CONTINUOUS EVALUATION OF OPERATIONAL RISKS ON DEEP-LEVEL MINE EQUIPMENT

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ABSTRACT

Underground mining operations comprise complex systems that provide the service areas with cold water, compressed air and ventilation. Equipment is located on the surface and underground, which makes the monitoring thereof a challenging task.

A condition monitoring process on deep mines involves several types of parameters and equipment. Software tools and applications are used to analyse the raw data and identify operational risks. This automated analysis results in a substantial amount of risk information being generated on a regular basis. It is therefore necessary to examine the information for knowledge discovery to take place.

A software-based application was developed to categorise the risk information according to system class, parameter type and risk severity over a selected date range. The solution enables site managers to determine where critical risks occur repeatedly and what the maintenance impact is.

The newly developed application was used to evaluate the risk information of six mining sites over a period ranging from six to 12 months. Up to 96 daily risk identifiers per site were evaluated resulting in more than 17 000 values over a period of six months. The application and associated reports facilitated the identification of problem areas within the respective operation.

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1. INTRODUCTION

Too much data and too little information is a common occurrence in the 21st century. Enhanced hardware and software have given users access to greater processing power, immense storage capacity and advanced analysis methods [1]. Many industries are finding it difficult to gain insights from the data they now have at their disposal [2-4]. One example is the challenge that the mining industry is facing in the field of preventative maintenance. Effective maintenance strategies play an integral part in system availability. On deep-level mines, equipment up-time is vital to ensure uninterrupted production and adherence to safety regulations [5]. A condition monitoring system was therefore developed to assess the operational condition of mine equipment on a daily basis [5]. The risk assessment is based on the SCRF methodology developed by Van Jaarsveld [5, 6]. The methodology will be briefly discussed to provide some context.

Four regions of operation namely, safe, caution, risk and failure (SCRF) are used to characterise each input signal. The boundary for each region depends on equipment attributes such as type and size. A safe vibration amplitude for a large dewatering pump will differ from that of a small booster pump or a ventilation fan. Parameter specific boundaries are therefore used to assess each individual input.

The system performs a daily assessment to determine a risk score, and corresponding risk category, for each parameter. The risk category is translated to a health status level (1, 2 or 3) which the online platform converts to a colour marker (or format). Figure 1 shows the relationship between the risk category, health status and online formatting.

![Figure 1: Risk category and health status relationship [5]](image)

Parameters are grouped together, based on the type of measurement. As seen in Figure 2 single formatting value can thus be assigned to each parameter type according to the health status of the respective parameters. This is achieved by using the highest health status value from the input list.

![Figure 2: Process to determine format label [5]](image)

The same procedure is followed to determine a format label for each system, for example, the maximum health status of all the fans is used to format the collective fan system. The risk information is compiled in automated...
reports and made available on an online platform. A screenshot of the online platform’s overview page can be seen in Figure 3.

![Figure 3: Online platform overview page](image)

The risk information shown here are daily risk indicators, and therefore, over longer periods of time, it becomes overwhelming and difficult to evaluate manually. It was therefore necessary to develop a software application capable of interpreting and categorising the risk information.

2. BACKGROUND

Deep-level gold and platinum mines can reach depths of up to 4 km below the surface [7]. Successful ore extraction at these depths require complex systems operating together. These systems include compressed air, cooling, dewatering, hoisting and ventilation systems [8]. These operation-critical systems are typically distributed across the mine, from the surface to the deepest levels [9]. The physical conditions in a typical mining environment, particularly at deep levels, can be very harsh [5].

2.1 Need for maintenance

The harsh conditions in deep-level mines holds multiple health and safety risks for mining personnel. Health and safety risks include, hot air, polluted air and flooding. Multiple systems are relied upon for mitigation of these risks.

The high virgin rock temperatures at these depths cause high air temperature, while mining equipment’s exhaust fumes pollutes the air [10-12]. Cooling systems are typically situated on the surface, but can be installed underground if deemed necessary [9, 11]. The cooling systems dehumidify and cool ambient air, which is then fed down the mine to deeper levels via the ventilation systems [13]. Cooling and ventilation systems are therefore integrated to achieve safe air temperatures and safe atmospheric vapour compositions in underground mining environments [14].

In underground mining operations, water is constantly released from subsurface fractures (fissure water). Water is also sent down the mining levels for cooling and mining purposes [9]. These large volumes of water create the risk of flooding in underground mining operations, especially at deeper levels. Multistage pumping systems mitigate this risk by continuously pumping water to the surface [9, 15-17].

Operational systems are not only responsible for safe working conditions. Compressed air systems power mining equipment such as pneumatic drills, mechanical ore loaders and refuge bays [18]. Equipment availability is a major contributor to a mine’s productivity [19, 20].

Equipment up-time and reliability in deep-level mines are thus critical for workplace safety and production and can be largely affected by the maintenance strategy applied. Ill-maintained equipment tends to develop malfunctions and will eventually break down [21]. Maintenance after equipment failure (reactive maintenance) typically results in extended equipment downtime and increased maintenance compared to maintenance before equipment failure (proactive maintenance) [19, 22, 23].
Maintenance costs of mining equipment vary depending on the type of the equipment and the maintenance strategy used. These costs can amount to 25-40% of overall equipment costs (including procurement and operational costs) [24, 25]. Since mines are on a tight budget, avoidable operational and capital expenditures should be kept to a minimum [10, 26]. These expenditures include component replacement cost, secondary damage to additional components in vicinity and loss of production due to equipment downtime. A cost optimised maintenance strategy is therefore crucial in mines.

Maintenance strategies can be divided into 5 types [19]:

- **Breakdown maintenance**: Repairs to failed or broken-down equipment. This typically entails replacement of components.
- **Corrective maintenance**: Upgrades to components with a flawed design to improve reliability.
- **Preventative maintenance**: Aim is to prevent equipment failure. Two sub-categories are described below:
  - **Time-based maintenance (TBM)**: Maintenance done on a predetermined schedule.
  - **Condition-based maintenance (CBM)**: Maintenance done based on the current condition of equipment.
- **Reliability-centred maintenance**: Only perform preventative maintenance on parts which directly affect overall system reliability.
- **Total productive maintenance**: In addition to production responsibilities, operators are responsible for reporting on maintenance needs. The aim is to maximise production, while maintaining equipment reliability. This strategy requires highly trained and knowledgeable operators.

Preventative maintenance strategies are desirable as they aim to avoid expensive repair and replacement costs and unplanned downtime [24, 27]. CBM’s statistical analysis relies more on actual data, while TBM’s statistical analysis relies more on theoretical equipment life cycles. CBM is therefore preferred over TBM as it is more practical and often more accurate than TBM [28].

### 2.2 Condition monitoring and CBM

Condition monitoring is a tool to assist with CBM. Condition monitoring involves data acquisition and data processing. Data acquisition consists of constant measurement and logging of equipment’s operational parameters. Data processing involves analysis of the logged data, with the purpose of detecting changes in the operational parameters that may be indicative of a potential fault. CBM can utilise this condition monitoring information to make maintenance decisions [22, 29].

Various specialised condition monitoring methods can be used in deep-level mines. These methods include vibration frequency monitoring (spectral analysis), acoustic emission monitoring, visual monitoring, oil particle analysis and infrared thermography [30-32]. These specialised condition monitoring methods are expensive to implement and tend to require highly skilled personnel to utilise and maintain. Basic protection systems are used to prevent machines from operating outside of their design specification. Input values are continuously compared to a relevant trip limit. These systems will therefore initiate an automatic trip sequence when a violation occurs. The measurements are typically only used on a real-time basis to ensure safe operation instead of being used for monitoring purposes. However, the available data from these systems can be used to develop simpler and cheaper methods for condition monitoring [33].

Basic protection system’s data can be analysed to determine mining equipment health and to identify operational risks. This simplified method of condition monitoring was used to successfully apply CBM in the mining industry [5, 6, 33]. This condition monitoring method is useful for daily CBM decision making, but lacks long-term tracking of operational risks.

Long-term tracking of operational risks can provide valuable insight into the maintenance strategy performance. Literature on performance tracking of maintenance strategies is limited [34]. A SWOT (strength, weakness, opportunity and threat) analysis was done on maintenance strategies in the manufacturing industry. The analysis indicated multiple benefits of evaluating an organisation’s maintenance strategy. The efficiency of the maintenance strategy was improved. The analysis assisted with improving the adaptability of the maintenance strategy to the changing business environment. The analysis also assisted with the development of contingency plans [34].
3. SOLUTION DEVELOPMENT

An application was developed to categorise the risk information according to system class, parameter type and risk severity. Considering the system class information, four mining systems were available. These systems include Pumps (P), Compressors (C), Refrigeration plants (R) and Ventilation fans (F). Two parameter types were available via the basic protection system, namely temperature (T) and vibration amplitude (V). Depending on instrumentation availability and equipment type, Table 1 lists the parameters that were considered for analysis.

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<thead>
<tr>
<th>Pump drive end (DE) temperature</th>
<th>Pump drive end (DE) vibration</th>
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The notation that will be used consists of the relevant system identifier, followed by a subscript of the relevant parameter type identifier. The pumping system's vibration risk information can therefore be denoted as P\(_\text{V}\). Figure 4 displays the various system classes and parameter types that were evaluated and how they can be combined for different types of analyses. For example, a user can choose to view the combined compressor risk information for all the parameter types (C\(_T\) and C\(_V\)).

The risk analysis is performed daily and the corresponding risk information is added to a database. Three levels of severity are used, namely low (1), medium (2) and high (3). The medium-risk occurrences are given a warning label, while the high-risk occurrences are given a critical label. It is therefore possible to only view the critical count, or view both the warning and critical counts when selecting the system and parameter types.

A few simple steps are followed to configure and generate a new report. A script-based application provides the user with several options to compile the required information. The setup procedure can be summarised as follows:

- The user exports the relevant risk information for the required date range.
- The user selects whether only critical counts are included.
- The user selects daily or monthly graphing intervals.
- The user adds charts by defining a system and parameter type for each chart.
Figure 4: System classes and parameter types

Figure 5 is an example of risk information that was exported for an arbitrary number of input tags. The different types of evaluation options are illustrated in the figure. The evaluation options determine which of the input values are included in the analysis. For example, if a parameter type evaluation is performed, all the input values corresponding to the selected parameter type (highlighted in blue) will be considered irrespective of the system class. Each of the analyses are performed over the entire date range to determine a warning and critical count for each day. The results can then be compiled in monthly totals.

Three charts are added to the report by default. For illustration purposes, both the critical and warning counts will be included in all the examples given. The first chart (Figure 6) displays the totals of all the systems with

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Figure 5: Risk information with evaluation options

Three charts are added to the report by default. For illustration purposes, both the critical and warning counts will be included in all the examples given. The first chart (Figure 6) displays the totals of all the systems with
both parameter types. The second chart (Figure 7) provides a distribution between the relevant systems, while the third chart (Figure 8) provides a distribution between the parameter types. The user can add additional charts as needed e.g. a system evaluation of the compressed air system (Figure 9).

Figure 6: Risk information overview

Figure 7 displays the risk distribution between the four major systems that were evaluated.

Figure 7: System class risk distribution

Figure 8 displays the risk distribution between the two parameter types that were evaluated.
4. IMPLEMENTATION AND RESULTS

The risk information of six deep-level mines was evaluated. The availability of the risk information depends on the respective site implementations. It was therefore possible to evaluate some sites’ information over a period of 12 months. The number of individual risk identifiers depends on the number of mining systems and subsystems on each site. 96 daily risk identifiers were used in one of the site evaluations, which resulted in more than 17 000 input values for a period of six months. Two site evaluations will be discussed in more detail.

4.1 Case study 1: Mine A

The systems on Mine A that were evaluated included pumping, cooling and ventilation. 48 risk identifiers were evaluated over a period of eight months. The evaluation therefore consisted of 11 520 input values. Figure 10 displays the system distribution of Mine A’s risk information. This risk distribution clearly indicated that the majority of the risks occurred on the cooling and ventilation systems.
The parameter distribution is shown in Figure 11. It is evident that most of the risks are related to vibration.

Another interesting revelation was the increase in critical risks (high risk severity) on the cooling system (Figure 12). These risks were related to high vibration measurements on three refrigeration plants. This was seen as a high priority due to the fact that the refrigeration plants provide the underground operations with cold water and a cold-water supply interruption could force the mine to halt production.
4.2 Case study 2: Mine B

Four mining systems were evaluated on Mine B. 40 risk identifiers were assessed for a period of 12 months. The assessment therefore consisted of 14 400 input values. A risk overview, for all the systems, is shown in Figure 13. It is clear that the number of operational risks decreased during the first nine months. During the next three months, however, there was an increase in risks. These risks mainly occurred on the pumping and compressor systems. This assessment highlights the importance of a continuous evaluation: to immediately be made aware of new or re-emerging system risks.

The system-specific evaluation for Mine B’s compressor is shown in Figure 14. The risks that were initially identified were resolved. During the last month, there were a number of critical risks that were detected. Maintenance personnel can therefore schedule the required maintenance. Site supervisors can now also verify, on a monthly basis, that the issues have been resolved.
5. CONCLUSION

Due to the operating depths of deep-level mines, equipment maintenance is a challenging task. It is not feasible for mine personnel to perform manual inspections regularly. An automated system was therefore developed to perform a condition monitoring analysis to identify operational risks. However, over longer periods of time, the risk information becomes too substantial for supervisors to gain insights from.

A new software application was subsequently developed to categorise the risk information according to the system class, parameter type and risk severity. The application is used on a monthly basis to evaluate the change in equipment condition.

The results from the system have already enabled mine personnel to identify problem areas within their operations. Maintenance efforts can therefore be focussed on critical and recurring issues. Site supervisors are also able to follow up on equipment overhauls that were performed. Future work includes an assessment of the long-term use of the application to quantify the benefit thereof.

REFERENCES


