors, or as irrelevant.
- Regrouping of production stops. Each stop was arranged into adjusted categories that were more general.

The adjusted categories were as follows:

- **Automation Software.** Problems pertaining to the automated system itself, such as problems with routes and tripping of laser gates.

- **Automation Hardware.** Problems pertaining to the equipment necessary for automation, such as broken cameras, scanners, laser gates and antennas.

- **Minor Breakdowns.** Breakdowns which do not hinder the LHD from doing its main function. Problems with cabin doors, driver’s seat, radio communication and malfunctioning sensors and measuring devises.
➢ **Mayor Breakdowns.** Problems with the mechanical essentials of the LHD which makes it incapable of driving, such as broken transmission, axels, electrical systems, engine and starter engines.

➢ **Blocked access.** General external circumstances in the mine that hinder the loading activities, such as maintenance- and construction work on the loading levels, falling boulders and suboptimal ventilation or watering of dust and lingering blasting fumes.

➢ **Daily inspection.** Regular controls and daily maintenance of the LHD.

➢ **Lacking media.** Missing or broken media support on the loading level, such as water, pressurized air, ventilation and electricity.

➢ **Loading.** Problems with the loading activity itself.

➢ **Oil and hydraulics.** Problems with severed hoses and leakage or shortage of oil.

➢ **Punctured tires.** Repair and replacement of flat tires.

➢ **Refueling.** Refueling of diesel and other fluids.

➢ **Organization.** Logistical problems, training of personnel and meetings.

➢ **Misc.** Miscellaneous stops not covered by other categories.

After sorting all production stops into adjusted categories, downtime and the number of occurrences of each type of stop were summed and plotted in a diagram for to make visualization and comparison easier.

It must be remembered that automatic loading constitutes a much smaller part of the total amount of engine hours compared to manual loading. This is shown in figure 23, where it is seen that automated loading takes up 21% of all engine hours.
To make a fair comparison possible, it is necessary to make the analysis as if the two operating modes had the same amount of engine hours. This is achieved by multiplying the time spent in manual mode by a certain fraction, so that the amount of time becomes equal for both manual and automated loading. This fraction is then applied to production stops as well, resulting in the amount of downtime being representative of the reduced time in action. The calculation is as follows:

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>Engine hours (EH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic</td>
<td>3109:24:06</td>
</tr>
<tr>
<td>Manual</td>
<td>11371:28:24</td>
</tr>
</tbody>
</table>

Table 4. Amount of engine hours for both operating modes

\[
\text{Manual EH} \times X = \text{Automatic EH}
\]

Solve for X:

\[
X = \frac{\text{Automatic EH}}{\text{Manual EH}}
\]

With values taken from table 4 above:

\[
\frac{3109:24:06}{11371:28:24} = 0.273438769 \approx 0.273
\]

As seen this fraction is 0.273 or 27.3%. By multiplying the downtime for manual loading with this ratio and then plotting it together with that for automatic loading, a fair comparison can be made.
6 Results

What follows are the results of the case study of the Garpenberg mine using the previously described metrics.

6.1 Time related metrics

6.1.1 Time percentage of operating modes

Figures 24, 26, 28 and 30 are pie charts that visualize the distribution of engine hours between manual and automatic loading. The red portion of each diagram shows the percentage of manual loading to the total time, while the blue portion indicates the percentage of automatic loading. Automatic loading constitutes 24% of total time for Roger (Figure 24), 29% for Roy (Figure 26), 17% for Rudolf (Figure 28) and 14% for Rolf (Figure 30).

Figures 25, 27, 29 and 31 show the distribution of downtime for manual and automatic loading. These are also pie charts, where manual loading is colored red and automatic loading is colored blue. In this case, automatic loading constitutes 28% of downtime for Roger (Figure 25), 20% for Roy (Figure 27), 17% for Rudolf (Figure 29) and 26% for Rolf.

Rudolf has a percentage of operating mode and downtime that is exactly the same while for Roger the difference is only 4%, which is well within the margin of error for this comparison. For Roy the percentage of total engine hours spent in automatic mode is 29% while the amount of downtime occurred during automatic loading is 20% of the total, thus there is a 9% underrepresentation for automatic loading and automatic downtime for that machine. For Rolf the opposite is true with automatic loading accounting for 14% of total engine ours but 26% of downtime, thus showing a 12% overrepresentation of automatic loading and downtime for that machine.

With two machines showing a very small difference between the percentages of downtime and engine hours, and two machines showing a difference of about 10% either way, there is no clear similarity between the four LHDs and thus there is no certain difference between automatic and manual loading in regards to the relationship of downtime and engine hours.
Figures 24-25. Distribution of engine hours

Figures 26-27. Distribution of engine hours

Figures 28-29. Distribution of engine hours
6.1.2 Distribution of engine hours and downtime

The distribution of time can be seen in figures 32-35, where engine hours, unspecified downtime, and mode specific downtime is collected in bar diagrams. Each diagram pertains to one LHD, where time is separated based on mode of operation, left for automatic, right for manual. The blue portion of each bar is the total amount of engine hours that a LHD has been active for during one year. The red portion is the total hours of unspecified downtime that has occurred during one year, while green and purple signifies downtime specific to automatic and manual loading respectively.

Manual loading constitutes between 2500 and 3250 hours, while time spent during automatic loading constitutes between 420 and 1095 hours. It is important to remember that Rolf has only been in action since the beginning of 2016, and thus only data up until September is included, resulting in less production time.

Stops specifically due to manual causes constitute a very small part of all downtime, although Roy had a larger amount than the other machines. The data shows that this was caused by two stops totaling 33 hours with the cause being lingering gas from blasting. Stops that were attributed to automatic operation make up a slightly larger proportion, and for Roy and Roger these are as large as 50% of all downtime. These stops were specific to the mode of operation, such as problems with cameras, gates, scanners and software for automatic loading and things like AC and problems with the cabin for manual loading. The vast majority of production stops were not specific to the mode of operation but to general circumstances in the mine, which collaborates with the results found by Gustafson et al.
Figure 32-33. Distribution of mode specific stops, downtime and engine hours

Figure 34-35. Distribution of mode specific stops, downtime and engine hours

6.1.3 Distribution of loading activities

Figure 36 shows the distribution of loading activities during 24 hours. The x-axis shows the time of day, starting at 06:00. The y-axis shows the number of concurrent loading jobs at every time during the day. The red curve signifies manual loading while blue signifies automatic. Manual loading peaks at around 1000 concurrent loading activities while for automatic loading this number is around 170. A gap can be seen during shift change, between 15:11 and 18:29. This is because no loading activities were reported during that time span.

As expected the results show dips during lunch breaks and a complete stop during shift changes. This is true for both manual and automatic loading. Although the dip is smaller for automatic loading, the amount of loading jobs is also much smaller, as figure 23 show that automatic loading accounts for 20% of the total amount of engine hours during 2015 (2016 in the case of Rolf).
6.2 Production related metrics

6.2.1 Tonnage loaded per hour and per activity
Figure 37 shows the raw tonnage loaded for each machine during one year. Each bar represents the production for one LHD and is divided into automatic loading, colored blue, and manual loading, colored red. As can be seen manual loading produced between 350,000 and 460,000 tons of ore while automatic loading produced between 40,000 and 120,000 tons.

Figures 38 and 39 show the mean production per hour and loading activity for each LHD, where manual and automatic loading is visualized in separate bars, with the blue bar being the tonnage for automatic loading and the red one being the mean tonnage for manual loading.

Table 5 shows the average total tonnage loaded manually and automatically, seen per hour and per loading activity. The highest mean production is colored green in the table. Table 6 shows the mean time for each loading activity for each LHD, both seen as a whole and separated for each mode of operation. Each activity lasts between three and four hours.

There are small but clear differences between the two modes of operation. Manual loading seemingly gets a higher hourly production on average while automatic loading gets higher tonnages per loading activity on average. When looking at the four LHDs separately, three out of four machines follow these results in each case. These results are consistent with the literature and the general view held that automated loading is not as efficient as of now compared to manual loading in the short term, but that more time can be used to load ore and that automation does compete in the long term.
Roy shows a mean hourly production that is 20 tons higher than manual loading, and a difference of almost 200 tons per loading activity. Table 6 supports this, as it shows that Roy has had the longest mean activity times.

![Total production for one year.](image)

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Mean tonnage per loading activity</th>
<th>Mean tonnage per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated loading</td>
<td>558</td>
<td>123</td>
</tr>
<tr>
<td>Manual loading</td>
<td>496</td>
<td>128</td>
</tr>
</tbody>
</table>

Table 5. Mean tonnages per hour and per loading activity.

![Production averages Tons per hour](image)

![Production averages Tons per activity](image)

Figure 38 mean tonnages per hour separated by machine.  
Figure 39 mean tonnages per activity separated by machine.
Table 6. Mean time per loading activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>Roger (517)</th>
<th>Roy (517)</th>
<th>Rudolf (517)</th>
<th>Rolf (517)</th>
<th>Grand Total</th>
</tr>
</thead>
</table>

6.2.2 Fuel economy

Figure 40 shows the fuel consumption for all machines in liters, irrespective of mode of operation. Fuel consumption varies between around 32,000 and 12,000 liters. Figure 41 shows the total engine hours for each machine. Each bar is divided with automatic loading being colored blue and manual loading being colored red.

In both figure 40 and 41 the LHDs are ordered in the same way from left to right: Roger, Roy, Rudolf and Rolf. This is to ease the comparison between engine hours and fuel consumption.

What is apparent is that Roy has not consumed nearly as much as Roger and Rudolf. This coincides with Roy having the largest percentage of automatic to manual operation, while at the same time having the second largest time spent in action as seen in Figure 41. There are many reasons for this difference in consumption however, since the layout of mining levels may vary and that fuel is not only expended then loading but when doing any other kind of task, like moving between levels or, indeed, driving to a workshop for repairs and maintenance.
Figure 40. Fuel consumption for each machine during one year.

Figure 41. Sum of engine hours for each machine.
6.3 Reliability related metrics

6.3.1 Preventive and corrective maintenance
Figure 42 shows the distribution of PM and CM for Roy, Roger and Rudolf, with the blue bar representing corrective maintenance and the red bar representing preventive maintenance. PM and CM is measured as percentages and can be read on the y-axis.

All machines have a PM of over 90%, with no clear connections between modes of operation. Rolf was excluded from this diagram because of massive deviations, where 100% of maintenance was CM. This was due to reporting errors combined with the reduced time in action garbling the data. It must be stressed that this metric was based on the number of maintenance jobs and not the total time these jobs took, as explained previously.

![Distribution PM/CM](image)

Figure 42. Distribution of preventive and corrective maintenance.

6.3.2 Availability
The following diagrams show modified availabilities of the LHDs to emphasize different causes for production stops. Figures 43-45 show availability in regards to All stops, Breakdowns and Boulders. In each case availability is shown as two bars for each LHD, with automatic loading being colored blue and manual loading being colored red. Availability is shown as a percentage and can be read on the y-axis.

The results are rather clear, as in regards to both all stops and breakdowns automated loading has a higher availability. There is an explanation for this thought, as automated loading makes up for a much smaller part of the total time in action as manual loading. Therefore it is natural that the availability creeps lower as time goes by. This can be seen in figure 45 where Rolf has a 100% availability. This means that during the first nine months 2015, no blocked access was caused by boulders. The other machines, having been active for longer, have lower availability.
Thus no significant differences can be seen regarding availability between automated and manual loading, since the biggest difference for any machine is still less than 10%.
6.3.3 Analysis of production stops

Figure 46 shows the downtime for each type of production stop for automatic and manual loading respectively. It is a direct comparison between operating modes, while figure 47 shows the weighted downtime with modified values. Production stops are separated into different categories where downtime is shown as two bars, blue for automatic loading and red for manual loading. Downtime is measured in hours, shown on the y-axis.

As can be seen, automated loading has a lower amount of downtime in all but three categories. Unfortunately this is countered by automated loading having essentially two whole categories of its own. Automation also had more downtime due to Organization. The very few reported stops due to automated software when performing manual loading is puzzling, since the automated system has nothing to do with manual operation. The cause for these is probably that the LHD made a transition between operating modes, and thus had to spend a few moments stationary. This standstill was then reported as a manual stop.

The three biggest categories differ depending on mode of operation, with manual stops falling largely into Blocked access, Minor breakdowns and Oil/Hydraulics. For automation the biggest category were instead Automaton Software, followed by Blocked access and Minor breakdowns.
Figures 48-55 visualizes two things. First they show the total downtime in hours for each machine and mode of operation in the form of a blue graph, and secondly they show the number of occurrences for each type of production stop, in the form of a red graph. The different categories of production stops can be seen along the x-axis. Since these diagrams contain two separate graphs, the y-axis also measures two different things. Seen on the left side of the diagram is the occurrence of stops while seen on the right is hours of downtime.

What can be clearly seen is the relationship between occurrence of stops and the downtime they cause. Some stops occur often but have little impact on production such as daily inspection and refueling, while others occur more seldom but have a bigger impact. Blocked access is such a stop that for some machines account for a disproportional amount of downtime.
For manual loading, the curve follows the columns in figure 47, with three distinct peaks marking the most common stops: Blocked access, Minor Breakdowns, oil and hydraulics. For automation the same can be said, although the distribution is less consistent between the machines. Still, Automation software, Blocked access and Minor breakdowns are the most common stops for automated loading.
6.4 Safety concerns

During the relevant timespan of this thesis, three safety incidents occurred in which a machine was either buried in a cave in ore was struck by boulders. Roy, Roger and Rudolf each had one incident each. Table 7 show the downtime caused.

<table>
<thead>
<tr>
<th></th>
<th>Downtime (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roy auto</td>
<td>1:19:00</td>
</tr>
<tr>
<td>Roger man</td>
<td>6:51:00</td>
</tr>
<tr>
<td>Rudolf man</td>
<td>23:52:00</td>
</tr>
</tbody>
</table>

Table 7. Downtime caused by rock falls/cave-in
7 Conclusions

7.1 Uncertainties and error sources
There are two main error sources to consider in this thesis, one being data manipulation, and the other being the sources of data.

7.1.1 Data manipulation
Human error is a risk when compiling and manipulating large amounts of data in excel, as values may be left behind or overwritten when data is copied, moved, and formatted. The functions used to calculate the metrics may also be erroneous, with the possibility of using the wrong data.

The vast difference in engine hours between automatic and manual loading may also skew the results, since this proportional difference must be included in every comparison. This weighting of data may be done wrongly, or fail to include hidden factors important to availability, downtime or production. Also analysis based on means can be uncertain, since different amounts of data may cause these to creep.

7.1.2 Uncertain sources of data
A mayor problem when producing the metrics was the uncertainty of the raw data procured from databases. There were numerous reported stops of production that showed a timestamp of 00:00:00, meaning that a stop produced no downtime, and also stops that contributed a large amount of downtime while not specifying the causes. Some of these could clearly be seen as erroneous but when the time values within certain categories of stops are more uniform, the issue of distinction is a big one. It also appears that during 2015, there was a change of reporting system, as a category named OLD was present, which used a different kind of reporting. Thus there may be differences to the kinds of stops present in the two systems, as well as categories that should have been compiled into a single one.

There was a discrepancy found between the two databases used in this thesis, Gantt and Maximo. Maximo records maintenance, and is the source used to produce the preemptive and corrective maintenance percentages (Figure 42). Gantt on the other hand was the basis for the diagrams showing the distribution of production stop causes (Figures 46-55). Both of these list breakdowns, their causes and the amount of downtime. They do not match however, as there are breakdown recorded in one but not the other. It was necessary to use them both as Maximo specified PM and CM, something that Gantt did not record.

7.2 Maintenance and reliability
Regarding reliability and downtime it is obvious that manual loading has had a lot more downtime than automatic loading since it constitutes around 80% of all engine hours, and thus about the same amount of downtime. Blocked access is the clearly the most common stop, which agrees with the results found by Gustafson et al. This fact remains even when a proportional comparison is made, although it is closely followed by automation problems. The validity of this proportional analysis, with downtime and occurrence being weighted by the different amounts of time spent in action during
the two operational modes, is strengthened by figures 48-55 where the data has not been weighted in this way but were the relationship between different kinds of stops is still roughly the same. Automated loading seems to be more reliable than manual loading when looking at stops not themselves caused by the automated system and equipment, but this higher reliability is countered by the automation specific problems causing a large amount of downtime by themselves. Mayor breakdowns were quite rare for all machines, while minor breakdowns and oil/hydraulics proved more common, being the largest categories after those attributed to the automated system and the mining environment. In all these categories automation had fewer production stops.

The relationship between PM and CM were consistent between machines and mode of operation with three out of four machines having a PM of more than 90%. Again, this is based on the number of maintenance jobs, not their duration. Therefore the percentages put forward may be skewed by the fact that the very few number of CM jobs may have taken a lot of time to fix, and by the same token, PM which include daily maintenance and other regular controls may have been performed very rapidly. With the lack of data this is however the best analysis available of PM and CM.

Regarding the different types of availability put forward in this thesis, for breakdowns and boulders it lays above 97% with very little difference between modes of operation. For all stops the availability is lower and the differences are greater, but still above 90% with less than 10% difference between automatic and manual loading. Automated loading had a higher availability than manual loading in all cases, but that is to be expected since, as stressed earlier, manual loading has spent a lot more time in action and has had a lot more time to accumulate stops, boulders and breakdowns. Therefore the differences between modes of operation are not significant enough to say that one is better than the other.

### 7.3 Production

The results agree with the literature in that manual loading had a higher tonnage produced per hour, but that automated loading produced more in the long run, since when looking at tonnage per activity automatic loading catches up to manual loading. All machines follow this pattern except for Roy, having a higher production both per hour and per loading activity. Roy also had the longest mean activity time and the largest amount of engine hours spent in automatic mode. Roy should therefore be studied more thoroughly to find out why it has worked so well.

With the production results being as they are, the further development of automation should focus on lengthening the time spent continuously loading and the mean time between stops to capitalize on this long term efficiency. The following thought experiment shows that three LHD could do the work of four if automation were more aggressively implemented:
Yearly production (Tons) | Sum of time per activity (days) | Mean tonnage per hour
---|---|---
Automated Loading | 313430,264 | 106,0950694 | 123

Manual loading | 1242778,808 | 404,3921875 | 128

Table 8. Thought experiment part one.

Tables 8 and 9 contain all the data needed to calculate how many LHDs it would take to load an amount of ore equal to the current yearly production. The mean tonnage per hour was calculated in the following way:

\[
\frac{\text{Yearly production (tons)}}{\frac{\text{Sum of time per activity (Days)}}{24}} = \text{Mean tonnage per hour}
\]

<table>
<thead>
<tr>
<th></th>
<th>Active hours per day</th>
<th>Tonnage loaded per day</th>
<th>Days to load total tonnage</th>
<th>Number of LHDs needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated Loading</td>
<td>22</td>
<td>2708</td>
<td>575</td>
<td>2,3</td>
</tr>
<tr>
<td>Manual loading</td>
<td>13,2</td>
<td>1690</td>
<td>921</td>
<td>3,7</td>
</tr>
</tbody>
</table>

Table 9. Thought experiment part two.

The active hours per day for automated loading were based on continuous operation using a rotating shift system of six, eight or twelve hours, with two hours per day set aside for inspection and refueling. For manual loading a two shift system was assumed with 3,3 hours of active loading time before and after lunch break, which add up to 4*3,3= 13,2 hours per day. Thus the tonnage per day is:

\[
\text{Mean tonnage per hour} \times \text{Active hours per day} = \text{Tonnage loaded per day}
\]

By dividing the total yearly production by this value, the number of days needed for one machine to load all the ore could be calculated. To find the number of LHDs needed to decrease this amount of time to one year, the following formula was used:

\[
\frac{\text{Days to load total tonnage}}{\frac{360}{0,7}} = \text{number of LHDs needed}
\]

The value 0,7 is the assumed availability for all machines during the year. By doing all these calculations the number of LHDs required to load one full year’s production is acquired.
As seen these are decimal numbers, and so must be rounded up to the nearest whole number. For manual loading this number is 4, which is the actual number of machines in use today at Garpenberg. The required number of machines for automated loading is 3, meaning that if this level of automation could be achieved one LHD could be retired entirely while still managing the same production.

The fuel consumption also showed one interesting result, that being that Roy having consumed a lot less fuel than both Roger and Rudolf, while at the same time having spent the most time in automatic mode. As mentioned earlier however, there is no guarantee that this has anything to do with automation.
8 Recommendations to Boliden Minerals

There are two kinds of recommendations that can be made about automated operations in the Garpenberg mine, production related and reporting related.

8.1 Production

In order to capitalize on the higher long term production of automated LHDs it would be important to increase the utilization and decrease unnecessary downtime, since it would be more reliable than manual loading if the impact of automation specific problems were lessened. The reason for the increased downtime of automated vehicles is stops due to the automated system itself. The results show that there were some problems with perimeter gates accidentally tripping or otherwise not working. Problems with automated routs were also common, with the system failing to recognize its surrounding and thus tripping the safety switch. These problems are mostly due to the automated system not being able to handle the environment, and thus, attention should be given to make the surroundings more suited to automation, or otherwise reducing the risk of stops due to false safety alerts.

In addition the results show that production stops are not more severe for automated vehicles, but that they take longer time to fix, the reason being that problems are more difficult to solve remotely and that the driver is not on site to fix them. This may be remedied by personnel being more readily available for troubleshooting below ground. To continue the thought experiment previously put forward, with LHDs being active for 22 hours a day and setting aside two hours for inspection and refueling, it might prove beneficial if the personnel tasked with this daily maintenance remained on standby on site to fix problems as soon as they occur. Also the resetting of the automated system after a shutdown needs to be streamlined with the introduction of remote troubleshooting. A more long term solution would be to continue the development of automated systems to better handle the environment, and also physically redesign the mining environment itself.

One of the strengths of automation and teleoperation is that it both decreases traveling time and allows for production to continue when manual operation is not possible. Automation should therefore be used to enhance manual loading by filling in when the driver is not on site. Figure 36 show that every dip in automated activities corresponds with a similar dip in manual activities, this being mainly during lunch breaks and shift changes. These are the times when automation should be utilized the most to compensate. If it is at all possible, automation should also be used in conjunction with manual operation to compensate for traveling and startup times, since a remote operator does not need to move underground to drive the LHD. This may of course be difficult to implement from a safety perspective, as no personnel are allowed inside the perimeter of an automatic vehicle, even though the automated system would not be active. Tight communication and strict safety would be necessary for something like this to work.
8.2 Reporting
As mentioned earlier there are uncertainties and errors in the data caused by errors of reporting or data simply missing. An interesting metric would have been the degree of bucket filled, in order to investigate how easy the bucket is to fill tele remotely and to find the average of tons per bucket hauled. This was however not possible due to a lack of data. There was also a lack of maintenance reporting, with no end times recorded for service or repairs, which made it impossible to calculate PM and CM from that data. Therefore the data used were the same as for diagrams 45-54, which does not specify if a breakdown could be repaired on site or if it needed to be fixed in a workshop. Improved reporting would thus be very valuable for future studies.
9 Further research

This thesis has provided a general outlook and investigation of mine automation and also provided metrics for comparing manual and automating operation of LHDs. It should be used as a guide to further research and each of the metrics should be studied in greater detail.

Although not used in this thesis, both the data on production and downtime do have a location reported, which would make it possible to study these metrics in conjuncture with individual levels. This is a great opportunity to study the impact that layouts and surroundings have on the reliability and efficiency of automatic systems.

The maintenance of automatic LHDs should be studied to see how mode of operation affects wear and tear, in addition to fuel economy.
10 References


(http://www.sciencedirect.com/science/article/pii/S1537511015301914)


