Dependability Assurance for Automatic Load Haul Dump Machines

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Picture on the front page is adapted from
Technical Specification Sandvik LH625E-05
The research work presented in this thesis has been carried out at the division of Operation, Maintenance and Acoustics at Luleå University of Technology. I have received generous support from a large number of persons, who in different ways have contributed to finalizing this thesis.

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Anna Gustafson

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Luleå, Sweden
Load Haul Dump (LHD) machines are used in underground mines to load and transport ore and minerals. Loading and hauling blasted ore from drawpoint to dumping point constitute a significant portion of the production costs for mining companies. There are a number of operation modes available for LHDs, and there are many criteria to consider when selecting the best one. The use of automated LHDs has been widely discussed due to the potential to increase productivity. The increasing focus on safety and ergonomics also gives an edge to automatically operated loaders over manually operated ones. Mine managers must decide when it is preferable to use manually operated loaders and when to complement or replace these with automatic ones. Automation focus has over the years gradually shifted from having automated fleets of vehicles to the more flexible solutions with semi-automatic LHDs gaining safety as one of the main goals. Several issues must be resolved to maximize the benefits of automation. One is to improve maintenance, and moving from operator-assisted “fail and fix” to planned maintenance. Since the operator is removed from the machine during automatic operation and maintenance staff is not always available on short notice, it is crucial to increase planned maintenance to maximize the investment in automation. Another issue is the complexity of the mining environment, including both the infrastructure and external disturbances like oversized boulders and road maintenance, as these can throw the entire investment in automation into question.

The purpose of this thesis is to explore the maintenance actions connected to automated LHDs as well as the factors influencing the dependability of the machine. Research methods include a literature review, interviews, and data collection and analysis. Real time process data, operation and maintenance data have been refined, integrated and aggregated to make a comparative analysis of manual and automatic LHDs.

The analysis show that 75% of the stop occasions causing idle time for LHDs relate to the operating environment, 21.5% pertain to machine related issues and 3.5% are related to the infrastructure of the automatic system installed in the mine. There is no difference in what kind of maintenance actions that are taken for manually and automatically operated LHDs, but there is a difference in what type of failures that occurs more frequently for the different operation modes. For automation of LHDs too much unplanned repairs and maintenance
work significantly reduces the overall availability and can jeopardize the entire investment in automation. The difference between the semi-automatic and the manual LHD was found to be very small in terms of maintenance cost versus produced number of tons. However, a semi-automated LHD is an optimal machine regarding the ability to adapt to reconfiguring the operation mode to meet demands such as safety, flexibility and productivity.

**Keywords:** Underground Mining Industry; LHD; Automation; Operating Environment; Dependability; Fault Tree Analysis; Functional Safety; Reliability Centred Maintenance; Total Productive Maintenance; Maintenance Performance Measurement; Key Performance Indicators; Data Integration
LIST OF APPENDED PAPERS

Paper I

Paper II

Paper III

Paper IV

Paper V
# CONTENTS

1 INTRODUCTION ................................................................................................................................................. 1

1.1 STATEMENT OF THE PROBLEM ....................................................................................................................... 3

1.2 PURPOSE AND OBJECTIVE .......................................................................................................................... 3

1.3 SCOPE AND LIMITATIONS .......................................................................................................................... 4

1.4 RESEARCH QUESTIONS ..................................................................................................................................... 4

2 LOAD HAUL DUMP MACHINES ........................................................................................................................................... 7

2.1 FROM MANUAL TO AUTOMATIC OPERATION OF LHDS ............................................................................. 8

2.1.1 Past experiences with LHD automation ....................................................................................................... 11

2.2 MAINTENANCE OF UNDERGROUND MINING EQUIPMENT ..................................................................... 13

2.2.1 Maintenance experiences of manual LHDs ............................................................................................. 14

2.2.2 Maintenance experiences of automated LHDs .......................................................................................... 15

2.3 FACTORS INFLUENCING LHD AUTOMATION ............................................................................................. 16

3 RESEARCH METHODS ......................................................................................................................................... 19

3.1 LITERATURE REVIEW ........................................................................................................................................... 20

3.2 INTERVIEWS ...................................................................................................................................................... 20

3.3 DATA COLLECTION AND ANALYSIS ............................................................................................................ 20

3.3.1 Wolis system ................................................................................................................................................ 23

3.4 MAINTENANCE PHILOSOPHIES ....................................................................................................................... 25

3.4.1 Reliability Centred Maintenance (RCM) ................................................................................................. 25

3.4.2 Total Productive Maintenance (TPM) ....................................................................................................... 26

3.4.3 Functional Safety Analysis (FSA) ............................................................................................................... 26

3.4.4 Maintenance Performance Measurement (MPM) ..................................................................................... 29

4 RESULTS AND DISCUSSION ....................................................................................................... ......................... 31

4.1 MAINTENANCE PROCEDURES ....................................................................................................................... 31

4.2 DATA ANALYSIS ............................................................................................................................................... 33

4.3 PERFORMANCE ANALYSIS .......................................................................................................................... 35

4.3.1 Production performance ............................................................................................................................... 35

4.3.2 Maintenance performance ............................................................................................................................ 36

4.3.3 Fusion of Maintenance and Productivity KPI’s ....................................................................................... 39

4.4 FACTORS INFLUENCING THE IDLE TIME FOR LHDS ................................................................................. 39

5 CONCLUSIONS ...................................................................................................................................................... 41

6 FUTURE RESEARCH ............................................................................................................................................. 43

7 REFERENCES .......................................................................................................................................................... 45
1 INTRODUCTION

Loading and hauling blasted ore from drawpoint to dumping point constitute a significant portion of production costs for mining companies. This work is commonly done by Load Haul Dump (LHD) machines in underground mines. With the increasing complexity and degree of automation of today’s equipment, capital costs have steeply increased. Therefore, a cost-effective operation of equipment is essential. This has pushed manufacturers and users to decrease the cost of energy and maintenance by taking measures towards improvement of reliability, availability, and productivity of LHDs. The use of automated LHDs has been highlighted for a number of years, given its potential to increase productivity. Whether to continue to use manually operated loaders or to complement or replace these with automatic ones is a difficult decision for mine management. A detailed review is necessary to make an informed decision. The increasing focus on safety and ergonomics gives an edge to automatically operated loaders over manually operated ones. But in order to gain from the investment, it is crucial to increase the amount of preventive maintenance, since the operator is no longer there to perform maintenance or take the vehicle to the workshop. Important performance indicators (PI) and key performance indicators (KPI) to consider when making the decision are availability, reliability, productivity, and maintenance cost. In this thesis, real time process data and maintenance data from an underground mine have been refined and aggregated into KPIs to evaluate the benefits and drawbacks of manual and automatic LHDs.

Automatic Load Haul Dump (LHD) machines are used in mines to improve productivity and to increase the security of the mine’s personnel. With an automatic system, the operator can be taken out of the mine and simultaneously control up to three LHDs (fleet automation), with the possibility of increasing both productivity and security. As Poole et al. (1998) point out, when it is used in day-to-day operations, the automated process offers flexibility and convenience for the operators. In addition, the resulting health and safety benefits will lead to the long term wellbeing of the operators. There will also be manpower savings with less travelling time and the possibility of using one operator for multiple machines. Other advantages of automation include process consistency and the ability to counter labour shortages (Chadwick 2010). According to Parreira et al. (2009) the main
Objective of automation is to imitate the maximum physical and intellectual human capacity to improve productivity through increased accuracy.

Many issues and challenges, e.g. productivity, cost, reliability and availability, along with human factors and safety, come to the fore in discussions of automatically operated loaders. Woof (2005) has suggested that automatic tramming will result in reduced machine downtime over time. The benefit of lower costs for maintenance and spares comes from less wear and tear on drivelines, no overheated engines, optimized gear shifting and extended tyre life. There will also be less bucket spillage and collisions with the walls in automated tramming. Improved service life and reduced maintenance and tyre costs (Golosinski 2000) as well as increased life for tires (Dyson 2008) are other benefits deriving from the automation of LHDs. While there are many benefits of automation, the mining industry is a very complex operation, making it very difficult to implement full-scale automation. Disturbances like oversized boulders, road maintenance, lack of ore, full ore passes etc. make the automated system extremely sensitive; these issues must be taken care of to maximize the benefits of automation.

Dependability (Figure 1) is “the collective term used to describe the availability and its influencing factors: reliability, maintainability and maintenance supportability” (CEN 13306:2010). Dependability is not a numerical indicator but an umbrella term used to describe Availability, Reliability (measured with MTBF), Maintainability (measured with MTTR) and Maintenance Supportability (measured with Mean Waiting Time (MWT)). In this thesis, the concept of dependability is used as a term for the assurance and fulfilment of the included factors.

![Dependability Diagram](image-url)
The success of the LHD system is determined by performance attributes such as capability, safety, risk, quality, etc. (IEC TC56 2009). Dependability is a characteristic that defines how well these performance attributes can be achieved. The dependability and performance attributes can be visualized in different ways depending on which specific situation is described (see example in Figure 2).

Figure 2 Example of the application of dependability in a specific situation (Adapted from IEC TC56 2009)

1.1 STATEMENT OF THE PROBLEM

The complexity of the controlled mining environment and the infrastructure needed for automation are important issues to consider when optimizing the operation. The traditional navigation techniques require a lot of infrastructure to accommodate automatic operation. From fully automated fleets of vehicles, the focus of automation has gradually widened to include more flexible solutions, such as semi-automatic LHDs, with safety a main goal. In semi-automatic LHDs, the tramming and dumping are done autonomously but the loading is performed through remote control by the operator. Several issues must be resolved to maximize the benefits of automation. One is to improve maintenance strategy, especially preventive maintenance, as it is crucial for an operation to avoid the waste incurred by unplanned breakdowns. Another issue is the complexity of the mining environment; external disturbances can throw the entire investment in automation into question.

1.2 PURPOSE AND OBJECTIVE

The purpose of this thesis is to explore the maintenance actions connected to automated LHDs as well as the factors influencing the dependability of the machine. The objectives of this thesis are, more specifically, to:

- Study the dependability of LHDs with special attention to autonomous operation
- Study the production capacity of autonomously operated LHDs compared to manually operated LHDs
- Identify the external disturbances affecting the automatic operation of LHDs
1.3 SCOPE AND LIMITATIONS
The scope of this research is to study the maintenance of, and experiences with, automatically operated LHDs in underground mining. This thesis is based on manually entered data from the maintenance process and automatically produced production data; these have very different qualities.

This thesis has two main limitations. Firstly, the technical aspects of the navigation systems are not evaluated or analysed, as separate research is required. Secondly, the reliability of human beings is an important area to consider but is beyond the scope of this thesis.

1.4 RESEARCH QUESTIONS
To fulfil the purpose of the thesis and the objectives of the research, the following research questions (RQ) have been formulated:
1. How do Reliability, Maintainability and Maintenance Supportability affect the Dependability of automatic LHDs?
2. What maintenance actions are associated with automatically and manually operated LHDs?
3. What factors influence the productivity and idle time of LHDs?
4. How can the performance of automatic LHDs be evaluated and justified?

Table 1 shows the relationship between the appended papers and research questions. RQ 1 is discussed in Paper III-V. RQ 2 is answered in Papers I-V. RQ 3 is explored in Paper V, and RQ 4 is discussed in Papers III and IV.

Table 1 Relationship between the appended papers and research questions

<table>
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</tr>
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<tbody>
<tr>
<td>RQ 1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>RQ 2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RQ 3</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>RQ 4</td>
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<td>X</td>
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</table>

The research framework appears in Figure 3. Paper I introduces automated LHDs and summarizes the literature review. The paper also deals with past experiences of LHD automation, advantages and disadvantages of LHD automation and maintenance experiences. Paper II presents a case study describing the maintenance work performed on LHD machines in a Swedish underground mine. The concept of Total Productive Maintenance is used to include human aspects. Paper III uses the concept of Functional safety to analyse the performance of LHDs for the optimization of reliability, maintainability, availability and safety parameters. Papers III and IV discuss data
acquisition. Paper IV evaluates and compares production performance and maintenance performance resulting in the fusion of these indicators. The problem of external disturbances is mentioned in Papers III and IV; Paper V goes on to explain the disturbances causing idle time for LHDs and to show how this affects automatic operation.
An underground mining operation consists of several areas of operation as shown in Figure 4. The focus in this thesis is the first part of the operation where the ore and minerals are loaded from the tunnel or from a draw point by LHD machines and normally dumped into ore passes. The information on LHDs expressed in this chapter is general.

LHDs (Figure 5) are usually 8 to 15 meters long; they weigh 20 to 75 tons, and they run on electrical or diesel power. They generally operate in an often hot, dusty and wet environment at a relatively low speed of about 10-20 km/h.
Each LHD consists of two parts connected by an articulation point which gives them a high level of manoeuvrability in narrow mine drifts. Each section of the unit has a set of non-steerable rubber wheels. The back of the machine contains the engine, and the front contains the bucket. The bucket, the steering and the brakes are hydraulically operated (Larsson 2007).

2.1 FROM MANUAL TO AUTOMATIC OPERATION OF LHDs

Several operation modes and combinations are available for LHD machines, e.g.:

- Manual operation
- Line of sight remote operation
- Tele-remote operation
- Semi-automated operation
- Automatic operation

There are both advantages and disadvantages with the different operation modes and choosing the optimal mode is difficult. Since the machines are operating in a harsh environment, there are several issues that affect the decision. Besides the machine and personnel related issues there are mining related issues like fragmentation, oversized boulders, road conditions, ventilation etc. that must be considered when optimizing the operation.

Currently, manually operated LHDs (Figure 6) are commonly used to move ore in an underground mine. The operator remains in the cabin on the side of the vehicle throughout the load-haul-dump cycle. The side position of the cabin makes it possible for the operator to have a clear line of vision when the vehicle is moving forward or backward.

![Figure 6 Manually operated LHD working in an underground mine (courtesy of Sandvik)](image)
Because remote control offers limited sensory perception (Roberts et al. 2000), manual operation is faster than both remote control and tele-remote control. The disadvantages of manual operation include lack of safety, driver fatigue and basic human errors (Roberts et al. 2000).

An initial stage of automation is to operate the LHD by remote control while keeping it in sight. This technique is common practice in unsupported areas. An operator drives the vehicle manually to the brow (entrance) and then dismounts to drive it into the stope by radio remote control. At all times, the operator is close by and can see the LHD. Once the bucket is loaded and the vehicle is removed from the unsecured area, the operator climbs back onto the machine to manually drive it to the dump point. The procedure is slow because of the constant switching between manual and remote operation. It is also unproductive, as the operator’s limited view of the loading operation makes the bucket filling more difficult. And most important, it is not safe since the operator remains close to the unsupported ground (Figure 7).

![Figure 7 Line of sight operation (courtesy of Sandvik)](image)

Tele-remote operation is the next step in automation and is slowly gaining acceptance in the mining industry. Here, video cameras are installed on the LHDs to provide the remote operator with clear views forward and backward. The LHD is remotely operated during the complete LHD load/dump cycle by an operator who can be located in a safe and comfortable environment far from the vehicle. With this technique, the operator can only operate one vehicle at a time. The view is not always clear, as shown in Figure 8, and it can sometimes be difficult for the operator to manoeuvre the machine. Because of the limited sensory perception when operators run the machines remotely, the speed of the vehicles is lower, resulting in decreased productivity. Although the tele-remote operation has led to improved safety, costs have increased because of additional expenses for the required infrastructure (Dragt et al. 2005).
The next step in LHD automation is to allow the vehicle to drive automatically. Operators are still required to monitor vehicles and are still involved when filling the bucket, but they can operate one or several vehicles simultaneously from a safe environment. The operator’s station can be located either outside the mine or inside the mine in a van or office. Since such vehicles will faithfully follow programmed instructions, management can control the performance of the vehicle and also influence its wear and tear. In a fully autonomous system, the tramming and dumping as well as the loading of the bucket would be automated. However, bucket filling is very difficult for autonomous loaders due to, for example, fragmentation. Dasys et al. (1994) have developed a relatively simple algorithm using “off the shelf” sensors to fill the bucket automatically. Other approaches have been attempted but so far none has been applied to real production. In this thesis, when discussing automation, it is always the tramming and dumping that is automated while loading is done remotely by the operator.

Another possibility for operating the LHDs is using a semi-automatic system which opens up the possibility for other applications where mobility is required, such as open stop mining and transfer level applications. The semi-automatic LHD can be used in the same way as the fully automatic one, but it can also be manually operated when operation in automatic mode is difficult or impossible. The automatic system used for semi-automation is different than the fully automated system; less infrastructure is needed, and the operator can only control one vehicle. The LHD has to be taught the route between the load and dump points when entering a new production area (Chadwick 2010). Since these systems are more flexible than the fully automatic solution, the operator’s station is usually underground in a van or office.

For LHDs, automation involves the following variables: laser equipment on-board the LHDs, data processing features, broadband communications, sensors etc. The navigation techniques used for the underground LHDs differ slightly between systems but have the same purpose.
2.1.1 Past experiences with LHD automation

As shown above, mining companies generally use theautomatic system for tramming and unloading the bucket in combination with tele-remote control for loading the buckets (Dyson 2008). Several mines are presently using automatic LHDs; others have previously tested automatic systems but have ceased for different reasons. Figure 9 and Table 2 show these mines and their status with respect to the use of automatic LHDs and trucks. All mines that have been testing/using automatic LHDs have also been using conventional LHDs, either in a different section of the mine or in the same section.

Figure 9 Mines using or that have been using automated LHDs (Gustafson 2011)
Table 2: Overview of mines using automated LHDs (Gustafson 2011)

<table>
<thead>
<tr>
<th>Company</th>
<th>Mine</th>
<th>Country</th>
<th>Using</th>
<th>Manufacturer</th>
<th>Automatic system</th>
<th>LHD/Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teck Cominco and Barrick Gold</td>
<td>Williams mine</td>
<td>Canada</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>Truck</td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>Olympic Dam mine</td>
<td>Australia</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM</td>
<td>LHD</td>
</tr>
<tr>
<td>Boliden Mineral AB</td>
<td>Garpenberg</td>
<td>Sweden</td>
<td>Presently, starting up phase</td>
<td>Sandvik</td>
<td>AutoMine Lite</td>
<td>LHD</td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Diablo regimiento</td>
<td>Chile</td>
<td>Not currently in use</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>LHD</td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Pia Norte</td>
<td>Chile</td>
<td>Not currently in use</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>LHD</td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Pilar Norte</td>
<td>Chile</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>LHD</td>
</tr>
<tr>
<td>DeBeers Consolidated mines</td>
<td>Finsch mine</td>
<td>South Africa</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>Truck and previously one LHD</td>
</tr>
<tr>
<td>VALE INCO Limited</td>
<td>Stobi mine</td>
<td>Canada</td>
<td>Stopped 2005/2006</td>
<td>Wagner</td>
<td>Light wire guidance system LHD and truck</td>
<td></td>
</tr>
<tr>
<td>VALE INCO Limited</td>
<td>Creighton mine</td>
<td>Canada</td>
<td>Stopped approx. 2003</td>
<td>Light wire guidance system</td>
<td>LHD</td>
<td></td>
</tr>
<tr>
<td>Inmet</td>
<td>Pyhäsalmi mine</td>
<td>Finland</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine Lite</td>
<td>LHD</td>
</tr>
<tr>
<td>LKAB</td>
<td>Kirunavaara mine</td>
<td>Sweden</td>
<td>On and off from the 1980s, have recently installed one semi-automatic LHD</td>
<td>Sandvik</td>
<td>SALF4, AutoMine Lite</td>
<td>LHD</td>
</tr>
<tr>
<td>LKAB</td>
<td>Malmberget mine</td>
<td>Sweden</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM</td>
<td>LHD</td>
</tr>
<tr>
<td>Newmont Mining Corporation</td>
<td>Jundee mine</td>
<td>Australia</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM</td>
<td>LHD</td>
</tr>
<tr>
<td>XSTRATA</td>
<td>Brunswick division</td>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northgate Minerals Corporation</td>
<td>Stawell gold mine</td>
<td>Australia</td>
<td></td>
<td>Caterpillar</td>
<td>MINEGEM</td>
<td>LHD</td>
</tr>
<tr>
<td>Rio Tinto</td>
<td>Northparkes mines</td>
<td>Australia</td>
<td>Not in use, only tests</td>
<td>Caterpillar</td>
<td>MINEGEM</td>
<td>LHD</td>
</tr>
<tr>
<td>Rio Tinto</td>
<td>Diavik mine</td>
<td>Canada</td>
<td>Was used in 2010. Presently stopped due to going underground</td>
<td>Atlas Copco</td>
<td>Scooptram automation</td>
<td>LHD</td>
</tr>
<tr>
<td>Lappland Goldminers AB</td>
<td>Zinkgruvan</td>
<td>Sweden</td>
<td>1989-1990</td>
<td>GIHI</td>
<td>Painted lines on ceiling</td>
<td>LHD</td>
</tr>
<tr>
<td>XSTRATA</td>
<td>Mt Isa Mines Ltd</td>
<td>Australia</td>
<td>Project on hold</td>
<td>Sandvik</td>
<td>AutoMine</td>
<td>LHD</td>
</tr>
</tbody>
</table>
2.2 MAINTENANCE OF UNDERGROUND MINING EQUIPMENT

Maintenance is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform its required function (CEN 13 306:2010). According to CEN 13 306 (2010) standards, maintenance activities can be sorted into two major groups; Preventive Maintenance (PM) and Corrective Maintenance (CM) (Figure 10). CM is a reactive form of maintenance in which actions are taken after failure has occurred. PM is proactive, meaning that measures are taken to prevent failures from occurring. In the mining industry, it has been shown (Paper IV) that preventive maintenance constitutes about 90% of the maintenance work. Since CM is more costly than PM due to both production losses as well as quality losses, it is economically advisable to reduce CM.

![Figure 10 Maintenance overview chart (CEN 13 306:2010)]

Poor machine reliability in the design phase and human factors influence the occurrence of failures more than any other factors (Kumar 1990). It is further being described by the author that the failure characteristics of the equipment are influenced by e.g. the designed reliability. More failures are expected if a component or system has poor designed reliability. Mean time to failure (MTTF) is a simple measure of the arrival rate of failure. All failures have a cause and an effect; thus, after being identified, flaws can either be designed out or accommodated, thereby increasing the maintainability (Kumar 1990). Reducing the number of unscheduled breakdowns as well as reducing the repair time is important to improve equipment availability (Knights 2001).

Maintenance of underground mobile mining equipment is a challenge that involves several areas e.g. harsh environment, potential risks and distant location of workshops. The fact that the operative environment is very harsh makes it even more difficult to handle maintenance. When a machine breaks down, there are two ways to handle the repair. Either the equipment
has to be repaired on site at the production area or taken to the workshop. The difficulties involved in moving this type of large equipment are substantial but it might be difficult or unsafe to repair the LHD on site (depending on where and why it fails). The workshops and facilities are located outside the production area; this is a major constraint in the transportation of large equipment to the workshop. The maintenance issues were stretched by Vagenas (1990) when modeling the traffic control of the automated LHDs. Earlier machine breakdowns had not been taken into consideration during the modeling of traffic control. Vagenas suggested that simple maintenance policies should be taken into account whenever a breakdown occurs.

2.2.1 Maintenance experiences of manual LHDs

In a case study (Carter 2007) it was found that failures occurred in a LHD axle much sooner than expected, considering the number of operating hours. The results showed no component defects or deficiency but indicated that the failures corresponded to the use of a lubricant not suited for the climate. The expected life of both overhauled and new axles was met when the lubricants were changed.

Vayenas and Xiangxi (2009) performed a study in a large block cave operation in Palaboura mine in Chile in which they investigated the availability of 13 LHDs. They used both a basic maintenance approach and a reliability-based approach to determine fleet availability. They noted that problems with inaccurate and incomplete data affected their analysis. The focus in the mine is on maintenance and the improvements in production that can be achieved with good maintenance. Because an LHD breakdown disrupts the whole production chain, a good maintenance philosophy is essential (Chadwick 2008). Therefore, all machines have a 90 minute stop every day when everything is fixed. Even the most trivial fault is taken care of since it could develop into a major problem if not fixed directly. Operators are assigned to specific machines, which also have improved the performance (Chadwick 2008).

In a case study (Hall et al. 2000) in a gold mine in Chile, failure data for a manually operated LHD fleet were analyzed to see if condition based maintenance could save money in reduced corrective maintenance. Eleven scoops were involved in the study. With respect to the relationship between the number of failures and downtime, the results indicate only a very small difference in repair time regardless of what has failed. The study expected to find that critical systems were responsible for a significant amount of downtime, but this was not the case. The relationship between number of failures and downtime was almost linear. Failure data showed that hydraulics, cylinders, oil leaks and valves were the primary causes of downtime. The study concludes that lack of spares and labour influence repair time. During data retrieval, problems with lack of data were experienced and also data that were not recorded properly, like time between failures (TBF) (Hall et al. 2003). Hall et al. (2003) point out that because much of a mine’s equipment is mobile or semi-mobile it is difficult to formulate an effective maintenance strategy. Some factors influencing the maintenance costs of mobile equipment are:
• Increased number of failures due to disassembling and reassembling mobile equipment.

• Failures of mobile equipment in remote locations, making maintenance costly and difficult.

• Difficulties using condition-based maintenance on mobile equipment.

Other issues include the dynamic operating environment and the physical environment. In addition, there are problems due to operator practices, varying production demand and changes within the ore characteristics. It was also concluded that useful data can be obtained from system sensors on mobile equipment, from operator interfaces and from operation and maintenance (Hall et al. 2003).

2.2.2 Maintenance experiences of automated LHDs

In the late 1980s, LKAB, Kiruna, performed a reliability investigation on a fleet of LHDs (Kumar et al. 1989). Failure data from 19 LHDs were collected for a period of one year and analyzed, but because data were extensive, only the time between successive failures (TBF) for three machines was considered. The three machines studied were selected because of their age: neither new nor too old. In order to analyse the TBFs, the LHD was divided into the following subsystems: engine, brakes, hydraulics and transmission. From a reliability point of view, the two most critical subsystems were found to be hydraulics and engines. When a machine was stopped for routine maintenance, the TBFs for these stops were treated as censored failures. Investigators concluded that the overall maintenance cost could be reduced through preventive maintenance of the engines. The TBFs of the hydraulic system were evaluated in a second study (Kumar and Klefsjö 1989), using data from two years of operation. At this time, old, medium old and new machines were studied (two of each). Results indicated that in most cases, the TBFs were neither independent nor identically distributed. The study suggested an optimal maintenance policy for the studied LHDs. Another study indicated that the tire life was longer for an automatic LHD but bucket cost, fuel consumption per tonne of ore produced, oil and lubricant costs were about the same as for manual LHDs (Schweinkart and Soikelli 2004).

Woof (2009) states that automatic machines require less maintenance and have lower running costs because gears are changed at optimum times, and engines are not over-revved. As reliability and safety requirements are high, it is essential for an automatic system to have a robust self-diagnostic fault detection and fail-safe mechanism in place. However, due to maintenance issues, INCO (Stobie mine and Creighton mine) could not foresee having an entirely unmanned mine. Mining equipment is not very reliable, and the mean time between failures on components needs to improve before there can be less corrective interaction with the equipment (DeGaspari 2003).

Poole et al. (1998) describe how a RoboScoop W was modified so it could be autonomously operated at Stobie Mine. Since the intent was to reduce the need for the operator’s presence, various applications were added to increase the time between daily maintenance/service, such for example an auto lubrication system. Since the machine was not dependent on the
operator’s working hours, a “shift” for the machine could be based on either maintenance or service intervals.

In El Teniente’s Pipa Norte mine, the LHDs only leave the production area when there is planned maintenance or a major breakdown. Refuelling and lubrication are scheduled by the AutoMine system and are carried out in a specific station where the LHD is taken by the maintenance personnel. Daily maintenance functions are performed while the machine is being serviced. The availability of the fleet is based on planned downtime hours (for scheduled maintenance services), and unplanned downtime hours (for unscheduled repairs or breakdowns). The unplanned downtime in an automatic operation is difficult to estimate but the total downtime is believed to be about the same for the automated and manual machines. It is also believed that with condition monitoring, at least 15% of the potential failures can be identified and taken care of during planned downtime. The automatic tramming is believed to result in reduced machine downtime over time. The costs for maintenance and spares shall be lower because there is less wear and tear on drivelines and no overheated engines, optimized gear shifting and extended tire life. With automated tramming, there will also be less bucket spillage and fewer collisions with the walls (Woof 2005). The number of full-time workers is estimated to be the same whether the fleet is autonomous or manually operated, although the required technical skill level is higher for an autonomous fleet. The automated system at the El Teniente mine also requires more, highly trained service personnel.

The production trial (McHugh 2004) at the 42 Orange 20 Stope (ODO) noted that the underground maintenance crew did the re-fuelling at mid-shift according to the maintenance schedule. During re-fuelling, road maintenance was taken care of, and during service time, the lasers were cleaned with a rag.

2.3 FACTORS INFLUENCING LHD AUTOMATION

It is both costly and challenging to properly maintain mining equipment. Factors like complexity, size, competition, cost and safety continue to challenge maintenance engineers despite recent progress in maintaining equipment in the field. The issue has been further complicated by increased mechanization and automation (Kumar 1996). The maintenance costs of a typical mining company account for 30-65% of the total mine operation cost (Cutifani et al. 1996). Therefore, mining companies are focusing on optimizing preventive maintenance, reducing manpower, deferring non-essential maintenance, establishing more efficient spare part control. Good maintenance strategies are essential to optimize the maintenance of mobile mining equipment.

Automation of LHDs has been a reality for more than 20 years, but even so, the concept has not yet fully succeeded. Over the years, many mines have tried different navigation systems with different results. Automatic systems have been used successfully by several mining companies for such applications as tramming/hauling and dumping and tele-remote control to load the buckets (Dyson 2008). The use of an automatic LHD for backfilling operation has also been successfully tested (Larsson et al. 2008).
One reason why it is difficult to succeed with automation is the reliability of the machines and the unsatisfactory high amount of corrective maintenance required. The importance of high reliability is accentuated in all automation applications where the ambition is to remove operators from the equipment. It is undesirable to have an unreliable machine that can breakdown at any time anywhere in the mine. It is necessary to eliminate or minimize small “fixes” and concentrate service and maintenance work on regular, major stops that take care of the majority of the problems, see Figure 11. The upper part of the figure shows an example of preventive maintenance of LHDs. Here, all maintenance is taken care of at regularly planned periods. The lower part of the figure provides an example of corrective maintenance; many unplanned stops disrupt the operation. The optimization of preventive maintenance is essential with automation since the operator is no longer there to perform maintenance or take the vehicle to the workshop. To reduce costs, the general industrial trend is towards planned and condition based maintenance and to minimize all acute work. For automation in mines, this is even more important, as too many unplanned repairs and too much maintenance work in an LHD operation significantly reduces overall availability for the LHD and can jeopardize the investment in automation.

Figure 11 Example of preventive maintenance where the majority of the maintenance stops are scheduled versus corrective maintenance where a large number of the maintenance stops are unplanned with a “run to failure” philosophy.

LHD operation and especially when considering automation of LHDs is always challenging, as external disturbances like oversized boulders, road maintenance etc. can greatly influence operation. The number of registered stops (i.e., amount of idle time) resulting from external disturbances is very high. For manually operated LHDs the number of disturbances is as high as for automated LHDs, but the problem increases during automated operation. For every such disturbance, the LHD has to stop operating in automatic mode; the operator must go to the LHD and operate it manually, if possible, or try to fix it. Because the disturbances in the production areas of a mine are both complex and comprehensive, the environment is not well suited for automation. In 1997, a study evaluated the cost associated with oversized boulders (Kumar 1997). It found that the cost is very high and that an improved way of handling the boulders would decrease the total cost and increase productivity. Another study evaluating the performance of automatic LHDs showed that the highest percentage of faults could be attributed to external disturbances (Kumar and Vagenas 1991).
RESEARCH METHODS

The automation of LHDs is a complex problem; many technical areas have to function in order to operate the LHD in automatic mode e.g.:

- IT, communication system, navigation system
- Infrastructure, mine environment, control rooms
- Human issues such as skill, competence, training.

Given this complexity, the thesis deals with more than one or two known methods. The results presented here are based on the following methods:

- Literature review on manual and automatic operation of LHDs and maintenance of LHDs
- In-depth interviews with maintenance personnel (manager, planner) and person responsible for automation of LHDs
- In-depth interviews with LHD operator, both manual and automatic operation
- Analysis of maintenance and failure data
- Analysis of automatically produced production data

The data analysed in this thesis come from a case study of an underground mine in Sweden. The mine deploys 13 LHDs: 9 R2900G XTRA, 3 Toro 0011 and 1 Toro LH621, all operating from 2003 and later. Twelve are manually operated, and one is semi-automatic. The semi-automatic LHD has been in operation since 2006. The LHD operation is not a continuous process, and the LHDs only operate when needed. There is less production during the night because blasting occurs every night between midnight and one a.m. Manual loading cannot be resumed until the blast area has been ventilated. The semi-automatic LHD, however, can operate very soon after blasting, giving it a relative advantage.
3.1 LITERATURE REVIEW
A literature review has been performed on:
- automation of LHDs
- mapping existing and past experiences of LHD and truck automation
- maintenance experiences of manual and automatic LHDs and trucks
- general information on navigation techniques
- existing automatic systems and manufacturers

3.2 INTERVIEWS
In-depth interviews were conducted in a Swedish underground mine to retrieve additional knowledge concerning the maintenance of LHDs. The selection of interviewees was based on covering all levels of the maintenance department processes. The maintenance manager, maintenance planner, LHD operator and the person responsible for automation of LHDs were interviewed. The data from the interviews were collected through in-depth interviews (Waller 1932). The meaning of the interviews was not to convert the results into numerical form and thereafter statistically analyse them. It was to get a deeper understanding of the operators view on automatic and manual loading as well as the maintenance staff’s characterization of the maintenance procedures and practices. The complete results of the interviews can be found in Mkemai 2011, a Master’s thesis project co-supervised by the author of this Licentiate thesis.

3.3 DATA COLLECTION AND ANALYSIS
It can be very difficult to sort the data needed for reliability studies since it is not always available in a proper format (Kumar 1989). One way to handle the data is by using the concept of Knowledge Discovery from Data (KDD) (Han et al. 2011). The following steps from KDD were used for Papers III-V:
1. Data cleaning: during this step, noise and inconsistent data were removed.
2. Data integration: data from multiple data sources were combined. The production, maintenance and operational data are different in nature and originate from different sources but must be integrated to get a complete view of the operation and maintenance of the LHDs (Figure 12).
3. Data selection: the data relevant for the analysis were retrieved.

After the completion of steps 1-3, the analysis shown in Papers III-V could be performed.
Data covering the period from January 2007 to August 2010 have been collected and analysed for a manual and a semi-automatic LHD. Both machines are manufactured the same year, with the same specifications. The only difference is that the semi-automatic LHD has an automatic system fitted to it and can therefore operate in either manual or automatic mode. The data studied in this thesis include maintenance data, failure data and production data. The production and maintenance data are visualized in Figure 13. The maintenance data appear in the figure as “entrance” and “exit” times and represent the time for entering and leaving the workshop. These times are manually entered into the system. The “known times,” when production stops and starts, come from automatically produced production data and are very accurate. The time spent in the workshop (Figure 13) includes time to repair, as well as logistic times, such as waiting time in the repair queue or spare parts delays. In the mining industry, the actual repair times are rarely specified. This is an important weakness of the data collection system, and therefore it is not possible to evaluate the real abilities of the maintenance team in repair tasks because these times are hidden in the logistic aspects of workshop management. Furthermore, since enter and exit times to the workshop are manually entered into the system, their accuracy is not fully reliable.
Time data are entrance and exit time of the workshop but no times involved inside this service like idle time or logistic time.

Figure 13 Data time availability for KPI extraction

- Maintenance data: The workshop records contain information on the time spent in the workshop, the estimated time for entering and leaving the workshop, the reason for maintenance and the measures taken. The workshop data are manually entered into the CMMS (Computerized Maintenance Management System) and are not as reliable as the automatically generated production data. From the maintenance data, it is possible to classify the failures and maintenance types that correspond to the different components and sub-systems of the LHD.

- Operational data for the semi-automatic loader: The data consist of idle-times (giving reasons for the idle-times and the idle-time in hours), operation time in hours for the automatic mode and tonnage produced for each day. This information is only available for the semi-automatic LHD and is manually entered into the system by the person responsible for LHD automation.

- Production data: These are automatically and accurately generated production data regarding time for each bucket unload, ton/bucket, location of the loading and idle times.

As Figure 14 shows, if the workshop data are integrated with production data, one can determine when the LHD was operating and when it was idle due to maintenance. The
downtime registered between the loading on March 14 and March 15 shows a gap in production which, in this case, relates to the LHD being in the workshop.

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Table 1: Maintenance Data

**Figure 14 Example of integration of production and maintenance data**

### 3.3.1 Wolis system

The automatically produced production data come from the Wireless Online Loading Information System (Wolis) that the case study mine uses for wireless transfer of data from the LHDs to the underground database (Adlerborn and Selberg 2008). Wolis is a control, decision and support system that provides the automatically produced production data. Radio Frequency Identification (RFID) tags are placed in the entrance of the drift and at other strategic places so the exact location of the LHD and the places of the loading and dumping can be registered. The tags have three possible meanings: in, out and ore pass tags (see Figure 15 and Figure 16). An RFID reader that can determine the position of the LHD even at high speed has been installed on every LHD. An on-board Wolis-computer maps the ID-number of the tags to the correct drift or ore pass. The in-tag identifies the drift where the LHD is loaded, the ore pass-tag shows the exact dumping point and the out-tag is placed outside the drifts to ensure that an in-tag is not registering a passing vehicle. A weighing device attached to the bucket checks the weight of the content of the bucket and sends the result to the on-board computer. The weights are obtained by measuring the hydraulic pressure of the bucket and transforming the value into a weight. The advantage with this data is that it is possible to track down, for example, every bucket load in every drift, the bucket weight, unloading time, iron content etc. It is also possible to see how much ore has been drawn from a particular drift. Finally, it estimates how much ore remains to be loaded before blasting.
Figure 15 Example of placement of the RFID tags from the Wolis-system, in, ut (=out), schakt (=ore pass) (Courtesy of LKAB)

Figure 16 Production area, RFID tags are marked with circles (Courtesy of LKAB)
3.4 MAINTENANCE PHILOSOPHIES

Maintenance of LHDs can be based on several different philosophies (Figure 17). The decision inside the box depends on the choice of maintenance applied e.g. Reliability Centred Maintenance (RCM), Total Productive Maintenance (TPM), Preventive Maintenance (PM), Corrective Maintenance (CM) and Condition Based Maintenance (CBM) etc. The output becomes an assurance of the Dependability and Functional Safety etc. of the LHD.

3.4.1 Reliability Centred Maintenance (RCM)

The concept of Reliability Centred Maintenance (RCM) has yet to be explored in mining. It is a proactive strategy (Tomlingson 2010) for achieving extended equipment life and reducing or avoiding functional failures (Nowlan and Heap 1978). Today’s industrial equipment has been designed for high reliability with the goal of increased productivity to meet high demand. The equipment has also become more complex; thus, it is more challenging to maintain and requires highly trained personnel. When RCM is implemented, the benefits of having more complex equipment can be achieved. With the implementation of correct condition monitoring techniques, failures and their consequences can be predicted (Tomlingson 2010). The implementation of RCM requires the following eight steps (Tomlingson 2010); steps 1-4 were used in this thesis:

1. Selection of the most critical element: e.g. the LHD machine.
2. Identification of the function of the most critical element: e.g. loading and transporting ore.
3. Establishment of performance standards: e.g. number of tons moved per day under given operational conditions.

Figure 17 LHD maintenance system
4. Determination of types of failures: a failure is considered to be any equipment condition that does not permit the LHD to perform its function. A potential failure indicates that the failure process has started e.g. vibration, low hydraulic pressure etc.

5. Listing of the consequences of failures: e.g. what happens if the brakes fail?

6. Ranking of the consequences of failure: ranked according to safety failures, operational failures or non-operational failures.

7. Application of the most effective condition-monitoring techniques.

8. Establishment of an overall maintenance plan.

3.4.2 Total Productive Maintenance (TPM)

The concept of Total Productive Maintenance (TPM) is explained and used in Paper II. Simply stated, TPM aims to maximize equipment effectiveness by changing the corporate culture to improve a company’s personnel and plant. It seeks to develop a "maintenance-free" design, asking all employees to help improve maintenance productivity by stimulating their daily awareness (Nakajima 1988). TPM is a good concept to use in mining because human factors play a significant role in the operation of a mine. In fact, because operators are quite isolated, management has to handle both technological issues and human factors. Yeoman and Millington (1997) list the five pillars of TPM as:

- Increased equipment effectiveness: The formula for equipment effectiveness includes availability, the rate of performance and quality. All departments are involved in determining the equipment effectiveness (Moubray 1997).

- Training: The aim is to develop learning and understanding through real-life experience (Willmott and McCarthy 2001).

- Autonomous maintenance: TPM seeks to establish autonomous maintenance which refers to operator asset care (Willmott and McCarthy 2001).

- Early equipment management: In TPM, special attention is given to early equipment management or the reduction of the life cycle costs in the early stages of the process (Willmott and McCarthy 2001).

- Planned preventive maintenance: To improve the planning of preventive maintenance, it is important to avoid unnecessary maintenance. The best tool for condition monitoring is the operator who knows his/her equipment and feels responsible for it (Willmott and McCarthy 2001).

3.4.3 Functional Safety Analysis (FSA)

The concept of Functional Safety (IEC 61508 2010; IEC 61511 2003) resulting in the optimization of Reliability, Availability, Maintainability and Safety (RAMS) is an important goal for the company. Figure 18 outlines the steps to follow when analysing and optimizing the functional safety of the system. After stages 1 through 7 are performed, an optimization of the four RAMS parameters can be obtained. The concept of functional safety is discussed at greater length in Paper III.
In stage 1, a functional analysis was performed determining the utility of the LHD machine, i.e. a complete description of what it does, how it functions, its values or parameters, etc. The LHD consists of many different subsystems and components (Figure 19). The subsystems shown in Figure 19 were determined after the LHD and the maintenance data were analysed.

After defining the subsystems of the LHD, the machine’s parts were sorted into two major groups; repairable or non-repairable (stage 2 Figure 18). The quantification of all elements and their classification on the basis of the above makes it possible to analyse and predict Reliability, Maintainability, Availability and Safety. For that purpose, a large amount of data has been collected. With this data, the systems components was modelled with MTBF (Mean Time Between Failures) (EN 15341:2007), a reliability indicator, and MTTR (Mean Time to Repair) (EN 15341:2007), a maintainability indicator. MTTR is connected to the
workshop and the end user, while MTBF is connected to the system’s design and manufacture. Together MTBF and MTTR can confirm availability. The incidents/accidents that may have consequences on personnel or material safety are listed (Stage 3 Figure 18). The goal is to list the dangers of the system and their possible causes, evaluating the quality and the gravity of the consequences of accidents and the implementation of corrective actions.

An analysis of failure modes was performed in stage 4 (Figure 18). The analyses of failure modes and their effects (FMEA), proceeded by a functional and quantitative analysis, makes it possible to list and classify the predictable failures. The FMEA is intended to obtain an optimal system reliability drawing experience and expert opinion, using a simple and systematic analysis of possible failures. FMEA can be used in the design of the equipment and in its maintenance, making it an ideal tool for comparing the performed maintenance to the maintenance proposed by the experts and technicians (MIL-STD-1629A, 1980). Relevant failure modes have been identified in all subsystems described in the functional analysis visualized in Figure 19. Having good system maintainability, stage 5 (Figure 18), is essential, and together with reliability, it ensures the system’s availability. Maintenance tasks can be designed, and the phases and stages of repair can be analysed, so the qualifications of the personnel, material and tooling can be determined. Mean time to repair (MTTR) is a commonly used maintenance performance indicator; MTTR = Total time to restore/Number of failures (EN 15341:2007). The time spent in the workshop is used for maintainability analysis. The analysis from stage 6 (Figure 18) results in a reliability block diagram (RBD) (EN 61078:1996) (Figure 20) that shows that the subsystems of the LHD are serially configured and must be working simultaneously to get the desired function of the LHD. The results from the analyses in stages 4-6 are found in Paper IV and in Figure 27 and Figure 28.

In stage 7 (Figure 18) fault trees (FT) show the various combinations of incidents resulting in the occurrence of a predefined event. The concept of a fault tree was used in Paper V to find the causes of the LHD’s idle time, both machine-related causes and those related to the operating environment. A fault tree is a graphic model of the combination of faults that results in the occurrence of a predefined, undesired event (top event). The faults can be events such as hardware failures, human errors and software errors etc. that lead to the undesired top event. Since a fault tree is focused on the occurrence of the top event rather than modelling all possible causes for system failures it is important to remember that only the faults considered relevant are included in the fault tree. The basic concept of a fault tree is that an outcome is a binary event with the possibility of either failure or success. Besides events, the structure consists of “gates” that either allow or hinder the passage of fault logic up the tree. The event above the gate is the output of the gate, and the event below the gate is the input to the gate (Vesely et al. 1981). The objective of a fault tree is to show the
relationship between a potential event affecting the system’s performance and the causes of this event (Blischke and Murthy 2000). The following steps must be carried out in a successful Fault Tree Analysis (FTA) (Stamatelatos et al. 2002):

1. Identify the objective for the FTA.
2. Define the top event of the FT.
3. Define the scope of the FTA.
4. Define the resolution of the FTA.
5. Define ground rules for the FTA.
6. Construct the FT.
7. Evaluate the FT.
8. Interpret and present the results.

3.4.4 Maintenance Performance Measurement (MPM)

Maintenance performance measurement (MPM) can be defined as “the multi-disciplinary process of measuring and justifying the value created by maintenance investment, and taking care of the organization’s stakeholders’ requirements viewed strategically from the overall business perspective” (Parida 2007). MPM is used to measure the value created by maintenance. Good maintenance strategies are essential to optimize the maintenance of mobile mining equipment. Even though it is costly and time-consuming to measure performance (Parida 2007), it is important to establish and maintain relevant indicators (Lynch and Cross 1991). An indicator is a combination of a set of performance measurements. A key performance indicator (KPI) (EN 15341:2007) can consist of several indicators and metrics. KPIs are directly related to the overall goals of the company, including the maintenance function. Indicators should be exportable, easily understandable and lacking double interpretations.

The maintenance indicators MTBF and MTTR can be estimated from the historical maintenance data and have traditionally been used to evaluate the maintenance of LHDs (Kumar 1989). Other well-known maintenance indicators include downtime, utilization, cost and availability. In mining, an indicator used for productivity is often the number of tons produced/unit time. This concept has been used in Paper IV where it is further explained.
The LHD and its operating environment are complex systems which the success of production depends on. Productivity not only depends on the operation of the LHDs but also on the mining environment, including drift layout, fragmentation, size of boulders, navigation techniques etc. The maintenance procedures, maintenance performance, production performance and the external factors will be presented and discussed here and originates from the appended papers.

4.1 MAINTENANCE PROCEDURES
The production and maintenance departments of the case study mine (see Paper II) seek “to achieve optimum production under minimum or no obstruction”. The annual budget for LHD maintenance is 40MSEK, or 40% of the total annual maintenance budget. The occurrence of breakdowns greatly affects the maintenance planning budget through increased maintenance cost/ton. The interviews provided information on the maintenance activities associated with manual and automatic LHD machines. The maintenance planner plans repairs and spare parts availability. It is not easy to have spare parts available at all times; too much time can be spent on corrective maintenance by having to wait for them, thereby lowering production capacity. Inspection, oil change and refuelling of the mine’s LHDs occur regularly. The PM plan defines maintenance stops for the LHDs every 250, 500, 1000 and 2000 machine hours. In addition, the engine, converter and gearbox are changed according to the preventive replacement plan at 13000-14000 machine hours; the hydraulic pump and the transmission are changed after 8000 and 1000 machine hours respectively. Figure 21 shows the relationship between corrective maintenance (CM) and preventive maintenance (PM) for one LHD during the test period (2006-01 to 2010-08). All LHDs have similar graphs, making this one representative. The data for 2010 are collected for eight months; this explains the decrease in PM and CM. The data show that CM represents about 90% of the maintenance work which is far too high for an automated system. The loaded tons are also visualized in the graph; there seems to be an almost linear relationship between loaded tons and maintenance time which implies that the more tons that are loaded the more maintenance the LHDs require.
When using automatic LHDs, it is important to increase the planned maintenance and decrease the unplanned maintenance. It is undesirable to have a machine that can breakdown at any time in any place, as there is no one there to perform maintenance or take it to the workshop. One drawback with automated LHDs is that at failure or breakdown someone has to physically attend to the machine to fix it or take it to the workshop. If the system has to be frequently changed to manual operation due to unplanned breakdowns, this can put the entire investment in automation in question.

The results of the interviews confirm that working with semi-automated LHDs is safer compared than manual operation especially when there are gases and fumes in the production area or when there is a risk of cave-in or falling rocks. They also show that more hours can be used for production since it is possible to work soon after blasting. However, the result also clearly shows that not all operators prefer to work in the automated mode. Some prefer the manual mode for the following reasons:

- Better feelings of physical presence during operation: During manual operation the operator gets a better feeling of the LHD and the surroundings and can listen and sense if there is a problem with the machine. In automatic mode it can be challenging to see when there is a need for road maintenance.

- Loading the bucket: It is easier to handle the loading process manually when the material contains oversized boulders.

- Road maintenance: After each shift in automatic mode, someone has to go to the LHD and manually operate the machine to clean and maintain the road. The roads become more damaged during automatic operation since the machine is programmed to follow the exact same route each loading cycle.

- High speed operation: Manual operation offers more flexibility and can be performed at higher speed, resulting in more loaded tons.
When calculating maintenance indicators, e.g. reliability and availability, the most common source of input data is the workshop record which, in one way or another, is manually fed into the system. This human interference needs to be considered when analysing the data since it points to the possibility of errors in the calculations. When the workshop data and the automatically produced production data were compared, on many occasions when the machine was supposed to be in the workshop, it was really operating and vice versa. One third of the manually entered times are not consistent with the automatically recorded production times. Therefore, only using workshop data for reliability and availability analysis makes the results unreliable. One example of corrupt data is visualized in Figure 22. The table shows automatically produced production data; times given in the table represent the time registered for one bucket weight just before the bucket is unloaded. During the period 20XX-04-18 to 20XX-04-19 the LHD was, according to the workshop record, in the workshop for repair of the gearbox, the hydraulics and the parking brake, but the automatically produced production data (Figure 22) show that the LHD was being operated.

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The LHD operation is not continuous; this means that the LHD has to be available whenever it is needed. For this kind of operation, the failures are divided into time and demand related failures (Figure 23) so the correct calculations can be performed to determine availability. This concept is similar to the concept of Availability on demand presented in Kumar and Akersten (2008). Time related failures occur while the machine is
being operated. Demand related failures occur when the machine is required to be operating but a failure prevents it from performing the operation. Since the LHD operation is not continuous, it becomes especially important to have the LHD available whenever needed. By collecting the quantitative data of each machine (MTBF and MTTR) for time and demand related failures, it is possible to determine the availability.

![Figure 23 Timing diagram for time and demand related failures](image)

- **Example of time related failure:** During 20XX-07-17 the LHD was operating according to the automatically produced production data shown in Figure 24. Integrating this data with the maintenance record shows that the production stopped after unloading at 20:10 due to a machine shutdown. This is a time related failure since the failure occurred during operation.

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<td>2008-07-17</td>
<td>20:08</td>
</tr>
<tr>
<td>2008-07-17</td>
<td>20:10</td>
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</tbody>
</table>

![Figure 24 Example of time related failure](image)
• **Example of demand related failure:** During 20XX-02-02 the LHD was operating according to the automatically produced production data shown in Figure 25. After 08:18 the production stopped according to the automatically produced production data which indicates that there was no operation after this time. At 05:50 the next day, the LHD was expected to operate but failed to start according to the maintenance record. This is a demand related failure as the failure occurred when trying to start the LHD after a period of no operation.

<table>
<thead>
<tr>
<th>DATE</th>
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<th>PRODUCTION DATA</th>
<th>MAINTENANCE DATA</th>
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<tr>
<td>20XX-02-03</td>
<td>05:50</td>
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</table>

**Figure 25 Example of demand related failure**

### 4.3 PERFORMANCE ANALYSIS

The main goal of the production and maintenance department in the case study mine is “to achieve optimum production with minimal or no obstructions”. The key performance indicators of the department include cost per ton (SEK/ton), mean time to failure (MTTF) and equipment downtime. The maintenance planner or maintenance engineer is responsible for measuring these indicators. In the following sections, production and maintenance performance are analysed separately and then compared.

#### 4.3.1 Production performance

One consequence of availability optimization is increased capacity. The performance of the LHDs is measured in tons/month; the company seeks to produce 100 000 tons/month per LHD.

The production performance analysis in Paper IV partly answers RQ 4 and shows that the filling rate (ton/bucket) is similar for both LHDs. The manual machine seems to move more tons/machine hour; this can partly be explained by the difference in cycle times. Figure 26 shows the frequency of cycle times of the load haul dump cycles for one year for the semi-automatic and manual LHDs. Cycle times depend on the structure of the mine and the
location of the loading and dumping points. The frequency of cycle times longer than 8 minutes is higher for the semi-automatic LHD. This can be explained by the fact that for part of 2009, the semi-automatic LHD was operating in automatic mode in a very long mine tunnel. When comparing the different operation modes for the semi-automatic LHD, it was found that the LHD produces more ton/machine hour in the manual mode than in the automatic mode. The reason for the different cycle times is not clear; possible explanations are that it is generally faster to load the bucket when the operator is in the machine and that manual operation is performed with higher speed.

![Figure 26 Frequency of cycle times for the load haul dump cycle of manual and semi-automatic LHD](image)

There is not a big difference in utilization between the manual and the semi-automatic LHD. The semi-automatic LHD operated in automatic mode for about 50% of the total operating time.

### 4.3.2 Maintenance performance

The maintenance department uses indicators like MTBF and MTTR. Availability is another frequently used indicator for the maintenance department where the target is to have 9 out of 13 LHDs available at all times. With the maintenance planner’s input, the production manager and repair crew attempt to meet this target. In this case it was for example found that for one LHD operating for 2336 machine hours during one year, there were 39 failures giving a MTBF value of 59.9 hours. The total time to restore these 39 failures was 557 hours which means that MTTR equals 14.3 hours. The waiting times are not properly recorded (see Figure 13) in the data base. The waiting time between the LHD leaves the workshops and starts operating is known, but the waiting time inside the workshop is
unknown which means that an exact figure for the WT is not available. The availability, reliability, maintainability and maintenance supportability are all ensuring the dependability of the LHD.

Additional failure and maintenance data was collected and analysed regarding one semi-automatic and one manually operated LHD. The data was recorded during 4 years and 10 months. After collection, the data was sorted and categorized for the subsystems of the LHD according to Figure 27 which shows the different number of breakdowns associated with different modes of operation. The preliminary risk, based on number of failures indicates that the most critical components based on number of failures are different for the manual and semi-automatic machine.

- Semi-automatic loader: Most critical subsystems are the hydraulics followed by the electrical system, engine and transmission.
- Manual loader: Most critical subsystems are the hydraulics followed by the electric system, cabin and chassis.

![Figure 27 Number of failures for semi-automatic and manual LHD over 4 years and 10 months](image)

Valuable information can be extracted from this graph because the failures will be different in number and severity depending on the operating mode used. It is clear that the transmission and engine has more work orders and also more time spent in the workshop for the semi-automatic LHD than the manual. This shows that the engine and transmission
suffers when operating in automatic mode. It can also be seen from the maintenance data that although the numbers of failures for chassis are equal for the two machines the maintenance data shows that the repair time is much higher for the manually operated LHD. This difference in repair time can partly be explained by the fact that the positioning system makes the automatic LHD operate in the middle of the mine tunnel whereas manually operated vehicles is more likely to scratch or hit the tunnel walls.

Figure 28 show the total time spent in workshop associated with different modes of operation. The size of the boxes in the graph represents the percentage of the total time spent in the workshop for each subsystem. The most critical components differ for the manual and semi-automatic machine.

- Manual loader: Based on time spent in the workshop, the most critical subsystem is the chassis, followed by the brake and hydraulic systems.
- Semi-automatic loader: Based on time spent in the workshop, the most critical subsystems are transmission, engine and hydraulics systems.

It can be seen from the repair data that although the number of work orders for the hydraulic system is quite high the corresponding repair time is short.

The maintenance issue was an early argument for automation of LHDs. Increased tyre life, due to smoother, optimized gear shifting, has frequently been reported. Less wear on transmissions and drive lines and no overheated engines have been noted as well. Nevertheless, it is also acknowledged that maintenance personnel require more extensive skills and experience.
4.3.3 Fusion of Maintenance and Productivity KPI’s

In Figure 29 the total costs for both corrective and preventive maintenance are presented versus the accumulated production in tons. In the figure no clear difference between the manual and semi-automatic LHDs is seen. If the productivity increases, the maintenance costs simultaneously increase for both machines. The balance between production and maintenance cost is an important issue, and it seems difficult to lower the maintenance cost while simultaneously increasing productivity. By combining the productivity indicator and the maintenance indicator a common tool to the production and maintenance departments are provided. It is in both their interests to optimize the indicators.

![Figure 29 Maintenance cost versus accumulated ton for semi-automatic and manual LHD during one year](image)

4.4 FACTORS INFLUENCING THE IDLE TIME FOR LHDS

The results from Paper V answer RQ 3 and are partly presented here. The reasons for down time for the LHDs can be divided into three main categories; mining related issues, machine related issues and issues related to the automatic system (Figure 30). The data analysed was reported for one LHD during one year. The numbers in the figure represent the number of times that one LHD was idle for that particular reason during one year. The total number of recorded stops resulting in idle time for the LHD during this particular year was 1470 according to the production data. The number of stops that could be traced to mining related issues was 1103. For machine related issues, the figure was 316, and for the automatic system, it was 51. The real numbers might be higher than those shown in the figure, as operators may not always enter the data into the system. At any rate, they are not likely to be lower. The figure tries to give a complete picture of when the machine can operate in manual and/or automatic mode. At times, the LHD can be operated in manual mode in another area in the mine, for example, when the area used for automation is closed for safety reasons or other work-related issues. The figure shows when having a semi-automatic machine is helpful, namely, during the night when gases from the blast have to be vented and no human can be in the production area. Even more frequently, there are problems with dust and gas; at these times, the LHD can be operated in automatic mode but not in manual. It is important to isolate the different reasons for idle time to maximize the value of automatic operation.
LHD machines are depending on the operating environment in order to function in an optimal way. Mining related issues stands for 75% of all stop occasion causing idle time. About 21.5% of the stop occasions are caused by machine related issues such as corrective maintenance, preventive maintenance, refueling, inspections and oil checks. About 3.5% are related to the infrastructure of the automatic system installed in the mine. The automatic LHDs are functioning well and the reason to why the concept of automation has not yet fully succeeded is linked to the mining related issues visualized in Figure 30. However, every unplanned stop whether it is caused by the operational environment or a machine breakdown becomes an issue that disturbs the automatic operation and needs to be controlled.
5 CONCLUSIONS

RQ 1. How do Reliability, Maintainability and Maintenance Supportability affect the Dependability of automatic LHDs?

Reliability, maintainability and maintenance supportability are all ensuring the dependability of the LHD. By avoiding failures, reliability directly contributes to the achieved uptime. Reliability is measured with MTBF which in Paper IV was calculated to be 59.9 hours for one LHD. By optimizing the MTBF, reliability increases. High reliability is a necessity for LHD automation, as the operators have been removed from the vehicle and are no longer available to perform maintenance or take the vehicle to the workshop. At the workshop, maintenance staff is not always available on short notice. In mining applications, it is undesirable to have a machine that is unreliable. It is therefore necessary to eliminate or minimize small “fixes” and concentrate service and maintenance on regular, scheduled stops that take care of the majority of the problems (see Figure 11). As this is not normally the case in today’s mining industry, it is difficult to succeed with LHD automation. An important factor for the success of automation in mines is to improve machine reliability and change corrective maintenance in favour of preventive maintenance.

With an optimized maintainability the downtime can be reduced since the repairs are being performed faster. It is shown in Paper III that the critical components based on number of work orders are different for the manual and automatic LHD (see Figure 27). The maintainability differs depending on the operation mode used (see Figure 28). Different kinds of failures occur and the repair time differs for the operation modes e.g. the numbers of failures for chassis are equal for the two machines but the maintenance data shows that the repair time is much higher for the manually operated LHD (Paper V). Too many unplanned stops and repairs in an LHD operation significantly reduces overall availability for the LHD and can jeopardize the investment in automation.

Maintenance supportability is measured in MWT and shows the ability for the maintenance organization to provide correct maintenance support. Minimizing the waiting times optimizes the maintenance supportability. This can for example be performed through training of the maintenance crew and by optimizing the spare part control (Paper II).
RQ 2. What maintenance actions are associated with automatically and manually operated LHDs?

Mines typically apply a planned time based maintenance program whereby machines are maintained every 250 machine hours, 500 machine hours etc. Despite this preventive maintenance program, 90% of the performed maintenance is corrective (see Figure 21 and Paper IV). Even though the maintenance actions associated with manually and automatically operated LHDs are the same, there is a difference in the type of failures that occur more frequently. The transmission and engine suffer more in automatic operation, while the chassis has a longer repair time in the manual LHD. The latter case is not due to the machines being designed differently; rather, manually operated LHDs tend to hit the tunnel walls more frequently than automatic LHDs.

RQ 3. What factors influence the productivity and idle time of LHDs?

The mapping and analysis of the registered stops causing idle times shows that 75% of the stops causing idle time for LHDs relates to the operating environment (Paper V). Better fragmentation to avoid big boulders, better constructed roads to avoid road maintenance etc. must be considered to successfully operate automated LHDs. Future focus must include better maintenance planning in order to reduce the number of corrective maintenance events. About 21.5% of the stops causing idle time pertain to machine related issues including inspection, refueling, oil checks, corrective maintenance and preventive maintenance. Only 3.5% are related to the infrastructure of the automatic system. If humans are to be taken out of the production area, a substantial amount of work has to be done to minimize mining related disturbances.

RQ 4. How can the performance of automatic LHDs be evaluated and justified?

The performance of the LHD can be evaluated using indicators like maintenance cost and productivity. In this case there is not a notable difference between manual and semi-automatic LHDs (Paper III and IV). However, a semi-automated LHD is an optimal machine regarding the ability to adapt to reconfiguring the operation mode to meet demands such as safety, flexibility and productivity.
Based on the conducted research, the following areas are recommended for future research:

- **Dependability analysis of LHDs**: Integration with automatically produced data to remove corrupt data. With better and more reliable data, analysis of the dependability of LHDs can be highly accurate.

- **Maintenance optimization**: Today, all mines apply a planned time based maintenance program whereby machines are maintained every 250 hours, 500 hours etc. Despite this preventive maintenance program, 90% of the performed maintenance is corrective, according to Paper IV in this thesis. This percentage is far too high for automated systems. When using automatic mobile mining equipment, it is essential to optimize the maintenance to gain from the automation investment.

- **Human factors influence on automatic operation**: One way to increase equipment reliability and to decrease the number of failures is to improve the human factors. A complete study of how humans influence the automatic operation is an essential step in optimizing the automatic operation.

- **Condition monitoring**: A low failure rate can be achieved by constantly monitoring the operating parameters of these devices. The ability to plan maintenance can be improved by the increased use of condition monitoring and condition based maintenance. These techniques are commonly used in stationary plants but are rarely used for mobile mining equipment. However, with the increasing use of computerised control systems, more detailed analysis and better control of on-board equipment and sensors are possible.

- **Markov modeling**: An interesting approach for further research concerns the transitions between the states defined in Paper V.
7 REFERENCES


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APPENDED PAPERS
Performance of Automated LHD machines: A Review

Performance of Automated LHD machines: A Review

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The importance of LHD (Load Haul Dump) machines in most mine operating systems is evident today. The cost of operation and maintenance is one of the challenges, while high availability and reliability are others. The latter will be increasingly important when automatic LHD machines are used more frequently. A key factor for automated LHD system is the planned maintenance process, as all corrective maintenance or accidental break-downs rapidly deteriorate the production system where operators are not present and maintenance personnel not available on short notice. A challenge for manufacturers is to improve the engineering design of their machine and related components (hydraulic systems etc) so as to make them more reliable and also making the machine easy to maintain. The demands on the overall communication systems and new and higher competence and skills needs on operation and maintenance personnel are a few factors that make many mines reluctant to the higher investments in Automated LHD systems. This paper reports some experiences with automated LHD machines in Scandinavia and the rest of the world and examines some of the issues that make the application of automatic LHD machines restricted by large operators and prohibitive by small mines. It also deals with the maintenance aspects of automated LHD systems and provides some initial considerations from a major Scandinavian research project in the field.

Keywords: Automation, LHD, maintenance

1 Introduction

LHD's are used in most underground mines for loading and transporting of ore/minerals. The LHD's usually have a length of 8 to 15 meters and the weigh is between 20 to 75 tons, using both electrical and diesel power. They generally operate at a relatively low speed of about 20-30 km/h in an often hot, dusty and wet environment. Their structure consists of two parts connected by an articulation point which gives them a high level of manoeuvrability in the narrow mine tunnels. The purpose of using automatic loaders in mines is mainly to improve productivity and to increase the safety for the personnel. With an automatic system the operator can be taken out of the mine and from distance control a number of LHD's, increasing both productivity and security at the same time. Poole et. al. (1998), mentions that the automation process is used in day-to-day operations and that the process offers flexibility and convenience for the operators. The health and safety benefits will result in a long term wellness of the operators. There will also be manpower savings due to less travelling time and one operator for multiple machines. Another aspect of going automatic is the benefits of maintenance and Mäkelä (2001), mentioned that an automatic machine, designed with high reliability, will last longer since it requires less repair than a manual one. Due to the obvious advantages with automatic LHD’s, several initial steps have been taken towards making LHD’s driverless. It is already common practice in underground mines to operate LHD’s into unsupported areas using line-of-sight remote control. Here, an operator drives the vehicle manually to the brow (entrance) and then dismounts to drive the LHD into the stope by radio remote control. At all times the operator is close-by and can see the LHD. Once the bucket is loaded, the operator climbs back onto the machine to drive it...
manually to the dump point. This procedure is slow because of the constant change between manual and remote operation. It is also unproductive because the bucket is difficult to fill due to the operator’s limited view of the loading operation. Most importantly, it is not fully safe since the operator’s remains close to the remote controlled vehicle and the unsupported ground. Tele-remote operation is the next step towards automated vehicles and is slowly gaining acceptance in the mining industry. For this operation method video cameras are installed on the LHD’s to provide the remote operator with clear views forward and backward. The LHD is remote (with vision) driven by the operator during the complete LHD load/dump cycle. An operator can be located in a safe and comfortable environment a long distance from the vehicle but can still only operate one vehicle at a time. The next step for LHD’s and trucks is to allow them to drive autonomous. Operators will still be required to monitor and be involved at some points but would be able to operate several vehicles simultaneously from a safe environment. Since such vehicles will faithfully follow programmed instructions, management has the flexibility to control the performance as well as the wear and tear of the vehicle. Automated LHD machines are manufactured by different companies. Most dominating manufacturers are; Atlas Copco (former Wagner) and Sandvik (former Toro) from Sweden and Caterpillar (Elphinstone) from USA/Australia (figures 1-3). Each supplier offers a number of different models of machines with different capacities and sizes. In addition to these vehicles, software’s and surrounding systems for automation of LHD’s and trucks are also being introduced as an integrated part of the system. The conditions and needs for automation might vary between countries and mines due to different parameters, yet, the technology is being developed and used in some of the mines in the world.

Figure 1. Automated LHD system (AutoMine™) from Sandvik with the operator’s environment (courtesy Sandvik).
2 Past experiences with LHD automation

To date automatic systems are mainly being used for tramming/hauling and dumping. Despite the number of successful automation projects the mining companies still uses tele-remote control to load the buckets (Dyson 2008, Mining-technology.com). There have been a small number of tests using automated bucket filling but none which have been successful. The usage of an automatic loader for a backfilling operation has also been tested.

2.1 Automatic loading operations

A project to develop an automatic loading system at Noranda started in 1990 and was further developed after that. The system was first tested on a Wagner ST-8B machine at Noranda’s Brunswick division in 1997. The automatic system was tested for a week and compared with one good operator from the mine. Bucket loads, mucking and tramming were compared with good results. The loads achieved with the automatic loader were 4% larger than the loads by the remote control operation. The automatic loader filled the bucket 24% faster than the operator. These two combined gives an improved productivity depending on the tramming time (Hedman, 1998).
Olympic Dam Operation in Australia (ODO) is Australia’s largest underground mine and have been involved in development and testing of automated LHD’s for four years. A test trial was performed, at the 42 Orange 20 Stope (at ODO), using the Caterpillar Autodig™ for loading the buckets together with automatic tramming and dumping. After no more than three shifts it was disconnected due to the following three reasons. It was difficult to make a correct manual setting of the Autodig™ because of the large variations in rock sizes. It was only in about 30% of the time that the Autodig™ managed to fill the bucket at one pass. “The Autodig™ would try to straighten out the machine while bogging on left full lock causing the rear end to swing into adjacent wall during reversing” (McHugh, 2004).

2.2 Advantages with LHD automation

In October 1998 the first semiautonomous Tamrock 2500 was commissioned for operation in LKAB’s Kirunavaara mine, Sweden. The goal was to improve the utilization of the LHD’s and one operator to control three LHD’s. With the autonomous system the productivity improvements started to be positive. One significant improvement was the increase of the tyre life thanks to the optimised dumping and braking of autonomous LHD’s. Another advantage was that the autonomous LHD dropped fewer rocks. Even though tyres, transmissions and other components were not damaged as frequent, LKAB expects more maintenance improvements once the system is improved (Chadwick 2000). At Inca’s Stobie Mine in Ontario, a “light wire” guidance system has been used successfully for several years. The operator handles up to three LHD’s at one time. It was reported in 1999 that six LHD’s were used in the Stobie Mine and they claim improved service life, reduced maintenance and tyre cost. (Golosinski 2000) Hedman mentions that time savings was one of the major benefits when using automatic LHD’s at the Stobie Mine. Up to two or three hours were saved per shift in travelling. The concept was implemented on the LHD’s successfully and the operators were positive to the change. A more precise prediction on failure could be made on engine, tyres, frame etc. since the incoming data could be evaluated in a new way. Another benefit with autonomous LHD’s was longer operation cycles for the machine. In 2003 two of El Teniente’s mining areas, Pipa Norte and Diablo Regimiento, were to be automated in several areas in order to increase productivity (Sandvik, 2009). They were using fully automated TORO 0010C LHD loaders, three in Pipe Norte and three in Diablo Regimiento (by June 2005) with possibility of seven more, which were operated from a single control room (Schweinkart and Soikkeli 2004). The loading was carried out using teleremote control, the hauling and dumping were autonomous and a guidance system together with a traffic management system controlled the units from the dump and back (Sandvik 2009 and Schweinkart and Soikkeli 2004). In 2004, the El Teniente Mine in Chile was the first mine to use advanced autonomous LHD in large scale production. (Mining technology.com) Woof (2005) means that the AutoMine™ system at El Teniente mine in Chile requires more highly trained service personnel than before. The automatic tramming will over time result in reduced machine downtime. The benefit with lower costs for maintenance and spares comes from less wear and tear on drivelines, no overheated engines, optimized gear shifting and extended tyre life. There will also be less bucket spillage and collisions with the walls when using automated tramming. The Jundee mine in Australia has successfully been using two automatic Caterpillar R2900 LHD’s for 18 months,
since the beginning of 2008. The operator is responsible for the actual bogging using telemetry and the rest is handled by MineGem™. They have been able to use one machine less which reduces the operator costs with at least the same production. The wear and tear of the machines is less and the machines stay off the walls and can go faster with the automated system. The operators can be productive three hours more per day since they can operate the vehicle from outside of the mine and don’t have to travel up from the mine during blasting. They have also removed the need for secondary piles in the mine (Miningnews.net 2009). At the production trial at the 42 Orange 20 Stope (ODO) a new R2900 loader were used. It generally took four shifts before the operators were comfortable with the system. The tramming and dumping were automated and the speed was tested up to 20 km/hour. The autotram system could work through shift breaks, during major stope firings and through dust. The shift handover took only a few minutes above surface. The maintenance personnel commented that the automatic vehicles could drive faster (12 km/hour) than the manual (5 km/hour) where the roads were in bad conditions since the operators could get injured driving on the damaged road. A comparison was made between an automatic and manual loader driving on a road with good conditions during 15 cycles. It was found that the cycle times for the manual loader were shorter than for the autonomous. (McHugh, 2004) During 2003 ODO was using two automated LHD’s and reported an increase in production of 40% (CSIRO, 2008). Malmberget mine, LKAB, are working with the MineGem™ team and the Swedish Caterpillar dealer Pon Equipment AB to try out a Caterpillar R2900G LHD for automated operation (Casteel 2008). They had a 12 month testing period that was very successful. The mine manager Björn Koorem says that the production has shown to be increased with between 10-20% when using an automatic LHD. Other advantages like increased utilization and production and less machine damage will be appreciated with time (Caterpillar, 2008).

2.3 Disadvantages with LHD automation

Because of maintenance issues INCO (Stobie Mine and Creighton Mine) can not see that the whole mine should be unmanned. Mining equipment is not very reliable and the mean time between failures on components needs to be better before there can be less interaction on the equipment (DeGaspari, 2003). SALT II: LKAB in co-operation with Tamrock conducted a full scale test of LHD’s equipped with a guidance system in the late 80’th. The LHD’s brought nearly one million ton iron ore to the shafts during the test period. The results were ok but didn’t manage the production and availability goals. During the test, sub level stooping was used as production method, not sublevel caving that is presently being used. The fact that it wouldn’t be cost effective to implement a technology greatly based on infrastructure was the main conclusion. The test gave input to economical simulations (Bergström and Wigden, 1998). At the test trial, at the 42 Orange 20 Stope (Olympic Dam Operation in Australia), previously described, it was noticed that the bucket teeth would touch the wall if the speed was too high in reverse when trying to attempt a corner too fast. Except for that, collisions with the walls were minor during automated mode (McHugh, 2004). For the Stobie mine, one disadvantage with autonomous LHD’s was that the movement between the levels became more difficult since the cab was removed from the automated LHD and therefore the operator had no place to sit (Hedman, 1998). Casteel (2008) points out some of the problems with automatic systems. He claims that some of the issues are that it is rather costly to
install the automatic systems and that the mine needs to meet some specific physical requirements. This means that it seems like large-scale mining will get more significant benefits from installing the whole package where production can be increased in large cycle applications. Casteel further mentions that the system can be fitted to suit smaller operations as well though it is easier to install the technology in mine sections that have planned to use it.

### 2.4 Maintenance experiences

Woof (2009) states that the automatic machines require less maintenance and have lower running costs because gears are changed at optimum times and engines are not over revved. A similar statement is made at Mining-technology.com where it is written that the maintenance requirements will be less using an autonomous system since the driving is always perfectly matched with the situation. The reliability and safety requirements are high which makes it essential for the system to have a robust self-diagnostic fault detection and fail-safe mechanism in place. Poole et. al. (1998) describes the changes made to a RoboScoop W so it could be autonomously operated at the Stobie Mine. Since the intent was to reduce the need for the operator to be present at the LHD, different applications were added to increase the time between daily maintenance/service. An auto lubrication system was also added. Since the machine is not dependent on the operators working hours a “shift” for the machine could be based on either maintenance or service intervals. In the El Tenientes Pipa Norte mine the LHD’s will only leave the production area when there is planned maintenance or major breakdown. Refuelling and lubrication is scheduled through the AutoMine™ system and will be carried out in a specific place of the mine to where the LHD has been brought by the maintenance personnel. The shift and daily maintenance functions will be performed while the machine is being serviced. The availability of the fleet is based on planned downtime hours (for scheduled maintenance services), and unplanned downtime hours (for unscheduled repairs or breakdown work). “There is no experience to accurately predict unplanned downtime in an automatic operation.” It is believed that condition monitoring would be possible to use in order to achieve a diagnostic capability so at least 15% of the potential failures of the manual operation can be identified and taken care of during the planned downtime. It is suggested that the downtime will be about the same for the automated machines as for the manual. The number of full time service/maintenance personnel is estimated to be the same whether the fleet is autonomous or manual although the technical skill level is required to be higher for an autonomous fleet. In case of a LHD breakdown, the LHD is prepared for manual control and all other LHD’s will be excluded from that actual tunnel (Schweinkart and Soikkeli 2004). At the production trial at the 42 Orange 20 Stope (ODO) the maintenance was described as follows; the underground maintenance crew took care of the re-fuelling at mid shift according to maintenance schedule. During the re-fuelling, road maintenance was taken care of and during service time, the lasers were cleaned with a rag (McHugh, 2004).

### 2.5 Availability and reliability of automated LHD

LKAB started 1987 a project together with ARA (present Sandvik) called SALT I. The objectives were driverless machines and remote/automatic controlled LHD’s operated from a control room. The project didn’t fulfil the objectives and were shut down 1991.
The availability was low for the LHD’s and they didn’t reach the expected production level (Hedman, 1998). To deal with this issues a second project, SALT II, was launched, see section 2.3. McHugh (2004) describes a four month long production trial in 2002-2003 at the Purple Stopes (Olympic Dam Operation in Australia) with the MineGem™ system. The total systems availability was over 90%. The main cause of downtime was the reliability of the radio cell. Breakdown maintenance and oversize boulders were the biggest cause of utilization downtime. When comparing the autotram operation with an average manual loader it was found that the automatic loader worked 1.9 hours more per shift. Two different Atlas Copco LHD’s were used during an extensive field trial in the Kvarntorp Mine (Atlas Copco testing facility), Sweden, during 2006-2007. The test was first conducted with an Atlas Copco ST1010C LHD and later with a ST14 LHD. The results were compared with previous recorded manual operators. Based on a large number of repeated tramming operations, the system was found to have a remarkably high reliability (Larsson et al. 2008). The Stawell gold mine in Australia, owned by Leviathan Resources (later acquired by Perseverance Corp.) started using a MineGem™ system for an automatic loader in August 2005. Since the working environment is very bad at the mine it is a big improvement to have an automatic LHD operation. They say that 50% or more of the material is being transported with MineGem™-enabled machines and that the reliability of the system is 85-90% (Casteel 2008). Rio Tinto’s Northparkes Mine has is using MineGem™ and claims that the availability of the system is more than 95% and that it is operating 10 hours per 12-hour shift (Caterpillar 2007).

3 Discussion

Over the 20 years of use of automated LHD’s in the mining industry some issues and challenges remain. The issues of productivity and safety are still the driving force for the investments in automated systems but the reported achievements differ. Even thought the loading capacity in some cases is reported lower than for manual loading some experiences show up to 50% increase in production over time. However, it is hard to fully comprehend the underlying reasons for the large variation in productivity gain. The availability figures vary between different applications. Even if low availability have been reported from the early tests more recent applications have shown higher availability as for example total availability of over 90% and shift availability of over 95% that is reported from tests in the Australian mining industry. The maintenance issue was early put forward as an argument for automation of LHD’s. Increase of tyre life, due to smoother, optimised gear shifting, has frequently been reported. Improvement have also been reported on less wear on transmissions and drive lines as well as no overheated engines. Nevertheless the more extensive skills and experience required by maintenance personnel have also been acknowledged. Even if, high availability has been reported, the importance of high reliability is accentuated in all automation application where the ambition is to remove operators from the equipment. It is necessary to eliminate, or minimize small “fixings” and instead concentrate service and maintenance work to regular, major stops that takes care of the majority of the problems, see figure 4. To reduce costs the general industrial trend goes towards planned and condition based maintenance as well as to minimize all acute work. For automation in mines this question is even more important since too much unplanned
repairs and maintenance work in an LHD operation significantly reduces overall availability for the system and can also jeopardise the entire investment in automation.

![Planed maintenance process](image1)

![Operator assisted maintenance process](image2)

Figure 4. Planed versus operator assisted maintenance process.

The concept of Design-out-Maintenance for LHD machines have been addressed in a large national project in Sweden sponsored by SSF and by Swedish industry e.g. Sandvik AB and Boliden Mineral AB. The project shall develop an approach that can help integrate maintenance needs at the engineering design stage using RAMS (Reliability, Availability, Maintainability and Supportability) with an LCC (Life-Cycle-Cost) perspective. Another possible way to increase reliability that has been suggested is by condition monitoring of vital parts of the machine. By monitoring strategic parts and controlling the remaining useful life an optimised maintenance procedure can be achieved bringing accidental and un-controlled stops to a minimum. Modern computerised control system can efficiently assist the data retrieval from the machine and the communication of data to the surrounding mining system.

4 Concluding Remarks

The usages and success of automated LHD systems has mainly focused on productivity and safety. However the operation and maintenance issues that constantly have been reported during more than 20 years of use of automated LHD’s cannot be neglected. High reliability is a necessity for LHD automation where the operators have been removed from the vehicle and maintenance staff is not always available with short notice. Going from “constant operators fixing” to planned maintenance is vital for automation. The design parameter for LHD will be addressed in a national research project in Sweden as well as the possibility to develop condition based technique that can predict remaining useful life an thereby optimize maintenance actions. The overall goal is to develop efficient automation systems for other and also smaller mines.

References


TPM framework for underground mobile mining equipment; 
A case study

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In underground mines, mobile mining equipment is critical to the production system. Drill rigs for development and production, vehicles for charging holes, LHDs for loading and transportation, scaling rigs and rigs for reinforcement and cable bolting are all important units in the process to generate a continuous ore flow. For today’s mining companies, high equipment availability is essential to reduce operational and capital costs and to maintain high production. High and controllable reliability is also important especially in attempts to automate the production equipment. This paper compares existing maintenance work in a Swedish and a Tanzanian mine. The various maintenance procedures are identified and evaluated based on a TPM framework.

**Keywords:** TPM, Maintenance, Maintenance strategy, LHD.

1. Introduction

Maintenance is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform its required function (EN 13 306 2001). The maintenance of mining equipment is both challenging and expensive. Over the years, remarkable progress has been made in maintaining equipment in the field, but factors such as complexity, size, competition, cost and safety continue to challenge maintenance engineers (Unger and Conway 1994). Increased mechanization, automation and amalgamation of processes within mines have further complicated the issue (Kumar 1996). Mining equipment maintenance costs range from 20% to over 35% of total mine operating costs, and they are continuing to increase (Unger and Conway 1994). To control these costs, mining companies have focused on areas such as optimizing scheduled maintenance operations, deferring non essential maintenance, reducing maintenance manpower, controlling inventories of spare parts more effectively and using contract maintenance support (Unger and Conway 1994). They look for better maintenance practices for their mobile

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equipment, especially in underground mining operations where control of maintenance costs requires effective maintenance planning.

It is possible to implement a successful maintenance planning system in a mine as long as systems and procedures provide a logical, disciplined approach to maintenance. Better control of maintenance through team work, proper and timely accomplishment of tasks such as data recording and reporting also play a major role. This paper discusses the concept of Total Productive Maintenance (TPM) and evaluates two case-study mines from a TPM point of view.

1.1 Total Productive Maintenance (TPM)

TPM consists of a range of methods known to improve reliability, quality and production. More specifically, TPM aims to maximize equipment effectiveness by changing the corporate culture to improve a company’s personnel and plant. Cultural change at a plant is difficult; it involves personnel working in small groups, machine operators having a role in the maintenance program and the maintenance department providing good support (Willmott and McCarthy 2001). TPM seeks to develop a "maintenance-free" design, asking all employees to help improve maintenance productivity by stimulating their daily awareness (Nakajima 1988).

In any industry, the performance of a company’s main priorities needs to be measured by means of key performance indicators. Common parameters include total system/plant effectiveness, system/plant productivity, availability, cost efficiency and quality (Moubray 1997). TPM is in the upper part of the hierarchical asset management pyramid shown below (Figure 1) since it involves both technical and human aspects. TPM is a good concept to use in mining because human factors play a significant role in the operation of a mine. In fact, because operators are quite isolated, management has to handle both technological issues and human factors.

Yeoman and Millington (1997) list the five pillars (Figure 2) of TPM as:
- Increased equipment effectiveness
- Training
- Autonomous maintenance
- Early equipment management
- Planned preventive maintenance.
In its measurement of overall equipment effectiveness (OEE), TPM goes beyond availability or machine uptime to factor in all issues related to equipment performance. The formula for equipment effectiveness must look at availability, the rate of performance and quality. This allows all departments to be involved in determining equipment effectiveness (Moubray 1997). Training is equally important in TPM; the aim is to develop learning and understanding through real-life experience. TPM also seeks to establish autonomous maintenance which refers to operator asset care. When establishing autonomous maintenance, there are seven steps to consider: these include creating an awareness of the equipment, order, cleanliness and discipline at the workplace. Others are creating and following cleaning and lubrication standards, and undertaking general inspections of the equipment. In TPM, special attention is given to early equipment management or the reduction of the life cycle costs in the early stages of the process. Finally, to improve the planning of preventive maintenance, details vary depending on the industry, but in all cases, it is important not to perform unnecessary
maintenance. The best tool for condition monitoring is the operator who knows his/her equipment and feels responsible for it. (Willmott and McCarthy 2001)

1.2 Maintenance types and strategies
According to EN 13306 (2001) standards (Figure 3), maintenance can be grouped into two major groups, Preventive Maintenance (PM) and Corrective Maintenance (CM). PM can be further subdivided into condition based maintenance and predetermined maintenance which implies that PM can be time based or condition based. CM can be subdivided into two subgroups: deferred and immediate. CM is a reactive maintenance approach; PM is proactive.

Figure 3 - Maintenance overview chart according to EN 13 306 (2001)

1.2.1 Corrective Maintenance (CM)
CM is the maintenance carried out after fault recognition and is intended to put an item into a state in which it can perform its required function (EN 13 306 2001). This is the most expensive form of maintenance, especially if it is urgent. Since there is little time for planning and coordination, the start-up cost and the cost of lost production can be large (Kumar et al. 2010). As it does not involve forecasting failure, CM is often applied when it is difficult to predict when an item will fail.
1.2.2 Preventive Maintenance (PM)
PM is carried out at predetermined intervals or according to prescribed criteria; it is intended to reduce the probability of failure or the degradation of an item (EN 13306 2001). All preventive management programs are time driven. The item to be maintained can either be replaced or reconditioned depending on its condition. As noted above, PM can be divided into condition based or predetermined maintenance (Coetzee 2004).

2. Case studies
This paper considers two case studies, a mine in Sweden and one in Tanzania. The work is limited to maintenance of mobile mining equipment with special focus on Load Haul Dump machines (LHDs). The research approach includes questionnaires, oral interviews, discussions with stakeholders and data collection.

2.1 Case study 1: LKAB Malmberget mine, results and analysis
LKAB's Malmberget mine is the second largest iron ore mine in Sweden. The mine is owned by Luossavaara-Kiirunavaara AB (LKAB) and has an annual production capacity of over 12 million tonnes of iron ore. It is located in Gällivare in the north of Sweden and contains about 20 ore bodies spread over an underground area of about 5 by 2.5 km. Seven are currently being exploited. Mining began in 1888, and since then, over 350 Mt of ore have been extracted. LKAB employs about 1,000 people at Malmberget. In 2009, Malmberget produced around 4.3 Mt of pellets out of LKAB’s total production of 17.7 Mt of pellets. Magnetite is the principal iron ore mineral, although some areas contain significant amounts of haematite (Net resources international 2011).

As it was not possible to interview all department members, we selected the key personnel responsible for the maintenance department activities; the selection process was based on covering all levels of maintenance department processes. Discussions and interviews took place with maintenance manager, maintenance planner, maintenance supervisor and operator of the LHD machine. The findings of the interviews and discussions are presented below, along with the data analysis.
2.1.1 Maintenance workshop and storage

Currently, the mine has about 50 mobile equipment units, including drill rigs, LHDs, scaling machines, charging trucks, etc. There are three types of workshops in the mine. The first repairs development vehicles (drill rigs, scaling machines, concrete trucks, trucks, etc.). The second maintains LHDs (Figure 4), scaling machines and big boulder trucks. The third deals with maintenance trucks, mining trucks, fire trucks and busses. Maintenance services from major services to small repairs, bearing and brake changing, transmission and motor changing are done in workshop two. The repair work includes boom repair, bucket repair and equipment structural repair. The maintenance team has up to 60 workers. Another 8 employees are at a high managerial level. The department has 3 shifts with 5 persons in each.

Figure 4 - Underground workshop (number 2); to the left is the LHD in maintenance and to the right is the front of the LHD with its bucket being removed for repair

The mine has an underground storage room at level 815m, where most of the materials and spare parts are stored. Various other special underground storerooms contain big materials and spares such as tires and buckets. The mine also has a storage room which is shared with Kiruna mine. Briefly states, the storerooms’ management function is to ensure an adequate inventory of parts to meet the mine’s needs. Figure 5 shows a storeroom with hydraulic pipes and tubes, as well as other spare parts such as fittings, bolts and nuts.
The purchasing department buys all spare parts and materials. The ordering of materials/spare parts and purchase procedures are the following. First, the work order is written using Movex, a resource planning, scheduling and inventory control software. A service person or maintenance planner is responsible for the work order. The manager approves the order and sends it to the purchase department who completes the order. If the spare part or material requirement is urgent, it is ordered immediately, and the paperwork comes later. The maintenance planner can also order materials that are not available in the storeroom or that are running short.

2.1.2 Maintenance work programs

The flow of maintenance work can be categorized into PM servicing and failure fixing/repair. Inspection is done by the operator at the start of each shift. PM servicing is done every 250, 500, 1000, 2000 machine engine hours; an overall inspection takes place after initial cleaning of the machine to identify other necessary maintenance tasks. Servicing of the engine, converter, gearbox, hydraulic pump and transmission system is done after a predetermined amount of machine hours. In addition to the workshop, a field service team fixes failures immediately when that is possible. The work order for each job is written by a service person or by the maintenance planner. Breakdowns, especially major ones, greatly affect the maintenance planning budget, and this is
normally shown in increased maintenance cost/ton. Major causes of LHD breakdown are faulty hydraulic systems, electrical systems, engines and tires.

2.1.3 Maintenance strategy
The maintenance strategy of the department follows the standard EN 13306, (2001). For a better understanding of the maintenance process, CM and PM data were analyzed for the LHDs were analyzed. We found that the amount of time spent for CM was on average 70 percent more than the time spent for PM during all years of analysis, 2006 to 2010. This means that attention must be paid to the CM time.

2.1.4 Maintenance performance indicators
The main goal of the production and maintenance department is to achieve optimum production with minimal or no obstructions. With the maintenance planner’s input, the production manager and repair crew attempt to keep 9 out of 13 LHDs available at all times. The key performance indicators of the department are cost per ton (SEK/ton), mean time to failure (MTTF) and equipment downtime. The person responsible for measuring these indicators is the maintenance planner or maintenance engineer.

2.1.5 Improvement groups
The department’s PM improvement plans include collecting suggestions from the workers in the department with a view to making improvements and providing savings. The ideas are reviewed by a committee; with the help of the maintenance planner, the committee calculates the savings potential, and an award is given to the person who makes the best suggestion.

2.1.6 Education and training
There is some training for the maintenance crew and the LHD operators, but it could be more effective and properly planned. There is a need to establish effective training schedules and programs for the maintenance staff. LHD operators receive on-the-job training during normal working operations under the supervision of an experienced operator (trainer); this takes two to three weeks depending how quickly the trainee
learns the work. When the new operator manages to run the machine, he/she is given the same work as the more experienced operators.

2.1.7 Health and safety issues
Risk analysis is normally performed in the mine and to ensure proper safety management, risks, incidents and accidents are continually reported and worked out. The plan is to improve safety through the immediate reporting of risks, incidents and accidents in the mine. Safety rounds are currently being made as well; every person has to visit 2 internal workplaces per year; high ranking employees (managerial level) have to visit 15 workplaces per year. They investigate how regulations are being followed and how workers use safety gears and equipment, escape routes and assembly points, and they conduct talks on other worker safety issues.

2.1.8 Continuous reliability improvement and feedback
The continuous reliability improvement system at the department is reactive, meaning that improvement groups are formed when a problem arises. Feedback is an important tool in any organizational department, but in this case, the feedback is not effective, especially to operators.

2.2 Case study 2: Barrick Gold Corporation Tulawaka mine, results and analysis
The Tulawaka mine is located in northwest Tanzania, in the Biharamulo District of the Kagera Region. It is an open-pit mine with an underground access ramp located at the bottom of the pit. Tulawaka is a joint venture between African Barrick Gold and Northern Mining Explorations Ltd. Barrick holds 70 percent interest and is the operator. In 2009, Barrick’s share of production was 66,000 ounces of gold at $413 per ounce, with Barrick’s share of proven and probable gold reserves estimated at 93,000 ounces of gold. Tulawaka’s life as of December 31, 2009, was estimated to be approximately two years based on proven and probable reserves. According to a Tulawaka responsibility report (2010) an updated mine plan based on the current successful underground mining is being prepared; this may result in the extension of the mine life. Current operating capacity of the mill operations is approximately 1,320 tonnes per day. Total production in 2009 was approximately 94,000 ounces of gold at an overall recovery rate of 94.1 per
A study of the operation and feasibility of mining the ore body below the pit with underground methods is being done as well.

At the Tulawaka mine, we interviewed maintenance personnel at different hierarchical levels.

2.2.1 Maintenance workshops and storage
Currently, the mine is not deep enough to accommodate an underground maintenance workshop and storeroom, although there are plans to construct one for minor repair and services. Maintenance is performed in a central surface workshop supported by the purchasing and warehouse units for materials and spare parts; the department also outsources maintenance. The workshop uses a team specialized in both surface and underground mining equipment. The department deals with the service of the following mobile underground mining fleet: 3 LHDs, 3 drill rigs and 3 tele-handlers. The maintenance work is done in three shifts and according to a Tulawaka responsibility report (2010) the maintenance department has about 25 employees. The maintenance department ensures continuous equipment availability and maintenance. The supply chain starts with the materials required by the department; the warehouse is contacted to check their availability. If spare parts or materials are not available, a quotation/proforma invoice for them is sent to the selected supplier, using a purchase requisition from the system. The major causes of LHD breakdowns in the mine are hydraulic system or electrical system, wear and tear caused by friction and expansion and contraction of materials.

2.2.2 Maintenance strategy
The department categorizes maintenance as planned maintenance, unplanned maintenance, corrective maintenance and condition monitoring. Preventive maintenance as a planned maintenance activity has been a key in the successful implementation of maintenance practices at the mine. But to ensure continuous availability and reliability, the department has designed the following improvement plan:

- Prepare maintenance schedule based on hours interval
- Put in place the maintenance kits
- Conduct condition monitoring and oil analysis
• Perform pre and post PM inspection
• Put in place all proper tooling for maintenance activities
• Introduce a service report system

Future plans of the department to reduce downtime include the following:
• Complete backlogs in a timely manner during planning downtimes
• Educate operators to report all defects they see during operations, and plan for execution as fast as possible
• Educate mechanics in inspection methods
• Introduce condition monitoring

2.2.3 Maintenance performance indicators
The main maintenance performance indicator at the mine is availability; this is the first priority in assessing maintenance effectiveness.

2.2.4 Education and training
The maintenance crew is trained in two ways. The first is classroom training; during training, the crew is removed from the work site to attend the session. Classroom training normally involves theories and discussions of the particular maintenance subject. The second is on-the-job training with the aid of an experienced maintenance worker.

2.2.5 Health and safety issues
The maintenance department follows the company philosophy which says that every person should go home safely and healthily every day. The mine is committed to achieving a zero-incident work environment with a safety culture based on teamwork and safety leadership. The company’s safety and health policy states that “nothing is more important than the safety, health and well-being of workers and their families”. Therefore, the department has implemented key safety programs and activities, including systems and policies, training for all crews, performance measurement, risk assessment processes, recognition programs for safety achievement, and a steady flow of information that keeps people focused on continuous safety improvement.
2.2.6 Continuous reliability improvement and feedback

To ensure continuous improvement of the maintenance process, the department provides feedback on the work and receives feedback from the production crew in daily meetings at the mine site.

3. Discussion

From a TPM perspective, the two mines have both similarities and differences.

Increased equipment effectiveness: From a maintenance perspective, neither mine uses the full concept of OEE; each has developed its own key performance indicators to control and manage maintenance and operation.

Training: Training is a very important issue for the development of multi-skilled persons. In mining workshops, the number of maintenance personnel is small. This reduces the reliability of the personnel, as training is oriented towards teaching specific tasks to specialists rather than training all workers to multitask. However, personnel can still be trained in basic tasks, so that a majority can perform them. Regardless of the amount of training in either mine, both could develop this further. Training needs to be continuous, well planned and documented. An evaluation of the current maintenance work in the LKAB mine maintenance department indicates the lack of an effective training program for staff members; this should be remedied. The department has to think of timely training so that the workforce can better maintain equipment. In Tulawaka, meanwhile, the reporting of downtime and repair has been a problem for the maintenance department; accordingly, the department should think of establishing standard reporting procedures. In addition, occasional training should be provided to the staff and the crew on how to report downtime.

Autonomous maintenance: The way to inspect and clean the machines is presently satisfactory in both mines but could be developed to improve maintenance and increase the workers’ sense of responsibility for the equipment and shop floor. Developing cleaning and lubrication standards would be a good first step. The policy of forming improvement groups or conducting discussions with the supplier when problems have already occurred needs to be reviewed. Feedback was identified as a problem in the LKAB mine: the shop floor workers do not receive feedback on the work they perform, and the planners do not get feedback on the performance indication measured data. If
workers receive feedback on their daily activities, they will perform better. Although there is some feedback in the Tulawaka mine, it could be better utilized and further improved.

*Early equipment management:* There is little information on this for either mine; however, it is our opinion that more could be done to reduce the life cycle costs of the equipment (LHDs).

*Planned preventive maintenance:* A mine maintenance workshop has to follow a strict PM plan because of agreements with the manufacturers and also because of environmental factors. Even so, improvements in proactive maintenance can improve the overall preventive maintenance. Maintenance departments should seek an optimal balance between a strict PM and improvements of PM. It is necessary to find the optimal PM improvement plan for each mine so the PM can be optimized. High CM is a problem, as it means a department frequently faces unplanned and immediate maintenance in its day-to-day activities. Proper PM planning and scheduling can reduce the high frequency of CM.

### 4. Conclusion

TPM is used in mining to eliminate waste by reducing or eliminating production time lost to machine failures. The goal of a TPM program is to ensure that fleets of mobile equipment and process lines are always available. By minimizing slow running equipment and downtime, maximum value is added at minimum cost.

However, successful TPM is a group effort where the entire organization works together to maintain and improve the equipment. New concepts such as autonomous maintenance and tools like OEE are worth considering but traditional methods continue to dominate; there is little desire to implement new techniques that directly involve workers.

The principal difficulties lie in the area of organizational change. When the organizational structure is flattened, teams can address issues with the greatest impact. As maintenance issues are addressed and total productive maintenance programs implemented, the true value of TPM begins to emerge. Employees join TPM teams, and operators are trained to perform routine maintenance items and assume an ownership role. This blurs the distinction between the roles of production and maintenance by
empowering operators to help maintain their equipment. The implementation of a TPM program creates a shared responsibility for equipment that encourages the greater involvement of all workers. In the right environment, this can be very effective in improving productivity.

A common misunderstanding is that the TPM method requires production employees to work more, thus reducing the number of maintenance personnel. This issue should be addressed to ensure that all employees cooperate with the implementation of TPM.

There are no strict rules for TPM application; rather, a tenable method for gradual and smooth application must be found. Workers from any level in the mine have to be gradually but constantly involved in the implementation of TPM. For good application of TPM, “top-down” involvement is fundamental, especially to change ways of thinking. For this reason, it is necessary to continue training and education, in both theoretical sessions and practical simulations, before on-site implementation takes place. In fact, after a simulation, the TPM approach should be tested in a pilot area.

In the starting phase, it is necessary to compile technical and economic information related to the performance parameters and to the costs of a maintenance system. An analysis of the starting situation allows a company to identify criticalities and to find possible solutions so that the next steps can be taken. Management procedures must be aligned with TPM, based on autonomous maintenance, work groups and increased worker competence.

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Maintenance indicators for underground mining equipment: a case study of automatically versus manually operated LHD machines

Maintenance Indicators for Underground Mining Equipment:  
a Case Study of Automatically Versus Manually Operated LHD Machines

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ABSTRACT
Key Performance Indicators (KPIs) are performance measures directly related to the overall goals of the company and some of them depend on the maintenance function. In mining companies top managers use the maintenance cost per unit versus budget as one of the KPIs. However many other technical, organizational and economical parameters in a company can be helpful during the decision making process.

In this paper the productivity of Load-Haul-Dump machines (LHDs), that is obtained when manual and/or automatic mode are used, are being analysed. The correlation between the productivity and the maintenance KPIs as well as the issues related to the acquisition of data will be shown in this paper highlighting the complexity of getting accurate decision process parameters.

It is recognized that the data for some of the components and failure modes originating from different sources are not compatible. This situation must be considered when compiling the data, especially to permit comparison the data should be made compatible. The problem of incompatibility is most severe when dealing with demand related failures. The philosophy and mechanisms of demand related failures as well as the methods used to denote the time and demand related failures in common form have to be taken into account.

Keywords: KPI, Indicator, Productivity, LHD, Automation

1. INTRODUCTION

There are several problems when using KPI as a maintenance measurement. Most of the problems are linked to the user who promotes, conducts and eventually uses them in their decision making.

- Too much data and too little information: The data acquisition has become relatively simple and cheap through the introduction of modern and powerful hardware systems and software. However, the enormous amount of data is a problem in itself and can be relatively difficult to analyze.

- The number of performance indicators: Identification of the key factors limits the number of indicators used for each FIGURE or department. Too many indicators only hinder the work for which they are made.

- Objectives and measures: There are situations where departments within the same company have conflicting interests in relation to the maintenance of their equipment. The purpose of the objectives is to ensure that a department’s efforts are aligned with the business needs and the company’s goal should be in focus.

- Time lag between action and monitoring results: Once a measure has been identified and implemented, the method of data collection and the frequency have to be specifically tailored to the factors involved: physical parameters, human factors, financial or organizational. Sometimes there is a lag between monitored result, for example time between failure, and action taken.

- Reasons for data collectors: The success of any measurement system is based on the data collection method used. When the data entering into a reporting system is poor or incorrect the result will be poor, unreliable and of little value. Massive data collections, which generate indexes un-known to the collector and with possible punitive burden on them, will result in suspicion and
unreliable data. If the data collector understands the purpose of the action, sees that the data collection is worth while and results in achieving his/her own objectives; the data will be more reliable.

All these problems happen for mining equipment where IT makes it possible to collect big amounts of data regarding to production, detailed movements of the equipments and duration of the activities. However, these kinds of assets have a blinking, non continuous, demand so KPI extraction becomes more complex. Considered equipment for this KPI study is the LHD that belong to this group of machinery and can be demanded in a non regular time basis.

The importance of LHD machines in most underground mines is evident today. The cost of operation and maintenance is one of the challenges, due to harsh environmental conditions, while high availability and reliability are others. The example used in this paper is a LHD machine that loads and transports ore in the underground mine. The decision to use manual loaders, which presently is the most common way of moving ore, is mainly due to the complexity of using autonomously operated loaders and the maintenance these vehicles requires. The discussion of using automatically operated loaders brings up a lot of questions and issues, mainly hard factors like productivity, cost, availability etc.

Production and maintenance data available in this study for this type of machinery can be described as follows and visualized in FIGURE 1:

- Production data: Automatically accurately generated production data regarding time for each bucket unload, ton/bucket, location of the loading and idle times.
- Maintenance data: Workshop records containing information about time spent in workshop, time entering and leaving the workshop, reason for maintenance and measures taken. This data are manually entered and are not as reliable as the production data that are automatically generated.

![Data time availability for KPIs extraction](image)

**FIGURE 1. Data time availability for KPIs extraction**

2. MAINTENANCE INDICATORS AND RAMS PARAMETERS

The search for good maintenance indicators leads to RAMS (Reliability, Availability, Maintainability and Safety) parameters which constitute a small and easily quantifiable parameter of the state of machinery, (Mora, 2002), and subsequent establishment of measurable objectives. The term functional safety was established for those which control board based on four parameters RAMS (FIGURE 2) is bounded by the values previously established by quantitative production, the manufacturer or any other user of the system.

Therefore functional safety is meant as a good tool to audit the maintenance function and propose appropriate measures to improve the deficiencies.
FIGURE 2. RAMS Parameters.

The following diagram (FIGURE 3) outlines the steps to follow when analyzing and optimizing the functional safety, (IEC 61511, 2003), of the system.


2.1 Stage 1. Functional analysis or organic functional architecture

The preliminary analysis should determine the utility of the LHD machine, i.e. a complete description of what it does, how it functions, values or parameters, etc. The functions performed by a system can be classified into five groups: Main features of Service or use, Functions of complementary service or use, Functions enforced Design features and Technical functions. These five functions are the functional architecture of the system and are essential for the further analysis and auditing system. As a result of this, FIGURE 4 shows the process diagram of an underground mining operation and is based on a case study performed at a Swedish underground mine. In the underground mining process the ore is excavated and loaded by one out of 10 LHDs. The machines transport the ore to the vertical shafts that are placed along the ore body and then dumped into the shaft. The ore falls, by gravity, down to the bottom of the shaft where it is loaded via a chute onto trucks for further transportation to one of several discharge stations. From the discharge station, the ore is being fed into a crusher (there are one crusher below each discharge station). After the ore has passed through the crusher, it enters a small buffer bin from which it is transported with a conveyor belt to one of several hoisters that take the ore up to the processing plant at the surface.
FIGURE 4. Flowchart from loading to processing plant. Adapted from Gustafson et al. (2008)

The focus of this paper is the first part where the LHD machines operates underground with loading and transportation of ore/minerals. The LHDs usually have a length of 8 to 15 meters with a weight of 20 to 75 tons, using either electrical or diesel power. Their structure consists of two parts connected by an articulation point which gives them a high level of manoeuvrability into the narrow mine drifts. The two sections of the unit each have one set of rubber wheels that are not steer able. The back of the machine contains the engine and the front contains the bucket. The LHD machines in the mine in this case study have two different operation modes, 9 of the LHDs are manually operated and one is semi-automatic:

- **Manual mode** (FIGURE 5): The operator remains in the cabin on top of the vehicle throughout the whole load-haul-dump cycle. The side position of the cabin makes it possible for the operator to see whether the vehicle moves in the forward or backward direction. Currently, manual operation of the LHDs is the most common way of moving ore in an underground mine. The advantage with manual operation compared to both remote control and tele-remote control is that the vehicle can move faster due to the limited sensory perception remote control offers (Roberts et al., 2000). Roberts et al. further describes the disadvantages with manual operation to be safety, driver fatigue and basic human errors.

- **Automatic mode** (FIGURE 6): In this case the operator controls one semi-automatic LHD from an office located inside the mine. From a safe environment the operators is required to monitor the vehicle and to be involved at some points in the loading cycle. The vehicle is transporting and dumping the ore autonomously and the operator only controls the vehicle during loading. The semi-automatic LHD can be manually operated when not used in automatic mode. In other cases, in other mining operations, where there are several automatic loaders involved in the operation, the control station could be located in an office inside or outside the mine and the operator could be able to operate several vehicles simultaneously from a safe environment.
2.2 Stage 2. Quantitative analysis

After defining the functional architecture the different parts of the machine can be sorted into two major groups with distinct treatment as repair or replacement:

- Reparable Items
- Non-repairable Items

The quantification of all elements and their classification on the basis of the above leads us to make analysis and predictions of Reliability, Maintainability, Availability and Safety. It is important to use indicators exportable, easily understandable and without double interpretations. The ideal is to use those indicators, coordinated by the international certification organizations (Svantesson, 2008). The quantitative data of the systems components can be modeled with the following parameters:

a) MTBF (Mean Time Between Failures).
b) MTTR (Mean Time to Repair), maintenance repair duration.

These parameters can be estimated from historical maintenance data. Since the LHD machines are operating in a harsh environment there are several issues that affect the operation and the total downtime. Besides the machine and personnel related issues there are mining related issues like fragmentation, oversized boulders, road conditions, ventilation etc that you have to consider when optimizing the operation. The LHD operation is not continuous and, as mentioned, dependent on other factors besides maintenance. For making MTTF and MTTR estimations it is important to match the data and classify it correctly. When calculating the reliability and availability figures the most common source of input data is the workshop record which in one way or another is being fed into the system by a physical person. This gives one reason for errors in the calculation and needs to be considered when analyzing the data. When comparing the workshop data with automatically produced production data it is clear that at several times when the machine is supposed to be in the workshop it is really operating and vice versa. This means that only trusting your workshop data for reliability analysis can make the results unreliable. Kumar (1989) mentions that it can be difficult to sort the data needed for reliability studies since it is not always available in a proper format.

2.3 Stage 3. Preliminary risk analysis

This analysis should be done from the beginning of the operation and must ensure the full and exhaustive list of incidents / accidents and may have consequences on the safety of personnel or material. Its goal is to move to list the dangers of the system and its possible causes, evaluating the quality of the gravity of the consequences of accidents and the implementation of corrective actions.

The preliminary risk, based on number of failures (FIGURE 7) and on time spent in workshop (FIGURE 10) indicates that the most critical components are different for the manual and semi-automatic machine.

- Semi-automatic loader: Most critical subsystem based on number of work orders are the hydraulics followed by the engine, electrical system, cabin and transmission. Based on time spent
in workshop the most critical subsystems are transmission and engine followed by hydraulics and automatic system.

- **Manual loader**: Most critical subsystem based on number of work orders are the hydraulics followed by the electric system, chassis, cabin and engine. Based on time spent in workshop the most critical subsystems are chassis followed by brakes, hydraulic system, electric system and other systems.

![Critical subsystems based on number of work orders](image)

In the graph we can observe different number of breakdowns associated with different modes of operation. We can extract valuable information from here because demand and time related failures will be different in number and severity depending on the operating mode used.

### 2.4 Stage 4. Analysis of failure mode or FMEA

Once the most critical components have been identified, a FMEA analyze has been performed. The analyses of failure modes, their effects (FMEA) proceed by a functional analysis and a study of predictive reliability (Quantitative Analysis), allow you to list and classify the predictable failures of a team. The FMEA intends to obtain an optimal system reliability drawing experience and expert opinion, using a simple and systematic analysis of possible failures. FMEA can be used in the design of the equipment and in its maintenance, is therefore an ideal tool for comparing the correlation between the performed maintenance and proposed maintenance by the experts and technicians (MIL-STD-1629A, 1980).

Whenever needed, the LHD has to be available which means that the failures need to be divided into time related failures (failures while operating) and demand related failures (failures when needed) (FIGURE 8). This is especially important since the LHD operation is not continuous. Time related failures are failures occurring while operating the machine. Demand related failures occur when the machine is required to be operating but fails to start. It is important to separate the time related and the demand related failures in order to sort the failure data correctly so the right calculations can be performed regarding for example availability and reliability of the machine. When finding the quantitative data of each machines (MTBF and MTTR) for time and demand related failures, it is possible to determine the availability.
TIME RELATED FAILURES
(Failure while working)

Downtime
Time in workshop
Uptime

DEMAND RELATED FAILURES
(Attempt to start and failure has happened)

Uptime
Time in workshop
Downtime
Planned shutdown

FIGURE 8. Timing diagram for time and demand related failures

In the production performance graph (FIGURE 9), based on automatically produced production data from 1 year for one LHD, it is possible to see how the production rate changes due to for example coffee-lunch and shift brakes. During the night the LHDs are being operated only on occasion which explains a part of the lower production during this period. There is also less production due to blasting which occurs every night somewhere between midnight and one. There can not be any loading until the blast has been ventilated. One advantage with having a semi-automatic loader is that it is possible to start loading much sooner after blasting than it is with manual operation due to safety reasons and the fact that the machine is not as sensitive to the gas from the blast as a human is.

The shape of this picture shows the demand of the machine and the different periods when the time related failures can be found i.e. during periods where the machine has been operating at the time of a breakdown. Otherwise in periods of less production where the machine is starting and stopping several times we can find failures when the vehicle doesn’t start, these are demand related failures that we shouldn’t mix with the previous ones. The data analysis will be much better when dividing the two different failure rates to different type of components e.g. demand related failures are often connected to for example the starter or the battery while the time related failures are related to for example hydraulics.
FIGURE 9. Average production rate per 24 hours for one semi-automatic LHD.

The comparison between the two modes of the semi-automated LHD is complicated by the fact that there can be a problem with the automatic system in the mine that makes it impossible to run the machine in auto mode but instead the machine is used in manual mode. There are both advantages and disadvantages with the different operation modes and choosing the optimal mode is difficult.

2.4 Stage 5. Maintainability analysis

Having good maintainability of a system is essential and ensures together with reliability, the level of the systems availability. A maintainability policy takes into account the maintenance policy and the reliability constraints. Thus we can define maintenance tasks and analyze the phases and stages of repair, determine the qualifications of the personnel, material and tooling.

The most popular indicator to measure is the quality of the maintenance functions, i.e. maintainability is MTTR. This parameter is a World class indicator and worldwide accepted. However available information for this analysis is the time spent in workshop as visualized in FIGURE 10. This time includes time to repair but also logistic time regarding to waiting time in repairment queue or spare parts delay. This is one of the most important weaknesses of the data collection system since it is not possible to evaluate the real abilities of the maintenance team in repair tasks because these time are hidden and mixed with logistic aspects of the workshop management. Further more the enter and exit times to the workshop are manually entered into the system which questions the accuracy. In this case study up to one third of the manually entered time are not consistent with the automatically recorded production times.
As a result of these analyses the system is being modeled in two ways. First, we integrate functional aspects extracted from the functional analysis. In this way the system can be visualized with a block reliability diagram (RBD) to show the machines or equipment in series, parallel and in reserve. All these critical subsystems must be working simultaneously to get the desired function since these components are serial configured in a Reliability Block Diagram approach (FIGURE 11).

FIGURE 11. Serial configuration of RBD based on criticality analysis
If the maintainability aspects are being introduced, the friendliest tool to show the function of the system is the Markov state diagram where transitions between uptime states and downtime states can be clearly studied (Samanta et al., 2004).

3. CONCLUSION

Maintenance KPIs should be obtained with the available data and aligned with corporative goals. A good metric is focused on maximizing the benefits and value added of each activity. Poor metric not aligned with these goals can often bring about unwanted results. Another element that plays an important role in the effectiveness of performance measures is the accuracy of the data. The introduction of wrong or corrupt data in the performance measurement system is very harmful. It simply leads to wrong decisions.

Often the data are few, poorly measured or can not be relied upon due to doubtful veracity. Understanding how to manage the reliability of data is the first step to get accurate and proper KPIs. Indicators such as MTBF and MTTR are particularly sensitive in terms of accuracy, because they are statistical averages of a physical variable. Its accuracy is linked to the number of items found and the observation period. The more data there is the higher accuracy the analysis gets. In the absence of large numbers of items, or if you wish to obtain the average time between failures for each machine, it is advisable to work with very large periods of observation to ensure the reliability of the results. In the case of blinking demand, MTBF is especially sensitive because we have failure rates related to both time and demand and therefore get two different MTBFs associated with these factors. Both of them can be merged adding these failure rates and it is important to be aware of the existence of these different types of failures and the consequences derived from them.

Regarding to MTTR the importance of proper data collection is highlighted to break down the time in workshop for the different components that provide users of valuable information of maintenance team skills and logistic management of the workshop.

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Maintenance Performance Analysis; A case study of Manual and Semi-automatic LHD machines

Maintenance Performance Analysis; A Case Study of Manual and Semi-automatic LHD Machines

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ABSTRACT
Loading and hauling of blasted ore from stopes to dumping points constitute a significant portion of the production costs for mining companies. This work is commonly done by Load Haul Dump (LHD) vehicles in underground mines. With the increasing complexity and degree of automation of today’s equipment, capital costs have steeply increased. Therefore, a cost-effective operation of equipment is essential. This has pushed manufacturers and users to try to decrease the cost of energy consumption and maintenance through measures directed towards improvement of reliability, availability, and productivity. The use of automated LHDs has been in focus for a number of years due to its potential to increase productivity. However, mine management needs adequate tools to decide where to continue with manually operated loaders, or where to complement or replace these with automatic ones. A detailed review is necessary to make an informed decision. The increasing focus on safety and ergonomics gives an edge to automatically operated loaders over manually operated ones. In order to gain from the investment it is crucial to increase the amount of preventive maintenance since the operator no longer will be there to perform maintenance or take the vehicle to the workshop. Important performance indicators (PI) and key performance indicators (KPI) to consider when making such decision is e.g. availability, reliability, productivity, and maintenance cost. In this study, real time process data and maintenance data, from an underground mine in Sweden, have been refined and aggregated into KPIs in order to be able to compare and evaluate the benefits and drawbacks with manual and automatic LHDs.

Keywords: KPI, Indicator, Productivity, LHD, Automation, Maintenance

INTRODUCTION
Maintenance is the combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform its required function [2]. It is both costly and challenging to properly maintain mining equipment. Factors like complexity, size, competition, cost and safety continue to challenge maintenance engineers despite recent progress in maintaining equipment in the field. The issue has been further complicated by increased mechanization and automation [10]. The maintenance costs of a typical mining company account for 30-65% of the total mine operation cost [4]. Therefore, mining companies are focusing on optimizing preventive maintenance, reducing manpower, deferring non-essential maintenance, and establishing more efficient spare part control etc. Good maintenance strategies are essential to optimize the maintenance of mobile equipment. Because it is costly and time consuming to measure
performance [13], however, it is important to establish and maintain relevant indicators [12].

An indicator is a combination of a set of performance measurements. A key performance indicator (KPI) can consist of several indicators and metrics. KPIs are directly related to the overall goals of the company, including the maintenance function. One KPI used by managers in mining companies is the maintenance cost per unit versus budget, but many other technical, organizational, and economic parameters can be helpful to decision making. For example, many mines use availability of production assets, production volume capacity and utilization as KPIs to evaluate the performance of the maintenance and operation groups [11]. Reducing the number of unscheduled breakdowns as well as reducing the repair time is important to improve equipment availability [8].

To achieve the production volume capacity, maintenance becomes the main improvement tool. For this purpose the maintenance performance has to be measured in order to optimize maintenance parameters such as availability. With IT, it is possible to collect large amounts of data on for example production, maintenance and duration of activities [5], but this can cause problems in the following areas [15]:

- Too much data and too little information: Through the introduction of powerful and modern hardware and software, collection of data has become relatively cheap and simple. However, a large amount of data can be difficult to analyze, making data a problem in and of itself.

- The number of performance indicators: The number of indicators used for each department is limited by the identification of the key factors. Having too many indicators can actually hinder the work.

- Objectives and measures: There can be situations where different departments within the same company have conflicting interests relative to the maintenance of their equipment. Each department’s efforts must be aligned with business needs and the company’s goals.

- Time lag between action and monitoring results: Once a measure has been identified and implemented, the frequency and method of data collection have to be specifically fitted to the factors involved: physical, human, financial, or organizational. There can sometimes be a lag between the monitored results, for example, time between failure and action taken. One cannot expect an immediate change in indicators when performing an action. It usually takes time to implement new strategies.

- Data collector: The data collection method ensures the success of any measurement system. When the data entered into a reporting system are poor or incorrect, the result will be unreliable and of little value. The data will be more reliable if the data collector understands the purpose of the action, collects the data appropriately, and achieves his/her own objectives.

Problems can arise when management fails to set goals at the highest level or fails to ensure that these objectives are correctly translated into sub-goals at lower levels. The objectives must be communicated through all departments to ensure that everyone is going in the
same direction. It is also important to have the right maintenance indicators. For example, using reliability, availability, maintainability, and safety as indicators yields a small and easily quantifiable amount of information on the state of the machinery [4] and the successful establishment of measurable objectives. Indicators should be exportable, easily understandable, and lacking double interpretations. Ideally, the indicators will be coordinated by international certification organizations [14]. The following two parameters can be modeled using the quantitative data of the system components:

a) MTBF (Mean Time Between Failures). MTTF = Total operating time/number of failures [3].

b) MTTR (Mean Time to Repair). MTTR = Total time to restore/ number of failures [3].

These parameters can be estimated from the historical maintenance data and have traditionally been used to evaluate the maintenance of LHDs [8]. Other well-known maintenance indicators include down time, utilization, cost, and availability. Availability is defined as the “ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided” [2]. In mining, an indicator used for productivity is often the number of tons produced/unit time.

This paper presents a case study analysing the productivity of manual and/or automatic LHDs. The correlation between productivity and the maintenance KPIs, as well as the issues related to the acquisition of data, highlights the complexity of defining accurate decision process parameters. LHD machines belong to the category of mobile mining equipment and have a blinking, i.e. non-continuous demand which make KPI extraction more complex [7]. Data originating from different sources are not compatible, and this must be considered in the analysis. For purposes of comparison, the data must be made compatible.

**CASE STUDY**

Figure 1 shows the process diagram of an underground mining operation and is based on a case study performed at a Swedish underground mine. In the underground mining process, the ore is loaded from the draw point by LHDs; this particular mine deploys 13 LHDs. The machines transport the ore to the vertical shafts along the ore body and dump it into the shafts. The ore falls to the bottom of the shaft where it is loaded through a chute onto trucks to be transported to one of several discharge stations. From the discharge station, the ore is fed into a crusher (there is one crusher below each discharge station). After the ore has passed through the crusher, it enters a small buffer bin from which it is transported on a conveyor belt to one of several hoisters that take it to the processing plant at the surface.

![Process Diagram](image.png)

**FIGURE 1** Flowchart from loading to processing plant. Adapted from [6]
This paper focuses on the first part of the process, looking at the LHD machines that load and transport the ore/minerals. The LHDs studied here are 11 meters long and weigh 55 tons. They run on diesel power. Each consists of two parts connected by an articulation point which gives them a high level of manoeuvrability in the narrow mine drifts. Each section of each unit has a set of rubber wheels that are not steerable. The front of the LHD contains the bucket, and the back contains the engine. The LHD machines in this mine have two different operation modes: out of 13 LHDs, 12 are manually operated and one is semi-automatic and operated from a control room (Figure 2). For this study, two LHDs, one manual and one semi-automatic, have been selected; they have the same age and specifications. Both were manufactured in 2006 by the same producing company. The only difference is that the semi-automatic LHD is fitted with an automatic system. The installation of the automated system was finalized during the first year of operation; starting in 2007, the semi-automated LHD could be operated in both modes, and it is easy to switch between modes. The vehicle is transporting and dumping the ore autonomously and the operator only controls the vehicle during loading via remote control. Basically, it is put into automatic mode for greater safety and productivity. More specifically, every night, blasting occurs and after that the gas has to be ventilated. Until the gas has been ventilated, no human can be in the production area. The semi-automatic LHDs can be used in automatic mode and continue to produce when there is gas and dust in the mine and humans cannot work.

![FIGURE 2 Autonomous operation (Courtesy of Sandvik)](image)

Manual loaders are most commonly used to move ore in underground mines, mainly because of the complexity of autonomously operated loaders. The complexity involves several areas that have to function in order to operate the LHD in automatic mode:

- IT, communication system, navigation system
- Infrastructure, mine environment, control rooms
- Human issues such as skill, competence, training.

A discussion of whether to switch to automatically operated loaders brings up problematic issues of productivity, cost, availability etc. The cost of operation and maintenance is especially challenging, given the harsh environmental conditions; high availability and reliability are other challenges. To make a decision, the different operation modes should be carefully evaluated using good KPIs. The functionality of the LHD can be represented in a block diagram structure [1]. All the critical subsystems shown in the diagram must be working simultaneously to get the desired function since they are serially configured in a RBD (Figure 3).
Since the LHD machines are operating in a harsh environment, several issues other than maintenance affect the operation and the total downtime. Besides machine and personnel related issues, certain mining related issues, such as fragmentation, oversized boulders, road conditions, ventilation etc., must be considered when optimizing the operation. Therefore, it is important to match the data and classify it correctly.

DATA
As noted, maintenance and production data covering the period from January 2007 to August 2010 have been collected and analysed for a manual and a semi-automatic (LHD Figure 4).

- Maintenance data: The workshop records contain information on the time spent in the workshop, the estimated time for entering and leaving the workshop, the reason for maintenance and the measures taken. The workshop data are manually entered into the CMMS (Computerized Maintenance Management System) and are not as reliable as the production data that are automatically generated. From the maintenance data, it is possible to classify the failures and maintenance types that correspond to the different components and sub-systems of the LHD.

- Operational data for the semi-automatic loader: The data consist of idle-times (giving reasons for the idle-times and the idle-time in hours), operation time in hours for the automatic mode, and tonnage produced for each day. This information is only available for the semi-automatic LHD and is manually entered into the system by the person responsible for LHD automation.
Production data (Table 1): Automatically accurately generated production data regarding time for each bucket unload, ton/bucket, location of the loading, and idle times. The downtime registered between the loading on January 1 and January 2 shows a gap in production which, in this case, relates to the LHD being in the workshop. The advantage with this data is that it is possible to track down, for example, every bucket load in every relevant mine tunnel.

**TABLE 1** Example of automatically produced production data with time for bucket unloading and bucket weight.

<table>
<thead>
<tr>
<th>Time</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-01-01 08:11</td>
<td>17.6</td>
</tr>
<tr>
<td>2010-01-01 08:17</td>
<td>13.0</td>
</tr>
<tr>
<td>2010-01-01 08:19</td>
<td>18.7</td>
</tr>
<tr>
<td>2010-01-01 08:22</td>
<td>18.7</td>
</tr>
<tr>
<td>2010-01-01 08:41</td>
<td>20.7</td>
</tr>
<tr>
<td>2010-01-01 08:44</td>
<td>21.4</td>
</tr>
<tr>
<td>2010-01-01 08:47</td>
<td>18.9</td>
</tr>
<tr>
<td>2010-01-01 08:49</td>
<td>16.4</td>
</tr>
<tr>
<td>2010-01-01 08:51</td>
<td>19.2</td>
</tr>
<tr>
<td>2010-01-02 06:10</td>
<td>14.5</td>
</tr>
<tr>
<td>2010-01-02 06:11</td>
<td>16.8</td>
</tr>
<tr>
<td>2010-01-02 06:13</td>
<td>15.6</td>
</tr>
<tr>
<td>2010-01-02 06:21</td>
<td>23.0</td>
</tr>
<tr>
<td>2010-01-02 06:29</td>
<td>22.4</td>
</tr>
<tr>
<td>2010-01-02 06:31</td>
<td>22.9</td>
</tr>
<tr>
<td>2010-01-02 06:33</td>
<td>22.6</td>
</tr>
<tr>
<td>2010-01-02 06:35</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Mean time to repair (MTTR) is a very commonly used maintenance performance indicator; MTTR = Total time to restore/Number of failures [3]. The time spent in the workshop (Figure 5) includes in the data collected from this case study mine both time to repair, as well as logistic times, such as waiting time in the repair queue or spare parts delays. This is an important weakness of the data collection system: it is not possible to evaluate the real abilities of the maintenance team in repair tasks because these times are hidden in the logistic aspects of workshop management. The logistic delay time is rarely specified and can many times be relatively large compare to the TTR. Furthermore, because enter and exit times to the workshop are manually entered into the system, their accuracy is questionable. Having automatically produced data is very unusual and is a great advantage when doing the analysis and calculations.

![FIGURE 5 Mean time to repair, MTTR](image-url)
When calculating maintenance indicators like reliability and availability, the most common source of input data is the workshop record which in one way or another is manually fed into the system. This human element needs to be considered when analysing the data since it points to the possibility of errors in the calculations. In this case study when the workshop data and the automatically produced production data was compared, it was found that occasionally when the machine is supposed to be in the workshop, it is really operating and vice versa. In this case study, up to one third of the manually entered times are not consistent with the automatically recorded production times. This means that only trusting workshop data for reliability and availability analysis might make the results unreliable.

It can be difficult to sort the data needed for reliability studies since it is not always available in a proper format [9]. Yet the LHD has to be available whenever it is needed. This means that the failures must be divided into demand related failures (failures when needed) and time related failures (failures while operating) (Figure 6). Since the LHD operation is not continuous, this becomes especially important. In order to sort the failure data correctly, it is essential to separate time related and demand related failures so the right calculations can be performed regarding availability. By collecting the quantitative data of each machine (MTBF and MTTR) for time and demand related failures, it is possible to determine availability.

![Timing diagram for time and demand related failures](image)

**FIGURE 6. Timing diagram for time and demand related failures**

**KPI SELECTION AND EXTRACTION**

The main goal of the production and maintenance department is to achieve optimum production with minimal or no obstructions. The key performance indicators of the department include cost per ton (SEK/ton), mean time to failure (MTTF), and equipment downtime. The maintenance planner or maintenance engineer is responsible for measuring these indicators. In the following section, production and maintenance performance are analysed separately and then compared.
Production performance

One consequence of an availability optimization is an increasing capacity. The performance of the LHDs is measured in tons/month; the capacity desired by the company is to produce 100 000 tons/month per LHD.

The production data in Table 2 show the ton/bucket and ton/machine hour for the semi-automated and manual LHDs. For the semi-automated machine, there is also a separation between tons produced in automatic and in manual mode. The filling rate is similar for both LHDs. The manual machine seems to move more tons/machine hour; this is partly explained by the difference in cycle times. Figure 7 shows the frequency of cycle times of the load haul dump cycles for one year for the semi-automated and manual LHDs. Cycle times depend on the structure of the mine and the location of the loading and dumping points. In cycle times longer than 8 minutes, the frequency is higher for the semi-automated LHD. This can be explained by the fact that for part of 2009, the semi-automated LHD was operating in a very long mine tunnel when it was in automatic mode. When comparing the different operation modes for the semi-automated LHD, we find that the LHD produces more ton/machine hour in the manual mode than in the automatic mode. The reason for the different cycle times is not clear; however one possible explanation could be that it is generally faster to load the bucket when the operator is in the machine.

<table>
<thead>
<tr>
<th></th>
<th>Semi-automatic</th>
<th>Manual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Automatic mode</td>
</tr>
<tr>
<td></td>
<td>ton/bucket</td>
<td>ton/machine hour</td>
</tr>
<tr>
<td>2008</td>
<td>19.6</td>
<td>241</td>
</tr>
<tr>
<td></td>
<td>333</td>
<td>285</td>
</tr>
<tr>
<td>2009</td>
<td>21.3</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>223</td>
<td>274</td>
</tr>
<tr>
<td>2010 (8 months)</td>
<td>22.3</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>266</td>
<td>306</td>
</tr>
<tr>
<td>Average</td>
<td>20.8</td>
<td>274</td>
</tr>
<tr>
<td></td>
<td>274</td>
<td>288</td>
</tr>
</tbody>
</table>

FIGURE 7 Frequency of cycle times for the load haul dump cycle of manual and semi-automated LHD
There is not a big difference in utilization between the manual and the semi-automatic LHD (Table 3). Table 3 uses clock hours; Table 2 uses machine hours. The semi-automatic LHD has been operating in automatic mode for about 50% of the total operating time; this seems reasonable given the reasons for using it in automatic mode.

<table>
<thead>
<tr>
<th>Year</th>
<th>Semi-automatic LHD</th>
<th>Semi-automatic LHD</th>
<th>Semi-automatic LHD</th>
<th>Manual LHD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operating hours</td>
<td>Operating hours</td>
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<td></td>
<td>Automatic mode</td>
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<td></td>
<td>(hrs/day)</td>
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<td>8.3</td>
<td>8.3</td>
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<tr>
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<td>6.6</td>
<td>8.2</td>
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</tr>
<tr>
<td>Year 3</td>
<td>2.4</td>
<td>4</td>
<td>6.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Year 4 (8 months)</td>
<td>3.3</td>
<td>5.7</td>
<td>9.0</td>
<td>9.8</td>
</tr>
</tbody>
</table>

The production performance graph (Figure 8) is based on automatically produced production data from one year for one LHD. From the graph, it is possible to see how the production rate changes due to, for example, coffee, lunch, and shift breaks. At night, the LHDs are operated only when needed, and this partly explains the lower production during this period. There is also less production due to the blasting which occurs every night between midnight and one a.m. There cannot be any manual loading until the blast area has been ventilated.

**FIGURE 8 Average production rate per 24 hours for one semi-automatic LHD.**

**Maintenance performance**

The maintenance department uses indicators like MTBF and MTTR to manage maintenance. Availability is another frequently used indicator for the maintenance department where the target is to always have 9 out of 13 LHDs available at all times. With the maintenance
planner’s input, the production manager and repair crew attempt to meet this target. When MTBF is calculated for one LHD, we find that in 2336 machine hours, there were 39 failures for that LHD. In this case, MTBF equals 59.9. The total time to restore these 39 failures was 557 hours which means that MTTR equals 14.3.

Table 4 shows the time between failures (calculated in machine hours (Mhrs)) for transmission, engine and hydraulic system for the semi-automated LHD. The data covers failures occurring during 3 years and 8 months. The LHD is here considered to be a repairable system. Some of the components in the subsystems are considered as non-repairable items and changed during preventive maintenance. These are treated as censored failures using the preventive replacement time as censored data.

![Table 4 Time between failures (TBF) for Semi-automated LHD. S = censored failure.](image-url)

For these LHDs, inspection, oil change and refuelling have taken place regularly. The PM plan is to maintain the LHDs every 250, 500, 1000, and 2000 machine hours. The engine, converter and gearbox are changed according to the preventive replacement plan at 13000-14000 machine hours; the hydraulic pump and the transmission are changed after 8000 and 1000 machine hours respectively. Figure 9 shows the relationship between corrective
maintenance (CM) and preventive maintenance (PM) for one LHD during the test period. All LHDs have similar graphs, making this one representative. The data for 2010 are collected for eight months; this explains the decrease in PM and CM. The data show that CM represents about 90% of the maintenance work; this percentage is far too high for automated systems. When using automatic LHDs, it is important to increase the planned maintenance and decrease the unplanned maintenance. It is undesirable to have a machine that can break down at any time in any place, as there is no one there to perform maintenance or take it to the workshop. If the system has to be frequently changed to manual operation due to unplanned breakdowns, this can put the entire investment in automation in question.

Figures 10 and 11 show the number of breakdowns associated with different modes of operation. This provides valuable information because demand and time related failures will be different in severity and number depending on the operating mode. The size of the boxes in the graph represents the percentage of the total number of work orders or total time spent in the workshop for each subsystem. The preliminary risk, based on number of failures (Figure 10) and time spent in the workshop (Figure 11), indicates that the most critical components differ for the manual and semi-automatic machine.

- Semi-automatic loader: Based on the number of work orders, the most critical subsystem is the hydraulics system, followed by the engine and electrical systems. Based on time spent in the workshop, the most critical subsystems are transmission, engine, and hydraulics systems.

- Manual loader: Based on the number of work orders, the most critical subsystem is hydraulics, followed by the electrical and chassis systems. Based on time spent in the workshop, the most critical subsystem is the chassis, followed by the brake and hydraulic systems.
FUSION OF MAINTENANCE AND PRODUCTION KPI’s

When the maintenance costs per accumulated ton are determined, no clear difference between the two LHDs can be found (Figure 12). When the data are plotted graphically, the slopes of the curves are almost linear; this means that the productivity rate is almost constant. If the productivity increases, the maintenance costs simultaneously increase. The balance between production rate and maintenance cost is the most important issue. It seems difficult to lower the maintenance cost while simultaneously increasing productivity. Combining the production indicator and the maintenance indicator gives a common tool to the production and maintenance departments. It is in both their interests to optimize the indicators.
CONCLUSIONS

Maintenance KPIs should be determined by aligning the available data with corporate goals. Each activity should have good metrics, focusing on maximizing the benefits and adding value. The maintenance and production departments must work together towards the same goal using a combination of maintenance and production indicators. Using contradictory indicators can cause unnecessary conflict, and balancing the tons produced with the maintenance cost is essential for the success of the operation.

To prevent the data from being poor and unreliable, the various systems need to be aligned and connected. If wrong or corrupted data are introduced into the performance measurement system, decisions can be based on faulty assumptions. Reliable KPIs require reliable data. Since indicators like MTBF and MTTR are statistical averages of a physical value and are particularly sensitive in terms of accuracy. With more data comes greater accuracy. For MTTR, proper data collection is important, so a company can break down the time spent in the workshop into various components; this provides users with valuable information on maintenance team skills and reveals the logistical management of the workshop.

In this study, real time process data and maintenance data have been aggregated to optimize the selection of productivity assets. This requires the fusion of very different data.

We find that the difference between the semi-automatic and the manual LHD is very small when it comes to maintenance cost versus produced tons; both indicators show similar slopes in the figures. There is no significant difference in exploitation results. However, the use of automatic LHDs is well justified when safety and environmental issues also are taken into account.

ACKNOWLEDGEMENTS

Swedish Foundation for Strategic Research (SSF) is acknowledged for their financial support.
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1. CEI 1078:1991, Analysis for dependability Reliability block diagram method
The Influence of the Operating Environment on Manual and Automated Load Haul Dump Machines: a Fault Tree Analysis

The Influence of the Operating Environment on Manual and Automated Load Haul Dump Machines: a Fault Tree Analysis

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Abstract
The use of automated Load Haul Dump (LHD) machines has the potential to increase productivity and improve safety, but there are many issues to consider when optimizing the operation. Today’s focus on improved equipment reliability is part of the problem; another issue is the special conditions and constraints of the operating environment. For automated LHDs, the latter are even more important, as humans have been removed from the production area and are not close by to solve problems. The purpose of this paper is to find the causes of LHD idle time and to determine how these affect the operation. In this study, real time process data and maintenance data, from an underground mine in Sweden, have been refined and integrated. It takes into account the complexity of the mine environment and discusses the factors to be considered when optimizing and automating the operation. The study uses fault tree analysis (FTA).

Keywords: LHD, Automation, Fault Tree Analysis, Operating Environment.

1 Introduction
Today, Load Haul Dump (LHD) machines are an important feature in most underground mines. Ore and minerals are loaded from the tunnel face or from a draw point by LHD machines and are normally dumped into ore passes. The LHDs can be operated in several different operation modes; this paper focuses on LHD automation in which the tramming and dumping are automated and the bucket is loaded by the use of remote control. Automation of LHDs has been a reality for more than 20 years, but even so, the concept has not yet fully succeeded. Over the years, mines have tried several different navigation systems and arrived at different results. Automatic systems have been used successfully by several mining companies for such applications as tramming/hauling and dumping and tele-remote control to load the buckets [1]. The use of an automatic LHD for backfilling has also been successfully tested [2]. But the automation of LHDs is a complex problem; many technical areas have to function when the LHD is operated in automatic mode e.g.:

- IT, communication system, navigation system
- Infrastructure, mine environment, control rooms
- Human issues such as skill, competence, training.

Some of the problems with automatic systems are pointed out [3]. For example, a mine needs to meet certain special physical requirements to benefit from an automatic system; it is also very costly to install. Arguably, large-scale mining will gain more significant benefits from installing an automatic system, as production can be increased in large cycle applications. It is also noted that the system can be fitted to suit smaller operations as well, but it is easier to install the technology in mine sections that are designed with automation in mind. Automatic loading takes
place in a secluded area in the mine. To ensure safety, the area where the automatic vehicles operate must be isolated by a physical barrier system. Any breach in the system will immediately stop the machines [4]. When it comes to automating LHDs, focus has shifted from having a fleet of fully automated vehicles to the more flexible solution of semi-automatic LHDs, with increased safety as a major goal. The automatic system used for semi-automation is different than the fully automated system: less infrastructure is needed, and the operator controls only one vehicle at a time. When the semi-automatic LHD is to be operated at another area, the infrastructure needs to be moved and the new area needs to be secured before the operation can start.

LHD operation encounters many disturbances related to both the harsh environment and maintenance. Automatic operation suffers from more unexpected breakdowns than manual operation since the operator is removed from the machine and is not close by to fix problems. The ultimate goal is smooth operation with few disturbances causing idle time for the LHDs. Therefore, this paper identifies the reasons why operation stops and evaluates the effects of such stoppages. It considers mining related issues linked to the operating environment and machine related issues, such as failures, inspections, service etc:

LHD operation and especially when considering automation of LHDs is always challenging, as external disturbances like oversized boulders, road maintenance etc. can greatly influence the operation. The number of registered stops (i.e., amount of idle time) resulting from external disturbances is very high. For manually operated LHDs the number of disturbances is as high as for automated LHDs, but the problem increases during automated operation. For every such disturbance, the LHD has to stop operating in automatic mode; the operator must go to the LHD and operate it manually, if possible, or try to fix it. Because the disturbances in the production areas of a mine are both complex and comprehensive, the environment is not well suited for automation. In 1997, a study evaluated the cost associated with oversized boulders [5]. It found that the cost is very high and that an improved way of handling the boulders would decrease the total cost and increase productivity. Another study evaluating the performance of automatic LHDs showed that the highest percentage of faults could be attributed to external disturbances [6]. If humans are to be taken out of the production area, a substantial amount of work has to be done to minimize mining related disturbances.

Another issue is the maintenance of underground mobile mining equipment, as this is both costly and challenging. Factors like complexity, size, competition, cost and safety continue to challenge maintenance engineers despite recent progress in maintaining equipment in the field. The issue is further complicated by increased mechanization and automation [7]. The maintenance costs of a typical mining company account for 30-65% of the total mine operation cost [8]. To reduce costs, mining companies are optimizing preventive maintenance, reducing manpower, deferring non-essential maintenance, and establishing more efficient spare part control etc. Good maintenance strategies are essential to optimize the maintenance of mobile mining equipment. Reducing the number of unscheduled breakdowns as well as reducing the repair time is important to improve equipment availability [9].

For automatically operated LHD, the challenges include the cost of operation and maintenance, availability and reliability. Human factors and safety issues are also important. It is difficult to succeed with automation because of the machines’ lack of reliability and the amount of corrective maintenance required. Reliability is extremely important in all applications where operators are removed from the equipment. It is undesirable to have an unreliable machine that can break down
at any time anywhere in the mine. It is necessary to eliminate or minimize small “fixes” and concentrate service and maintenance work on regular, major stops that take care of the majority of the problems. The upper part of Figure 1 shows an example of preventive maintenance of LHDs. Here, all maintenance is taken care of at regularly planned periods. The lower part of the figure provides an example of corrective maintenance where many unplanned stops disrupt the operation. The optimization of preventive maintenance is essential with automation since the operator is no longer there to perform maintenance or take the vehicle to the workshop. To reduce costs, the general industrial trend is towards planned and condition based maintenance and the minimization of all acute work. In mines, too many unplanned repairs and too much maintenance work in an LHD operation significantly reduces overall availability for the system and can jeopardize the investment in automation.

Figure 1 Example of preventive maintenance where the majority of the maintenance stops are scheduled versus corrective maintenance where a large number of maintenance stops are unplanned with a “run to failure” philosophy.

2 Fault tree analysis

The goal of this paper is to identify the most important causes of idle time for LHDs. To analyze idle times, it uses the fault tree analysis, described as a graphic model of the combination of faults that result in the occurrence of a predefined, undesired event (top event) [10]. The faults include hardware failures, human errors and software errors etc. that lead to the undesired top event. Since a fault tree is focused on the occurrence of the top event rather than modeling all possible causes for system failures, it is important to remember that only the faults considered relevant are included. The basic concept of a fault tree is that an outcome is a binary event with the possibilities of either failure or success. Beside events, the structure consists of “gates” that allow or hinder the passage of fault logic up the tree. The event above the gate is the output of the gate; the event below is the input.

The objective of a fault tree is to show the relationship between a potential event affecting the system’s performance and the causes of this event [11]. The following steps are carried out in a successful FTA [12] and will be used in the LHD analysis:

1. Identify the objective of the FTA: The objective of the FTA is “to analyze the reasons for idle time for LHDs”.

2. Define the top event of the FT: The top event is automatically defined once the objective has been defined. In this case the top event is “Idle time”.

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3. Define the **scope** of the FTA: To determine the scope of the FTA the following are considered: an indication of which failures are to be included, the operation mode, a particular design version and historical time period relevant to the system and the boundary conditions for the analysis. In this case, the boundaries are idle time related to mine, machine and automatic system. The model is a manually operated LHD with the capacity of loading 21 tons; the time frame is one year. For the parts in the fault tree related to the automatic system, the data have been taken from the semi-automatic LHD.

4. Define the **resolution** of the FTA: In the resolution of the FTA, the level of detail is decided. In this case, the top event is resolved in the following major areas; mining-, machine- or automatic system related failures with their input events. The level of detail is resolved to the basic events with the right information and probability data available to get the best possible estimation for the top event.

5. Define **ground rules** for the FTA: The definition of ground rules includes nomenclature and procedure for naming events and gates as well as manner for modeling failures. The names have been given according to the meaning of the event.

6. **Construct** the FT: The thinking and logic involved in constructing the fault tree as well as the symbols used are described here. The fault tree in this case is composed of three different symbols, the Or-gate, the Transfer-gate and the Basic event. For fault tree analysis the software Windchill Quality Solutions 2011 has been used. The definitions of the gates and events in the software are as follows: an Or-gate is “used to indicate that the output occurs if and only if at least one of the input events occur”; Transfer-gates “can be used to link logics in separate areas of a fault tree when an entire fault tree may not fit on one page”; and Basic-events are the “lowest levels in a fault tree and represents the occurrence of an event in the system being analyzed” (Figure 2). According to the software, “The Transfer in-gate links to the Transfer out-gate, which represents the top gate of another fault tree” or another part of the same fault tree.

7. **Evaluate** the FT: The qualitative evaluation gives information on the minimal cut sets for the top event. The quantitative evaluation gives the probability of the top event and also the dominant cut sets that contribute to the top event probability.

8. **Interpret** and present the results: The results must be interpreted in order to present concrete suggestions.

### Figure 2 Gates and events used in the Fault tree

#### Table: Gates and events used in the Fault tree

<table>
<thead>
<tr>
<th>Gate1</th>
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<table>
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</thead>
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<tr>
<td>Transfer out-gate</td>
<td>Basic event</td>
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#### 3 Case study

This paper is based on a case study performed at a Swedish underground mine. The focus is on the beginning stage of the mining process, namely the loading and transportation of ore and minerals performed by LHD machines. The mine deploys 13 LHDs: 9 R2900G XTRA, 3 Toro 0011 and 1 Toro LH621, all operating from 2003 and later. Twelve are manually operated, and
one is semi-automatic. The semi-automatic LHD has been in operation since 2006 and can operate in manual mode when not operating in automatic mode making it a flexible alternative. The LHD operation is not a continuous process, and the LHDs only operate when needed. There is less production during the night because blasting occurs every night between midnight and one a.m. Manual loading cannot be resumed until the blast area has been ventilated. The semi-automatic LHD, however, can operate very soon after blasting, giving it a relative advantage. The LHDs in this mine are about 11 meters long with a weight of 55 tons, using diesel power. The loading capacity per bucket is 21 tons. The manual and semi-automatic operation mode can be described as follows:

- **Manual mode** (Figure 3): The operator remains in the cabin on the side of the vehicle throughout the load-haul-dump cycle. The side position of the cabin makes it possible for the operator to have a clear line of vision when the vehicle is moving forward or backward.

- **Automatic mode** (Figure 3): In this case, the operator controls one semi-automatic LHD from an office located inside the mine. From this safe environment, the operator is required to monitor the vehicle and to be involved at some points in the loading cycle. The vehicle transports and dumps the ore automatically, and the operator only controls the vehicle during loading. The semi-automatic LHD can be manually operated when not used in automatic mode. The automatic mode is used to improve safety and to increase production during night shifts after blasting.

Maintenance, production and operational data from 2010 have been collected and analyzed for a manual and a semi-automatic LHD with the same specifications, both taken into operation in 2006. The only difference is that the semi-automatic LHD has an automatic system fitted to it and can therefore operate in either manual or automatic mode. The automatic system installed on the semi-automatic LHD consists of an on-board computer, radio, leaky feeder, 2 antennas, 2 ladars, and 2 cameras. The required infrastructure in the secluded area operated by automated LHDs consists of a safety gate, a safety cable, a telephone, a camera pointed towards the gate, a camera pointed towards the mine tunnel, omni-directional antennas, radio and a leaky feeder with directional antenna.

The idle time has to be reduced in order to gain from the investment in automation. Therefore, as a first step, the idle times must be identified. The concept of fault tree was used to find and
evaluate all factors causing idle time for the LHDs. This paper tries to provide a complete picture of the situation; it is not designed as a study of the machine and its maintenance.

4 Results

The analysis of the available data shows that the reasons for downtime for the LHDs can be divided into three main categories; mining related issues, machine related issues and issues related to the automatic system (Figure 4).

![Diagram showing idle time categories](image)

Each one of gate numbers 2, 6 and 9 can be further divided into basic events. The basic events shown in Figure 5 are mining related (gate 2). Events 1-3 always result in idle time; it is not possible to operate the LHDs during these circumstances. Events 4-11 also result in reported idle time; however, it would be possible to operate the LHD in manual mode during these events, either in the same area or another area. This, of course, depends on organizational issues and whether there is another place to load. During events 12 and 13, which lead to reported idle times, it would be possible to operate the LHD in automatic mode but not in manual mode.

![Diagram showing basic events](image)

- **Events**
  - 1 Road maintenance
  - 2 Moving machine
  - 3 Lack of personnel
  - 4 Charging
  - 5 Oversized boulders
  - 6 Drilling of oversized boulders
  - 7 Lack of ore
  - 8 Media
  - 9 Full ore pass
  - 10 Scaling
  - 11 Moving infrastructure to another area
  - 12 Blast gases
  - 13 Dust and gas

- **States**
  - Idle time
  - Manual mode
  - Automatic mode
An overview of the registered idle times is given in Figure 6. The data analysed was reported for one LHD during one year. The numbers in the figure represent the number of times that one LHD was idle for that particular reason during one year. The total number of recorded stops resulting in idle time for the LHD during this particular year was 1470 according to the production data. The number of stops that could be traced to mining related issues was 1103. For machine related issues, the figure was 316, and for the automatic system, it was 51. The real numbers might be higher than those shown in the figure, as operators may not always enter the data into the system. At any rate, they are not likely to be lower. The figure tries to give a complete picture of when the machine can operate in manual and/or automatic mode. At times, the LHD can be operated in manual mode in another area in the mine, for example, when the area used for automation is closed for safety reasons or other work-related issues. The figure shows when having a semi-automatic machine is helpful, namely, during the night when gases from the blast have to be vented and no human can be in the production area. Even more frequently, there are problems with dust and gas; at these times, the LHD can be operated in automatic mode but not in manual. It is important to isolate the different reasons for idle time to maximize the value of automatic operation.

According to Figure 4, the reasons for idle times can be sorted into three main categories and will be analysed accordingly.
4.1 Mining related issues:
About 75% of all stops leading to idle time for the LHD are due to mining related issues.

- **Cannot operate in manual or automatic mode**: The reasons why the machines cannot operate at all include: blasting which occurs every night around midnight, road maintenance, moving machine or lack of personnel (operators). The majority of the times the machine is idle in this category is due to road maintenance; the operator frequently fixes the road using the bucket of the loader and fills holes etc. This task is not suitable for automatic operation.

- **Can operate in manual mode but not in automatic mode**: This is mainly the case when charging is taking place, when there are problems with oversized boulders, or when the automatic system is being moved to another mine tunnel. The total number of stops in this category is more than 500 for one LHD during one year which gives a good indication of what kind of problems need to be solved if the operation is to be automated. If the operation is automated, the operator is not available on short notice to manage oversized boulders, for example. S/he must stop the automatic loading, go to the LHD, and take care of the problem.

- **Can operate in manual mode in another area but not in automatic mode**: When there are issues like lack of ore and a full ore shaft, it is not possible to continue the automatic loading (or the manual loading) in that particular area, but it is possible to operate manually in another area.

- **Can operate in automatic mode but not in manual mode**: One advantage with having a semi-automatic loader is that it is possible to start loading much sooner after blasting than with manual operation due to safety reasons; the machine is not as sensitive to the gas from the blast as is a human. It is important to note that there frequently are high levels of dust and gas not related to blasting (see Figure 6). Another advantage is that operator safety increases when s/he is taken from the production site and placed in a comfortable office at a safe location.

4.2 Machine related issues:
Almost 21.5% of the recorded stops are due to machine related issues. Included in this category are inspections, oil changes, refuelling, corrective maintenance (CM) and preventive maintenance (PM) (Figure 7). The LHD is considered a system divided into several subsystems connected in series. All these critical subsystems must be working simultaneously to get the desired function. In the fault tree (lower part of Figure 7), corrective maintenance is divided into the following basic events corresponding to the subsystems: Tires, Brakes, Hydraulics, Transmission, Bucket, Chassis, Automatic system, Engine and Electric system. In the fault tree, preventative maintenance is divided into basic events corresponding to service done after 250, 500, 1000 and 2000 machine hours (Figure 8). These service intervals are based on the manufacturer’s instructions.
Additional failure and maintenance data were collected and analysed for one semi-automatic and one manually operated LHD. The data were recorded over a period of 4 years and 10 months. After collection, the data were sorted and categorized for the subsystems of the LHD; Figure 9 shows the different number of breakdowns associated with different modes of operation. Determination of preliminary risk indicates that the most critical components based on number of failures are different for the manual and semi-automatic machines.

- Semi-automatic loader: Most critical subsystems are the hydraulics followed by the electrical system, engine and transmission.
- Manual loader: Most critical subsystems are the hydraulics followed by the electric system, cabin and chassis.

Valuable information can be extracted from this graph because the failures will differ in number and severity depending on the operating mode used. The repair data show that although the
number of work orders for the hydraulic system is quite high, the corresponding repair time is short. It is clear that the transmission and engine have more work orders and more time spent in the workshop for the semi-automatic LHD than the manual. This shows that the engine and transmission suffer when operating in automatic mode. The maintenance data show that although the numbers of failures for chassis are equal for the two machines, the repair time is much higher for the manually operated LHD. This difference in repair time can partly be explained by the fact that the positioning system allows the automatic LHD to operate in the middle of the mine tunnel; manually operated vehicles, meanwhile, are more likely to scratch or hit the tunnel walls.

![Figure 9 Number of failures for semi-automatic and manual LHD over 4 years and 10 months](Image)

4.3 Automatic system related issues:
About 3.5% of the total number of stops is related to the automatic system. When there are problems with the automatic system or communication system installed in the secluded area intended for automatic operation, it is possible to operate the LHD in manual mode at another area. When there is a lack of personnel trained to operate the LHD in automatic mode, it is possible to switch to manual mode and continue the loading. Looking at the failure data, it is clear that it is not the automatic system installed on the LHD that causes problems but rather the automatic system installed in the mine. However, it is not a major problem compared to the mining related issues.
5 Discussion
The trend in automation has changed from fully automated LHD fleets to the more flexible systems of the semi-automated LHDs where the operation mode can be changed depending on the need and situation. A main argument for automating LHDs is the increased safety which results when the operator is taken from the production area and placed in an office. However, several mining related issues, e.g. badly fragmented rock or boulders, must be taken care of for the automated operation to function without major drawbacks. The flexible solution with semi-automatic operation is a good compromise; it is safer and has the option of manual loading when the situation requires. When the operation is automated, machines cannot fail at any time anywhere in the production area. Thus, it is essential to switch from corrective maintenance to improved and optimized preventive maintenance.

6 Conclusions
Fault Tree Analysis is a useful tool for identifying what causes idle time for LHDs. It has for example successfully been used in Aerospace applications [12]. This method of analysis is well suited for this type of machine and its special operating environment. The analysis shows that 75% of the registered stops causing idle time for LHDs is related to the operating environment. Better fragmentation of rock to avoid big boulders, better constructed roads to minimize the need for road maintenance etc. are keys to the successful operation of automated LHDs. Better maintenance planning is also crucial to reduce the amount of corrective maintenance required. However, a semi-automated LHD is an optimal machine regarding the ability to adapt to reconfiguring the operation mode to meet increasing demands on safety, flexibility and productivity.

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8 References


