Fusion of Operations, Event-Log and Maintenance Data: A Case Study for Optimising Availability of Mining Shovels

Diego Galar[1], Hassan Bin Naeem[1], Håkan Schunesson[1], Luis Berges[2], and Bernardo Tormos[3]

[1] Department of Civil, Environmental and Natural Resources Engineering
Luleå University of Technology
SE-971 87 Luleå, Sweden
[2] Department of Design Engineering and Manufacturing
University of Zaragoza
50018 Zaragoza, Spain
[3] CMT-Motores Térmicos
Universitat Politècnica de València
46022 Valencia, Spain

Abstract. The modern mining industry is highly mechanised and relies on massive, multimillion-dollar pieces of equipment to achieve production targets. In an increasingly challenging international economic climate, mining operations are reliant on economies of scale to remain competitive. To maximise revenue, it is imperative that at each stage of the mining process, equipment is operating optimally without preventable and unnecessary interruptions. As a result, the focus of all mining operations is to increase equipment uptime and utilisation.

The data used for this investigation have been sourced from the Aitik mine, a large open pit copper mine in Northern Sweden. In the loading area, power shovels load trucks with blasted material for transport, either to the crushers or to the waste dumps. The Aitik mine employs various computer-aided applications to track and maintain mobile mining equipment like the shovels. These applications also serve as chronological operational and maintenance databases for the equipment. This paper's study of six mining shovels is based on the analysis of three data types: historical maintenance data from CMMS Maximo, operational data from mine management system Cat® MineStar™, and event-log data from individual shovels.

The results indicate that such a synthesis is viable. A regular time-lapse integration of the diverse data types displays potential and could prove helpful in achieving overall improvements in maintenance.

Keywords: Data fusion, maintenance management, mining shovels.

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1 Introduction

The Aitik open pit copper mine, located approximately 15 km south-east of the town of Gällivare in Northern Sweden, is the largest copper mine in Sweden. The ore deposit at Aitik consists of chalcopyrite and pyrite, primarily yielding copper, with secondary quantities of gold and silver.

The mine is owned and operated by Boliden Mineral AB, a large Swedish mining and mineral processing concern with operations elsewhere in Sweden and other parts of Europe. The Aitik mine complex comprises the open pit, crushing stations both inside the pit and on the surface, a mineral processing plant including two autogenous grinding mills and floatation cells, a system of underground and surface conveyors for ore transport, intermediate and main ore storage with a combined holding capacity of 230,000 tonnes, a tailings pond, facilities for equipment maintenance and office complexes. Figure 1 shows the flow of unit operations at the mine.

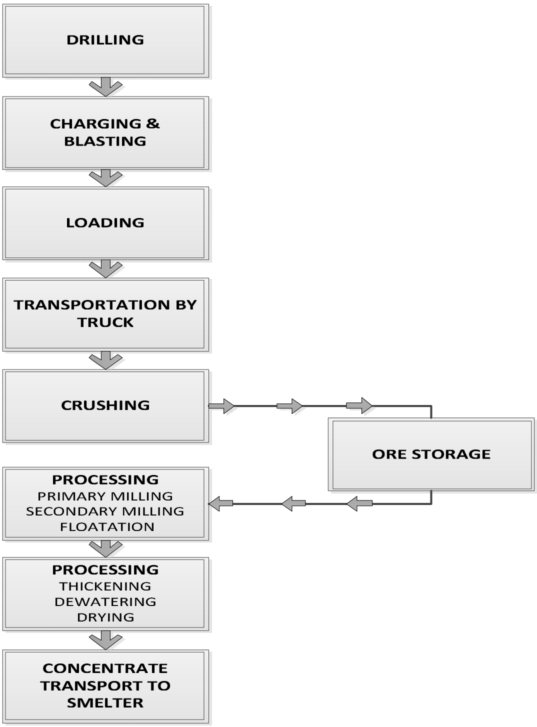

Fig. 1 Flow of Unit operations at the Aitik open pit copper mine.

Currently, the open pit is approximately 3 km long and 1.1 km wide. The operations inside the pit are divided into two sections, the southern section where the pit depth is 250 m and a northern section where the depth is 400 m. The open pit uses a conventional truck-shovel operation to load the ore and waste rock onto trucks for transport, either to the crushers or to the waste dumps.

The loading fleet at Aitik includes two Komatsu PC5500 electrically powered (1,800 KW) hydraulic-face shovels, two P&H 4100A and one P&H 4100C electric-rope shovel, Bucyrus 495 BII and B-E 295 electric-rope shovels, and two Caterpillar 994 wheel loaders. The transport fleet consists of 23 Caterpillar 793 trucks and nine Caterpillar 795 trucks, with the latter commissioned in 2010. The primary drilling fleet includes four Atlas Copco PV351 Pit Viper rotary blasthole rigs. Two Atlas Copco ROC L8S and two ROC D65S are contracted out and are used for smaller diameter holes and pre-splitting.

1.1 Scope of the Study

The broad objective of this study was to use the various data types available in the Aitik mine to maximise asset utilisation while minimising costs. A causative link between event-logs from the equipment and historical maintenance data from CMMS Maximo needed to be established in order to identify opportunities for improvements. The study aims to put actionable information into the hands of maintenance managers. Any new information gained as a result of this investigation could aid in decision making at the management level and potentially achieve improvements in the maintenance function.

1.2 Computer-Managed Maintenance Systems (CMMS)

A computer-managed maintenance system is an integrated set of computer programs and data files designed to provide users with a cost-effective means of managing massive amounts of maintenance, inventory control, and purchasing data (Cato & Mobley, 2001).

A CMMS provides computer attributes of data storage, retrieval, calculation, organisation and analysis of vast amounts of data. Manual systems often break down under the pressure of modern maintenance requirements. A computer-managed maintenance system is essential today if a company is to achieve economies in maintenance costs and increase equipment uptime. A reliable and accurate historical maintenance database is necessary to secure the organisation against loss of experienced maintenance personnel.

It is important to realize that a CMMS is not an alternative to an effective maintenance strategy; rather, it is a tool to be used by maintenance departments to achieve improvements in maintenance. A CMMS may amplify the effects of unsatisfactory maintenance practices, so it is essential to have a good maintenance program in place before implementing a CMMS. An effective maintenance strategy is vital to ensure that equipment keeps performing its intended function. Failures are inevitable, however, but with a CMMS historical database, most repetitive failures can be identified, analysed, and then avoided in the future.

1.2.1 Advantages of Implementing a CMMS

There are at least three advantages of implementing a CMMS. The first is increased labour productivity. Maintenance departments are plagued by under-utilisation of human resources due to what has been called a “firefighting environment,” whereby problems are tackled only after they occur. This can be avoided through better organisation and planning. A CMMS can help to improve labour productivity through the following:

- A centralised database of all relevant information required to carry out a successful repair is readily available and the time spent on searching for material is drastically reduced.
- The use of a CMMS can significantly reduce planning time through built-in planning aids. Better planning can ensure that both human and material resources are available in time and are directed towards the right location, thereby significantly increasing the efficiency of the maintenance organisation.

Better inventory management is another benefit; re-ordering can be automated and guesswork can be eliminated. Spare parts are requisitioned against specific work orders so there is a better control of inventory issuing. Also spares can be reserved for work orders to ensure that there is a sufficient inventory available for future planned work.

Finally, better planning and less firefighting can result in improved asset availability. A CMMS is a structured maintenance database which can enable the effective analysis of repair histories, eventually leading to improvements in the availability of an asset.

1.3 Maintenance from a Mining Perspective

The maintenance objective from a mining perspective necessitates the minimisation of equipment downtime to achieve production targets. Maintenance related costs account for approximately 30 to 50 percent (figure 2) of direct mining costs (Lewis & Steinberg, 2001), mainly because modern mining is highly mechanised and equipment dependent.

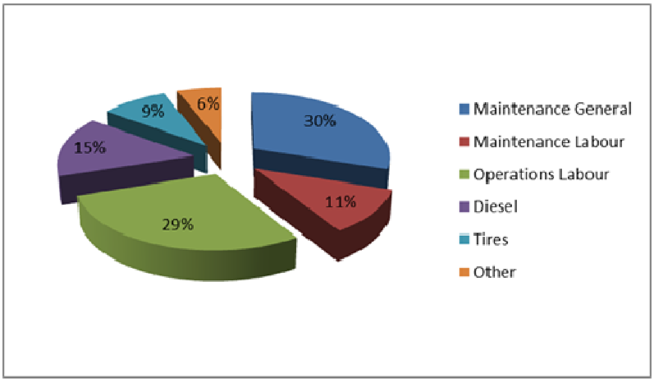

Fig. 2 Breakdown of direct mining costs. (Lewis & Steinberg, 2001)

However, the maintenance function in the mining industry differs from the maintenance function of other industries. Mining is fundamentally different from other large-scale manufacturing or process industries. It is characterised by a significantly higher degree of variation and the working conditions are far from ideal. For example, a manufacturing facility is a clean and secluded environment where equipment is protected from the elements. Mining equipment, on the other hand, has to perform outdoors and is susceptible to the adverse effects of harsh weather. In addition, a major portion of the equipment used in the mining industry is mobile or semi-mobile (Hall, 1997).This mobility has certain challenges.

- Mobile equipment can fail in inopportune locations that make repair extremely difficult and costly (Hall, 1997).
- The mobility of the equipment hinders the application of techniques such as continuous condition monitoring (Hall, 1997).

1.3.1 The Mining Environment

The mining environment is characterised by remote locations and harsh working conditions. Adverse effects of the environment and location on mining equipment include, but are not limited to, the following:

Factors which are a function of remote and inhospitable locations:

- Wide temperature ranges
- Large lead times for spare parts

Factors which are a function of harsh working conditions:

- Dusty environment due to material excavation
- Vibrations and shocks due to material handling
- Muddy and wet working conditions

1.3.2 Interdependency of Unit Operations

The open pit mining process is a chain of unit operations. In order to function, each unit operation is reliant on unit operations upstream (see fig.1). Since the modern mining process is highly mechanised, it is imperative that equipment at each stage is performing its intended function with no unnecessary interruptions. Any weak link in this chain of operations can create bottlenecks and, in extreme cases, jeopardise the whole operation. Bottlenecks in one area can lead to the underutilisation of installed capacity elsewhere in the mining chain, compounding the inefficiencies in the entire mining chain. This interdependency necessitates maximising existing capacity.

1.3.3 Costs of Equipment Downtime

Modern mining equipment is both expensive and massive. Mining operations are reliant on economies of scale to remain competitive; underutilisation of equipment can seriously undermine the advantages sought. Costs related to equipment downtime are indirect costs, which in a mining context translate to loss of production. The equipment needs to perform its intended function to ensure a quick and steady return on capital invested. Mine economic feasibilities are dependent on metal prices, but the market is volatile. Therefore, it is essential to optimise and sustain production by minimising equipment idle time.

1.4 Data Fusion from a Mining Standpoint

Profit oriented organisations endeavour to remain competitive; the most basic requirement is to increase revenue and decrease costs. Unfortunately, every organisation has islands of information, whereby information situated in different departments is seldom shared.

In the mining industry, a control system is available to track and optimise mine production. This system is very precise and any interruptions in production are logged with a high degree of accuracy. Universally acknowledged key performance indicators such as availability, mean time between failures and mean time to restore can be calculated with ease from these data, thus developing asset or fleet level awareness among management. However, these systems are production-centric and while they can record when an asset has broken down, they do not record details on what has happened or where.

The maintenance department must ensure that equipment is up and running. Most maintenance departments use some form of CMMS. A CMMS is a maintenance-centric system, providing a comprehensive and accurate database of historical maintenance data of the asset. It enables drilldown to the subsystem level; i.e., the ***wheres*** and ***whats*** can be answered by analysing the CMMS data.

Modern equipment is equipped with a multitude of sensors to monitor the health of components and issue warnings to the operator if certain predetermined thresholds are exceeded. These are useful in prefenting equipment degradation, since they issue warnings to the operator about equipment health and operating limits. However, according to Galar et al. (2012), attempts to integrate these Real Time Condition Monitoring (RTCM) systems into CMMS databases has received little attention.

A two tier integration methodology is proposed by Galar et al. (2012). This integration benefits the whole spectrum of mine personnel, from maintenance technicians all the way up to management. The former are more aware of equipment health and impending failures, while the latter can use this new information to plan maintenance actions and make informed policy decisions. The following benefits gained from this integration can have a direct positive impact on the mine's bottom line.

1.4.1 Effective Utilisation of Existing Capacity

Loading equipment is a crucial link in an open pit truck-shovel operation because a shovel failure has a direct impact on mill feed. Therefore, any increase in shovel availability and utilisation can have a significant positive impact on the mine's bottom line.

The mining business is dependent on metal prices, and the metal market is linked to the global economic outlook, which is highly unpredictable. This results in a high level of volatility in metal prices. To gain from a bull metal market, it is imperative that the mine operate at an optimum and sustained rate. To achieve this, each unit operation in the mining chain must operate optimally. High shovel availability can have a direct positive impact on production, allowing the mine to benefit from high metal prices. At the same time, an effective maintenance strategy can enable the mine to absorb the financial shocks of a bear metal market. In other words, regardless of the market, the mine can gain a competitive advantage through data fusion and realised gains.

Mining is a capital intensive industry. Modern mining assets are massive multimillion-dollar pieces of equipment. They represent a significant proportion of the mine's capital investment and operating costs. It is essential that they perform at an optimum and sustained rate so that the return on capital invested can be realized sooner rather than later. This, if achieved, can considerably reduce the payback period of the mine. It is important that to minimise asset idle time; the objective is to eliminate avoidable downtime to maximise the use of existing capacity. If existing equipment has a high availability, the need for standby redundancy can be eliminated, again reducing capital expenditure. Over the life span of the mine, this can significantly reduce outflows and increase profitability.

1.4.2 Increasing Asset Life

If equipment is maintained and operated correctly as a result of new information gained from the integration of different data types, there is an opportunity to increase asset life and delay new capital expenditure.

1.4.3 Ensuring Cost-Effectiveness in Maintenance

Meeting overall organisational objectives requires high equipment availability, but to remain competitive, it is imperative to minimise the cost of production. Maintenance costs in mining represent somewhere between 30 and 50 percent of the total operating costs. Achieving a streamlined operation requires high availability, but at a reasonable maintenance cost. Planned maintenance costs are lower in terms of both time and money spent on equipment. Less firefighting and more planned work will inevitably lead to reduced maintenance costs. Gains may include lower cost of production per tonne, since equipment is performing its intended function and operations are optimised.

2 Data Collection and Analysis

The data available from the maintenance department at Aitik include three distinct sets; historical maintenance data from CMMS Maximo, historical interruption time-logs from Cat® MineStar™, and event-logs from the individual shovels. The data used for this study span almost two years from March 2010 to March 2012 and provide information on six shovels.

The purpose of combining the data sets is to obtain useful and actionable information to improve the mine's maintenance function. However, the methods of data analysis differ for each data set and they are described below.

2.1 Historical Maintenance Data

The maintenance department at the Aitik mine uses IBM's CMMS Maximo. The overall structure of CMMS enables the drilldown of historical maintenance data, so that KPIs (Key Performance Indicators) such as MTBF (Mean Time Between Failures)and MTTR (Mean Time to Restore) can be calculated at both the asset and the subsystem level (figure 3). At the asset level, this exercise can gauge the relative performance of multiple assets within the loading fleet. At the subsystem level, KPIs can identify critical subsystems with high breakdown incidence or high restoration times. Once these are identified, analyses can be conducted to identify recurring failure modes. Further analyses can identify the root causes of the recurring failures, ultimately resulting in reduced failure frequency and improved equipment availability.

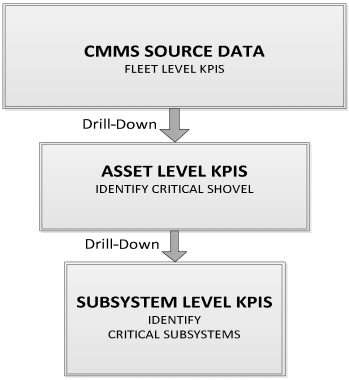

Fig. 3 Drill-down analysis for target identification through historical CMMS data

It is important to note the quality of CMMS data. Production-centric systems can provide accurate time-logs of asset downtime, but only a maintenance-centric system such as a CMMS contains finer details on the specifics of each failure, such as what has happened and where has it happened. The "whats and wheres" are only available from historical CMMS data.

2.2 Maintenance Performance Measurement

Maintenance Performance Measurement (MPM) is defined as the multidisciplinary process of measuring and justifying the value created by maintenance investment and taking care of stockholders' requirements viewed strategically from the overall business perspective (Parida and Chattopadhyay, 2007).

Present-day mining has evolved from a manual to a mechanised operation and is now steadily progressing towards automation. For this reason, today's focus is keeping equipment operational or returning it to production as quickly as possible once it has failed. These goals can be achieved through continuous improvement of the maintenance function (figure 4).

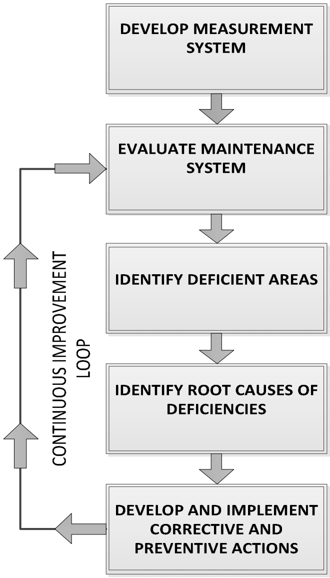

Fig. 4 Continuous improvement loop for the maintenance function

However, a fundamental question arises. Why should maintenance performance be measured? The following represent some answers to the question:

- What is measured will be understood better;
- What is measured can be assessed;
- What is measured can be managed;
- What is measured can be improved.

Three systems which can be used to measure maintenance performance include structured audits, performance indicators, and benchmarking (which may be utilised by the other two).

There is a lack of available performance indicators in the mining industry for external benchmarking, but they are available to gauge the relative performance of multiple assets internally. Performance indicators allow management to evaluate the state of the maintenance function and propose remedial actions.

2.2.1 Standard EN 15341- Maintenance Key Performance Indicators

The European Standard EN 15341 provides Maintenance Key Performance Indicators (KPIs) to support management's attempts to achieve maintenance excellence and utilise technical assets in a competitive manner.

These indicators may be used to:

- Measure the status;
- Compare (internal and external benchmarks);
- Diagnose (analysis of strengths and weaknesses);
- Identify objectives and define targets to be reached;
- Plan improvement actions;
- Continuously measure changes over time.

KPIs can be used to evaluate asset performance on different levels and compare the individual assets within the fleet, thereby identifying underperforming assets. As data from MineStar provide accurate time-logs of the various operational stoppages of shovels, they can be used to calculate the KPIs.

Table 1 Description of selected KPIs used in the study

- Operational Availability: Operational Availability accounts for all factors which can affect the operation of an item and is calculated using the following relation;

$$T2 = \frac{Achieved\ up\ time\ during\ required\ time}{Required\ time} \times 100$$

- Availability Related to Failures: Availability related to failures accounts for the time of an item lost due to breakdowns. It is calculated using the following relation;

$$T6 = \frac{Total\ operating\ time}{Total\ operating\ time + Downtime\ related\ to\ failures} \times 100$$

- Availability Related to Planned & Scheduled Maintenance: Availability related to planned and scheduled maintenance accounts for the time spent on maintenance of an item. It is calculated using the following relation;

$$T7 = \frac{Total\ operating\ time}{Total\ operating\ time + Downtime{:}\ planned\ and\ scheduled\ maintenance} \times 100$$

- Mean Time Between Failures MTBF: The mean time between failures is calculated using the following relation;

$$T17 = \frac{Total\ operating\ time}{Total\ number\ of\ failures}$$

- Mean Time To Restore MTTR: The mean time to restore an item to an up state is calculated using the following relation;

$$T21 = \frac{Total\ time\ to\ restoration}{Total\ number\ of\ failures}$$

Indicators generally relate maintenance costs to production costs. Alternatively, they make it possible to determine whether availability is adequate and if not, what factors should be modified. The KPIs selected for this investigation fall under the technical category of standard EN15341:2007 and are related to the availability of equipment, making them suitable for this study. In addition, the data required for the calculation of such KPIs are relatively reliable and accessible. The selected KPIs are listed and described in Table 1.

2.2.2 Definition of Terminology According to Standards EN 15341:2007 & EN 13306:2001

A short description of the terminology used to calculate KPIs appears in Table 2.

Table 2 Short description of the terminology used for calculating KPIs

Item: Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered. NOTE A number of items e.g. a population of items, or a sample, may itself be considered as an item.
Up time: Time interval during which an item is in an up state.
Down time: Time interval during which an item is in a down state.
Idle time: Time interval during which an item is in an idle state.
Standby time: Time interval during which an item is in a standby state.
External disabled time: Time interval during which an item is in an external disabled state.
Up state: State of an item characterised by the fact that it can perform a required function, assuming that the external resources, if required, are provided.
Disabled state: State of an item characterised by its inability to perform a required function, for any reason.
Down state: State of an item characterised either by a fault, or by a possible inability to perform a required function during preventive maintenance. A down state is sometimes referred to as an internal disabled state.
External disabled state: Subset of the disabled state when the item is in an up state, but lacks required external resources or is disabled due to planned actions other than maintenance.
Operating state: State when an item is performing a required function.
Idle state: Non-operating up state, during non-required time.
Standby state: Non-operating up state during the required time.
Required time: Time interval during which the user requires the item to be in a condition to perform a required function.
Required function: Function or a combination of functions of an item which are considered necessary to provide a given service.
Operating time: Time interval during which an item is performing its required function.

Table 2 (*continued*)

Downtime related to planned and scheduled maintenance: The total time of planned and scheduled maintenance works, which requires downtime.
Failure: Termination of the ability of an item to perform a required function.
NOTE 1 After failure the item has a fault, which may be complete or partial.
NOTE 2 "Failure" is an event, as distinguished from "fault", which is a state.
Fault: State of an item characterised by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.
Downtime related to failures: Total time lost due to failures.
Time between failures: The time duration between two consecutive failures of an item.
Total time to restoration: Sum of the times to restoration.
Time to restoration: Time interval during which an item is in downstate due to a failure. It includes administrative and logistics delays.
Total number of failures: Sum of failures

2.3 Event-Log Data

In some cases, the mine's event-log data consist of thousands of registered events; their analysis requires some sort of system. Isolated one-time occurrences or events must be excluded from the analysis, as a substantial sample size is required to recognise trends. Routine activities carried out by the operator are also registered in the data. Both these activities and isolated events were considered noise in this context; they were identified and excluded from the study.

First, a Pareto analysis was conducted to identify frequently recurring events. Pareto charts are useful graphical tools used in a Pareto analysis. The most important problem (for example, the highest cost, frequency, or some other measurement) is represented by the tallest bar, the next most important problem is represented by the next tallest bar, and so on (Leavengood and Reeb, 2002). Second, the events were further classified according to whether they were equipment induced or operator induced.

Finally, the consequences of these events to shovel health must be determined to find any correlation with historical maintenance data. Technical documentation found in event-logs is confidential and very difficult to find. At this stage, discussions with maintenance experts at the mine proved invaluable; in these discussions, we gathered the information required for our analyses.

3 Results and Discussions

This section details the results of the investigation.

3.1 CMMS-Maximo

CMMS Maximo information indicates a strong focus towards preventive maintenance at Aitik. For the work type category, around 69 percent of the total work orders are for preventive maintenance, while the remaining 31 percent are for corrective maintenance. There are four priority levels for work orders, namely, priorities 1 through 4, where priority 1 represents urgent work. The results show a substantial weekly preventive maintenance program in place at Aitik for mining shovels. In addition, priority 1 work orders only represent about 9 percent of total work orders, indicating less reliance on reactive work at Aitik.

Like any other computer based application, a CMMS is prone to the classic garbage-in garbage-out phenomenon. It depends upon the data entered into it to produce results for analysis. The database attribute of CMMS is not very useful if not enough information has been entered into it to begin with. In other words, the CMMS database has to be built up meticulously in order to get useful information out and make informed decisions. If an organisation is suffering from a chronic under-utilisation of an existing CMMS, the associated problems need to be examined in detail. This fact is particularly salient when there is an ageing workforce, since the loss of experienced maintenance personnel can cause problems in the future. To prevent this, it is beneficial to have a comprehensive historical maintenance database.

The goal is to use historical maintenance data to effect improvements in the maintenance function, but the lack of quality of CMMS data can impede successful analysis. The following are some general observations about how inaccurate historical data, exported from a CMMS, can impact an analysis.

- Populated fields: If the CMMS fields which are used on a regular basis are not always populated, analysis will suffer. If these data are available, the critical subsystems of an asset can be identified in terms of maintenance costs or time required to repair, depending upon the criteria for criticality set by the organisation. If, however, the fields of labour hours and costs are missing, the only reliable means of analysis is the number of work orders associated with each asset or subsystem. It is a reasonable assumption that the closed or completed work orders should contain costs and labour hour details. In the case of the mining shovel, knowing the costs associated with each subsystem or component can facilitate replacement decisions. If, for instance, it is observed from historical CMMS data that the repair costs associated with a subsystem/component are too high, management can decide to replace it with a new one.
- Referencing spare part requisition against work orders: If spare parts are requisitioned against specific work orders, the accuracy of the analysis is increased, as descriptions sometimes lack details. This referencing increases the accuracy of the analysis and provides another level of security against error.

- Accurate work order duration: Analysis can be hampered if the majority of the historical work orders from a CMMS lack reliable start and finish dates or this information is completely missing. For instance, it is a common practice to open and close work orders at exactly the same time. This practice goes against the intended goal of using a CMMS; it is a database and must be maintained correctly. Accurate work order duration information allows the calculation of useful KPIs, such as MTTR and MTBF at the subsystem level, to identify critical subsystems with respect to the time between subsystem failure or the time spent on maintenance.
- Asset number utilisation: If an asset number is not available in work orders, the analysis becomes difficult and tedious. It is impractical and time consuming to analyse large volumes of data manually. Historical maintenance data for the shovel comprise over 16 and a half thousand individual work orders, and an automated system is required to deal with the large volume of data. Data mining aids are useful tools for data analysis, but in this case they proved ineffective due to a lack of consistency within the available data. In the absence of asset numbers for a majority of work orders, the only way to identify individual work orders is to use the description column. However descriptions are subjective and depend upon the interpretations of the maintenance personnel. For example, the hoist mechanism is referred to as hiss, lyft, and hoist. As a result, we could not associate all individual work orders with the correct subsystems. If the asset number column is utilised, it guarantees an almost 100 percent work order association with shovel subsystems. Without an asset number, there is no other way to identigy individual work orders apart from the description column.

3.1.1 Shovel Subsystems

It is important to mention here that the shovels used at Aitik are either hydraulic-face or electric-rope types. Shovels 1142 and 1143 belong to the hydraulic-face type of mining shovels; shovels 1150, 1151, 1152 and 1160 are the electric-rope type. Some subsystems are unique a particular type of shovel.

Corrective maintenance is defined as “maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function” (EN13306:2001). Corrective maintenance is undesirable for any modern maintenance department, since it costs more and takes longer to complete. For the purpose of identifying shovel subsystems which require attention, corrective maintenance is a suitable criterion for criticality in the context of available CMMS data. Therefore, shovel subsystems are ranked according to the number of associated corrective maintenance work orders.

Across the shovel fleet, the crawler assembly has the highest number of corrective maintenance work orders. Assets 1151 and 1152 are exceptions; they are from the same manufacturer and have the highest number of corrective maintenance work orders for the crowler mechanism. The conditions at the Aitik open pit mine go some way to explaining these results. The mine is located in an area which receives high amounts of precipitation and, as a result, the pit conditions range from muddy to wet. Furthermore, the geological settings of the ore body and country rock are characterised by hard rock. These conditions may have been to blame for the high corrective maintenance on the crawler assembly. Asset-1143, which has the highest number of corrective maintenance work orders for the crawler assembly relative to other assets, has been operating in the deepest part of the mine where water ingress has caused unusually wet and muddy operating conditions. These conditions appear to be the primary reason for the high amount of corrective maintenance on the crawler assembly.

3.2 Cat MineStar System

The KPIs calculated in this case are based on accurate time-based data from Cat®MineStar™. MineStar is a mine management system whose uses include tracking the operating status of mobile mining equipment. Universal KPIs such as availability, MTBF and MTTR can easily be calculated using historical records from MineStar with a high level of accuracy, as there is little or no time lag for data entry into the system.

The MineStar system uses delay classes to classify the various work stoppages of the shovels. To classify the delays in the MineStar data, it is important to understand the definitions of different states according to standard EN13306:2001(figure 5).

It is necessary in to assign a state to the equipment to categorise the associated time into required or non-required time. The overarching objective of this exercise is to classify time (both uptime and downtime) to calculate KPIs.

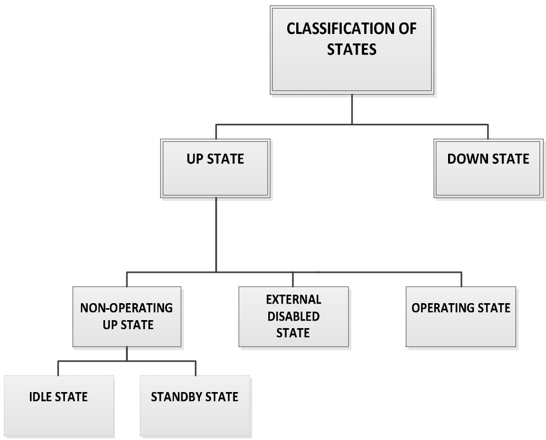

Fig. 5 Item states according to EN 13306:2001

3.2.1 Discussion of Results

Asset-1142 has a high availability amongst the shovels. The mean time between failures is the highest and it has the lowest number of failures, indicating that it does not fail very often. The mean time to restore for asset-1142 is also relatively low. However, asset-1142 has the lowest utilisation amongst the fleet in the timespan under consideration. It operated just 2900 machine hours and was parked idle for most of the time. This is one possible explanation for the respective KPIs.

Asset-1143 has relatively low availability. It has the highest mean time to restore amongst the shovel fleet, indicating that once it fails, it takes longer to restore it to an up state. Although it is a newer machine than asset-1142 which is a comparable shovel type, it has been operating in an unstable section of the mine. Rock falls repeatedly damage the shovel and, as a result, it has been down for maintenance for longer periods. This explains the high mean time to restore. In addition, it has operated 4200 machine hours, a significantly higher operating time relative to asset-1142. Asset-1143 displays another peculiarity; it is one of two shovels in the loading fleet with a downward trend for time between failures (figure 6).

Asset-1150 has relatively low availability. It has the highest number of failures and second lowest mean time between failures amongst the shovels, indicating that it fails more frequently. However, its redeeming feature is the mean time to restore, which is reasonably low. Asset-1150 is one of the oldest machines in the shovel fleet; it has been plagued by small electrical faults which explain the relatively low mean time to restore. It has operated a total of 4850 machine hours in the timespan of this study. Furthermore, asset-1150 exhibits a downward trend for time between failures (figure 7), or in other words, the time between failures is decreasing with each failure. This aspect correlates well with the age of this particular shovel.

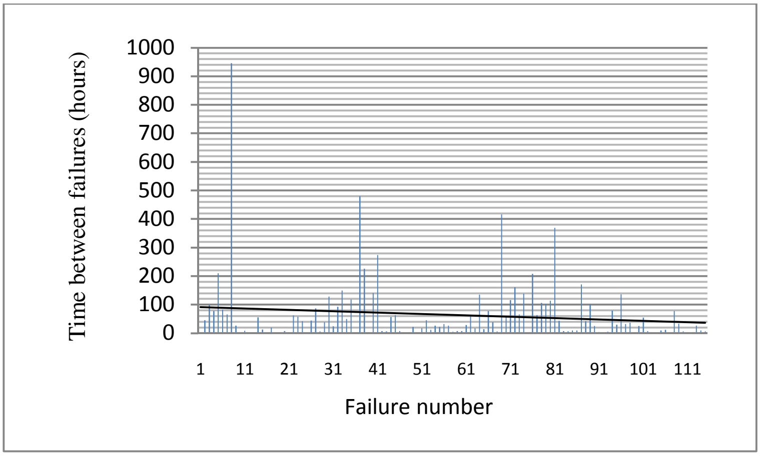

Fig. 6 Graph depicting downward trend of TBF for asset-1143

Asset-1151 has the lowest availability amongst the shovels. It does not score well in all indicators across the board. It has the lowest MTBF and the second highest MTTR; the number of associated failures is in the high range with the lowest availability related to failures amongst the fleet. Asset-1151 is also one of the older machines in the fleet. This machine was relocated to Aitik from another open pit mine where it had been in use for a significant period. It operated 3900 machine hours in the timespan of this study.

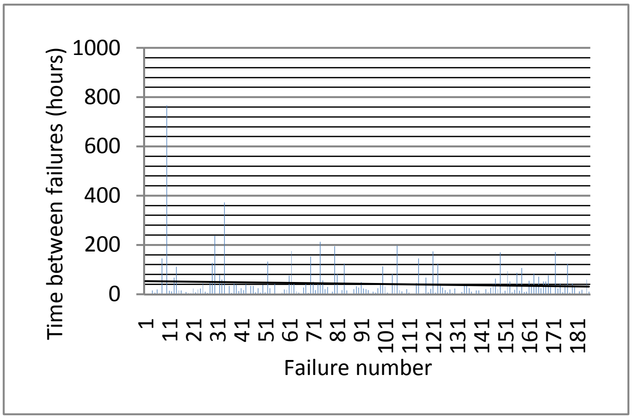

Fig. 7 Graph depicting downward trend of TBF for asset-1150

Asset-1152 has the highest availability in the shovel fleet. It has a reasonable score on MTBF, and the number of associated failures is also in the high range. However it has the lowest MTTR, indicating that it is affected by minor issues which require little time to restore. It operated 5100 machine hours, the highest amongst the fleet in the timespan under consideration. Asset-1152 was commissioned in 2010 and is the newest machine in the loading fleet at Aitik.

Asset-1160 has relatively moderate availability. Even though it has a high number of associated failures and the MTBF is in the lower range, the MTTR is reasonably low, and this seems to be its redeeming feature. In fact, it scores somewhere in the middle of most of the KPIs. It operated 4800 machine hours in the timespan under consideration.

Finally, we can make some interesting observations about the inherent characteristics of the shovels. The electric-rope shovels 1150, 1151, 1152 and 1160 have a similar MTBF which is lower than that of the two hydraulic-face shovels. The hydraulic-face shovels 1142 and 1143 have the highest MTBF and the lowest number of failures; however, their MTTR is also relatively high, indicating that once they fail, it takes longer to restore them to an up state.

These results are based on actual operational data; one benefit of such an analysis is that it may aid management to make decisions on the replacement of existing assets. It may also assist mine management in the procurement of new assets, as they can base their decisions on quantitative results.

3.3 Case Studies

The event-logs are classified according to whether they are operator induced or equipment induced. This section presents two case studies to demonstrate the viable and practicable use of data fusion. The objective is to identify opportunities for improvements in the maintenance function, leading to possible improvements in asset availability.

3.3.1 Case Study 1-Operator Induced Events

Pareto analysis identified the most frequently recurring events in the available historical event-log data. Pareto charts for the electric rope shovels 1150,1151 and 1152 are presented from figures 8 through 10.

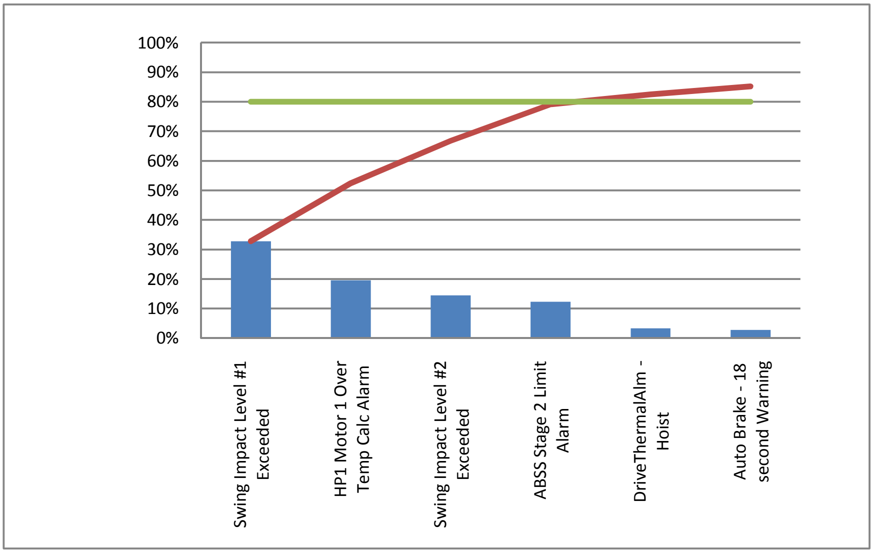

Fig. 8 Event logs Pareto chart for asset 1150

As the figure shows, operator induced events represent a major percentage of the event-log data for asset 1150. In addition, swing impact level # 1 and swing impact level # 2 were exceeded in 30 to 70 percent of the total data sample. However, asset 1150 was selected for further analysis for the following reasons;

- It has the most complete event-log data for the time period for which historical maintenance data from CMMS Maximo has been analysed.
- It has the second lowest MTBF.
- It has the highest number of associated failures.
- It has the greatest percentage of work orders connected with specific subsystems.

3.3.1.1 Asset 1150

In the mining industry, as in other modern industrial operations, production considerations always take precedence. But to ensure effective asset management, production and maintenance departments must take a collaborative approach.

Onboard events are also registered as operator negligence. Therefore we attempted to correlate historical maintenance data with event-logs. This analysis was conducted for six months from October 2011 until March 2012. It included events when the swing impact level # 2 was exceeded. The consequences of this event include cracking in the structural parts of the shovel, i.e., the boom and/or dipper handle. In discussions with maintenance experts at the mine, we discovered that structural damage is a serious problem because it takes longer to repair and, consequently, the shovel is not available for production.

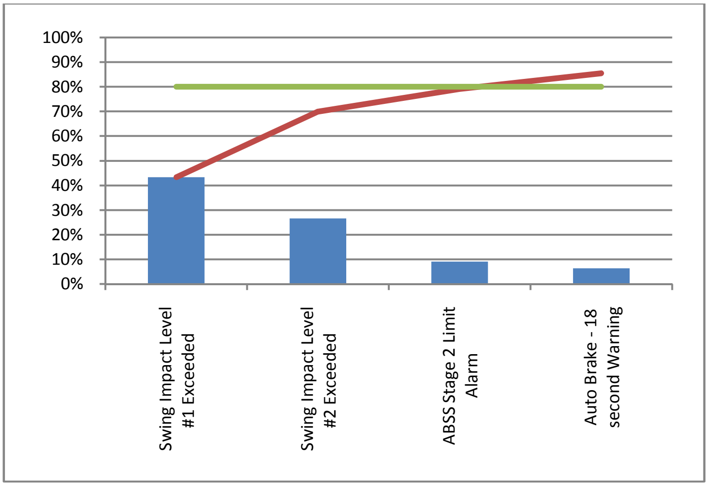

Fig. 9 Event logs Pareto chart for asset 1151

A strong correlation is visible between the frequency of event under consideration and historical maintenance data. Whenever operational limits were exceeded, maintenance personnel reported cracking in the boom. Corrective work orders for cracks in the boom were being reported in CMMS Maximo every month, with November 2011 being the only exception.

Due to production constraints, it is not always possible to avoid such incidents. However, structural damage to the shovels represents a significant risk, and needs to be minimised to increase shovel uptime. Operator induced events such as those involving exceeding operational limits can be analysed further to determine their causes, as a preventable positioning error or other operational problem may be responsible. In the long run, the focus must be on structural damage prevention rather than repair to increase the life of shovels.

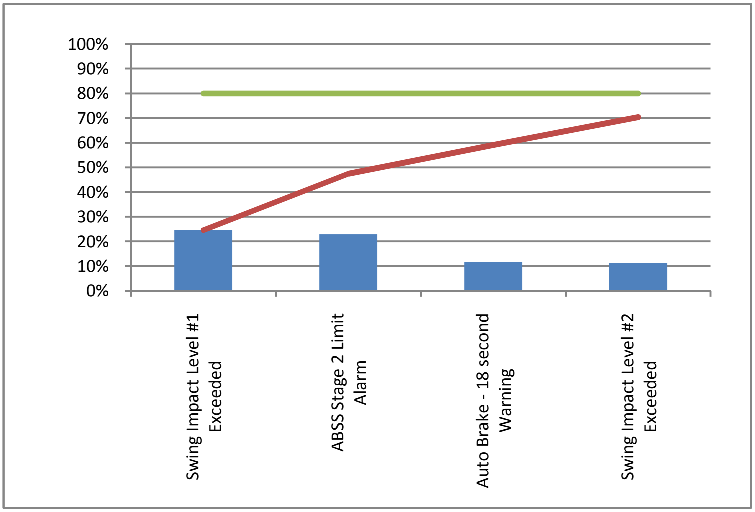

Fig. 10 Event logs Pareto chart for asset 1152

3.3.2 Case Study 2-Equipment Induced Events

Events are also induced by the various components of the shovels. During the course of the investigation, we observed that equipment induced events represent a minor proportion of the data sample. Even so, they required analysis to identify any potential for an improved maintenance function.

3.3.2.1 Asset 1160

Asset 1160 belongs to the electric-rope type of mining shovels. The crowd and swing mechanisms of the shovel use electric motors for their actions. To control their speed, the motors come equipped with brake assemblies. These brake assemblies are prone to wear and tear, and need to be replaced after a certain operating time. Asset 1160 has wear indicators fitted to both brake assemblies; these alert the operator and maintenance personnel to carry out maintenance actions. When we correlated wear events for both brake assemblies with historical maintenance data, we observed that as the daily event frequency begins to increase, a corrective maintenance work order is reported in CMMS Maximo.

Another interesting observation is that both brakes appear to have a similar maintenance interval of approximately four months. However, they are presently being replaced during different calendar months. It would be more efficient to amalgamate the repairs. When the shovel is down for maintenance for one brake component, the other may be replaced. For subsequent repairs, it can be a standard practice that if either component is worn out, the other is inspected, and depending upon its condition, a suitable maintenance action is undertaken. In the long run, this amalgamation of maintenance actions may reduce downtime for the shovel.

4 Conclusions

During the course of this investigation several things became clear. On the basis of our observations, we make the following recommendations.

- The CMMS database has a great deal of potential for improvement. Maintenance personnel need to maintain the CMMS database accurately and meticulously to gain any useful information from it in the future. To ensure the compliance of maintenance personnel, some procedures may require modifications. For instance, during the course of this study, we observed that the asset number hierarchy in the current version of CMMS is too complicated. In some cases, the asset numbers go down to the individual spare parts in the shovels. It is imperative that the asset number hierarchy be kept as simple as possible to ensure asset number utilisation by maintenance personnel. The asset number hierarchy need only go down to the subsystem level or possibly to the associated component level.
- During the analysis we noticed something interesting about the crawler assembly. The crawler assembly has the highest number of associated corrective maintenance work orders across the fleet. This is possibly due to the location of the mine, which receives a great deal of precipitation resulting in a high ingress of water. Thus, the conditions in the mine range from muddy to wet. Furthermore, the geological settings of the ore body and country rock are characterised by hard rock. Hard rock mining results in more wear and tear on the equipment. These factors, though, are a function of mine location and geological conditions, and are here to stay. One possible way to limit damage to the crawler assembly is to limit its use. In discussions with maintenance experts at the mine, we discovered that a transport alternative for shovels is under consideration. Such actions can limit the use of the crawler assembly over longer distances within the mine from one dig location to another and may result in reduced wear and tear. To justify capital investment into such alternatives, it is beneficial to conduct a comparative cost analysis. However, for such analyses, accurate and comprehensive historical maintenance data from CMMS are required. The associated labour hours and costs for repair on the crawler assembly can be useful to compare two options from a financial benefit standpoint, i.e. use of the crawler assembly for longer distance moves or an alternative transport arrangement which does not require its use. The alternatives can be compared in terms of financial viability over a set period. Such analyses provide a quantifiable way to justify a new investment.
- The event-log data show a noticeable correlation with the historical CMMS database. More specifically, there is a direct correlation between events recorded and maintenance actions reported. A time-lapse analysis of event-logs downloaded from the individual shovels could prove useful. However, the determination of a suitable frequency for data collection and subsequent analysis is difficult. The time needs to be long enough to yield a large enough

sample size and make any trends visible, but not so long that the damage is already done. In this case, one month sample size seems sufficient to recognize trends. Data mining tools can process the large amount of data and identify frequently recurring events. Additionally, a regular time-lapse analysis on events can aid in developing a proactive and collaborative approach to prevent structural damage to shovels. Finally, for asset-1160, the brake assemblies on the swing and crowd electric motors appear to have a similar maintenance interval. From an efficiency perspective, it is practical to amalgamate maintenance actions for these components.

At each stage of the study, a lack of accurate and comprehensive historical maintenance data from CMMS limited the extent of analysis. In other words, the unavailability of such data restricts the scope of research and reduces the opportunities to improve the maintenance function.

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