South Africa’s electricity supply is under pressure due to a lack of supply to meet demand [1]. Further, mining is one of South Africa’s largest electricity consumers with its electricity-intensive services such as compressed air, cooling, ventilation and others [2].

There is a need to reduce the operational cost on a mine as the electricity prices are set to increase at least 2% above South Africa’s inflation target [3].

Deep level gold and platinum mines in South Africa require extensive cooling and ventilation to create acceptable conditions for both people and equipment. Therefore, more than 40% of mine electricity consumption is used for cooling and ventilation [4].

The most common electricity management projects are Load Management (LM) and Energy Saving (ES). LM projects alter the electricity load profile according to the Eskom Time Of Use (TOU). Alternatively, ES projects reduce the amount of energy used by the system. Both types of projects realise a monetary saving.

Mining projects simulation

Mine cooling and ventilation systems differ. Therefore, in order to compare a project’s results with other project results, a typical mine was simulated.

As shown in Figure 1, the simplified typical mine has the following ventilation and cooling sub-sections:

- Pumping
- Surface service-water refrigeration
- Underground service-water refrigeration
- Surface air refrigeration
- Underground air refrigeration
- Ventilation fans (booster and main)
- A water distribution network

The power usage for the simulated mine is 22 MW as is shown in Table 1.

<table>
<thead>
<tr>
<th>System</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping</td>
<td>7,542</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>10,241</td>
</tr>
<tr>
<td>Fans</td>
<td>4,167</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21,949</strong></td>
</tr>
</tbody>
</table>

The work-weekday cost is determined in Table 2 at R79 M per annum taking the power over 24 hours and an average cost of 61c/kWh.

| Total hourly power       | 21,949 kW |
| Hours per day            | 24 h      |
| Weighted average power cost | 0.61 R/kWh |
| Number of week days      | 248 days  |
| **Annual cost**          | **R79 million** |

The mine has therefore been established with a baseline energy usage along with the annual cost of this usage.

Implementing a sequenced combination of cooperative projects on a typical mine resulted in substantial annual savings. This was due to substantial reductions in the ventilation and cooling electricity bill.
Further, there are the eleven cooling and ventilation LM and ES projects:

- Pump control [6]
- Fridge plant control [7]
- Thermal ice storage [8]
- Ice circulation [9]
- Energy recovery [10]
- Water-supply optimisation [11]
- Cooling auxiliaries [12]
- Auxiliary fans [13]
- Main fan control [14]
- Main fan carbon blades [15]
- Closed-loop underground Bulk Air Cooler (BAC) [16]

These projects are currently implemented ad hoc and are seldom combined unless they are on a low level of interaction with each other such as varying the pumping water supply to the fridge plant enables the fridge plant water processing to vary.

Therefore, an evaluation system is needed to combine and sequence their implementation to ensure that the maximum possible saving throughout the entire mine-cooling and ventilation system is achieved.

**Evaluation of projects**

Each project was evaluated against yearly monetary savings, potential risks and other factors. The monetary savings takes into account the effect the project has on the simulated and simplified typical deep level mine power profile as well as the Eskom TOU cost structure.

The monetary saving was normalised by being divided by the total cost.

The risks for each project were evaluated according to:

- Service delivery
- Production
- Environmental Health and Safety (EHS)
- Overhead cost
The risk matrix used in the evaluation of each project on this simplified typical deep level mine is shown in Figure 2. The hazard and risk of each project on the simplified typical deep level mine was determined from consultation, literature, deductions and the authors’ decades of hands-on experience in industry. The identified risk and hazard with regards to service delivery, production, EHS and overhead cost was evaluated against the magnitude and severity starting from Not possible to Catastrophic. Then the likelihood of the project’s risk and hazard was evaluated with regard to the aforementioned aspects starting from never to frequent. In the example it is seen that with regards to production, the Pumping LM project poses a risk or hazard which is insignificant in magnitude (scores a 1) and occurs seldom (scores a 1). The risk was quantified by multiplying the severity with the likelihood (1 x 1 = 1). The identified risk was then determined by multiplying the risk with the aspect weight. This would then give a weighed risk of 1 for the Pumping LM project with regard to service delivery (1 x 1). The weighed risk indicator was then determined by summing the weighed risks and dividing it with the total aspect weight (8/7 = 1,14). The maximum possible score that could be achieved for a risk would be 5 x 5 = 25. The maximum value or score that the weighed risk indicator could be is (25 x 1 + 25 x 2 + 25 x 3 + 25 x 1)/7 = 25. The risk is normalised to a percentage by being divided by the maximum possible value or score. For example 1,14/25 = 4.56 % which is rounded up to 5 %.

Other factors considered:
- Introduction of new equipment
- Upgrading of existing equipment
- Expanding the mine’s information network and monitoring capability
- Displaying and logging of important mine system variables
- Implementation time
- Down time required for implementation
- Interaction with other systems

These other factors were evaluated similarly to the aforementioned project risk for the simplified typical deep level mine. Each factor carried a weight as shown in Figure 3. Displaying and logging mine system variables in this study is deemed to be desirable and has a high weight of 9. The projects were scored according to each factor and again the score was determined from consultation, literature, deductions and the authors’ decades of hands-on experience in industry.
The weighted scores were then summed to achieve a total score of 374. The other factors total score is referred to as the strategy’s Project Appeal Indicator (PAI).

The PAI was also normalised to a percentage by being divided by the maximum possible value or score. As an example 347/700 = 49.57% which was rounded up to 50%.

Figure 4 shows the results of the annual cost savings of all the projects. The water-supply optimisation strategy, which operates by reducing the amount of water circulated and chilled, has the highest annual saving.

Figure 4: Yearly monetary saving.

The lowest annual saving comes from exchanging the main fan’s steel blades with carbon fibre blades. This is due to the project not interacting or influencing any other system.

Figure 5 shows the results from the risk evaluation. The highest risk projects are the carbon fibre blades, ice and three-pipe projects. They introduce new chemicals to the mine’s environmental health and safety structure. New equipment and technologies add to overhead running cost. As an example, if the main fan carbon fibre blades are designed or manufactured wrong, or hit with a blunt object it will break apart. There is instantaneously a reduction in service delivery of cool ventilation air. This negatively affects the health and safety of the employees underground. Border line production areas are brought to a halt and suspended with a reduction in ventilation and cooling.

These risks can be mitigated by ensuring the correct design. They can be mitigated by stringent manufacturing quality checks and controls. They can be mitigated by removing all possible blunt objects and having standby main fans available. Given this it is risks that are simply not there when compared to installing a VSD on a surface cooling auxiliary pump.

Figure 5: Risk evaluation of strategies.

However, since not all the evaluated projects can be implemented on a mine, there is a need to determine the best combination of projects.

Implementation of multiple technologies

Not all eleven projects should be implemented. The interactions between systems as well as clashes between projects were considered to determine the optimal project combination.

Ice circulation project is not considered because this simplified typical deep level mine already has underground refrigeration.

Thermal ice-storage project is omitted in favour of fridge plant control. This is done because an optimisation of cooling auxiliaries ES project is then also possible which will increase the total overall monetary saving. Table 3 summarises the best combination of projects.

Table 3: Best rated combination of projects.

<table>
<thead>
<tr>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump control</td>
</tr>
<tr>
<td>Fridge plant control</td>
</tr>
<tr>
<td>Turbine/three pipe</td>
</tr>
<tr>
<td>Water-supply optimisation</td>
</tr>
<tr>
<td>Cooling auxiliaries</td>
</tr>
<tr>
<td>Auxiliary fan</td>
</tr>
<tr>
<td>Main fan control</td>
</tr>
<tr>
<td>Main fan carbon blade</td>
</tr>
<tr>
<td>Closed-loop underground BAC</td>
</tr>
</tbody>
</table>

After an evaluation of individual projects has been done and the combination of strategies has been determined, there needs to be a sequence to implement the chosen combination.
Sequencing the implementation of projects

When first faced with determining the project sequence, it would be assumed that it is more economical to start with the biggest monetary saving and end with the smallest as shown in Figure 6. This would mean starting with the water-supply optimisation project and ending with the main fan carbon blades project.

A more risk adverse sequence of strategies from lowest to highest risk is shown in Figure 7. This means starting with the pumping project and ending with the main fan carbon fibre blades project. It is a significantly different path although it ends with the same strategy.

The other factors might also be considered in the decision to implement the proposed combination. Using the PAI as a guide this installation sequence would be as shown in Figure 9. This means starting with the water-supply optimisation project and ending with the auxiliary fan project.

The savings from a water supply optimisation project is realised on the pumping and refrigeration systems. Therefore, one needs to have information on the pumping and refrigeration systems before implementing a water-supply optimisation project.

The same applies to the optimisation of the cooling auxiliaries and turbines. The full potential would not be realised if the amount of water circulated was not first reduced with a water-supply optimisations project. Pumping supplies the fridge plant and therefore load management on the pumping system enhances the load management that can be done on the fridge plants.

With this, the sequence is thus to start with a pumping control LM project followed by a fridge plant control LM project. Once both plants’ energy load is managed and recorded one can implement a water-supply optimisation project.

The optimisation of cooling auxiliaries has less monetary saving than an energy recovery turbine. However, it is more risk averse and desirable to first install a cooling auxiliary project before a turbine.

Furthermore, with the network infrastructure being installed on all the pumping-, refrigeration- and mining levels, one can easily obtain data and implement a closed loop underground BAC project.

With the knowledge gained on the ventilation system one can also start implementing fan projects such as replacing all the auxiliary fans with more efficient fans.

Therefore, the main extraction fan control should be implemented next. With this data the carbon fibre blade savings can also be calculated.

Thus all the projects have been combined and sequenced as shown in Table 4 by looking at monitory savings, potential risks, PAI and the interaction and amalgamation relationship of the strategies.

This sequence is also validated and verified by the referenced dates of literature published on these strategies shown in Table 4.

The sequenced combination is applied to the simplified mine simulation to determine the resultant energy and cost savings. Most other evaluations only add the effect of each individual strategy. However, the result obtained from the simplified simulation also takes

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Project</th>
<th>Publication</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pumping</td>
<td>2003</td>
<td>[6]</td>
</tr>
<tr>
<td>2</td>
<td>Fridge plant</td>
<td>2006</td>
<td>[7]</td>
</tr>
<tr>
<td>4</td>
<td>Optimisation of cooling auxiliaries</td>
<td>2012</td>
<td>[12]</td>
</tr>
<tr>
<td>5</td>
<td>Energy-recovery turbine</td>
<td>20121</td>
<td>[10]</td>
</tr>
<tr>
<td>6</td>
<td>Closed-loop underground BAC</td>
<td>2013</td>
<td>[16]</td>
</tr>
<tr>
<td>7</td>
<td>Booster fans</td>
<td>20062</td>
<td>[13]</td>
</tr>
<tr>
<td>8</td>
<td>Main fans</td>
<td>2012</td>
<td>[14]</td>
</tr>
<tr>
<td>9</td>
<td>Main fan carbon blade</td>
<td>2013</td>
<td>[15]</td>
</tr>
</tbody>
</table>

1. This is a recent publication of an implemented energy-recovery system. Publications on turbines and their installations have been around since at least 1985 [13].
2. This publication tests the idea of a booster fan project. There is no publication on a successful installation that realised an energy-saving.
into account the interaction between systems and projects. It is therefore a more accurate reflection of the possible savings that are achievable on a mine cooling and ventilation system. An overhead centralised monitoring system can also be used to ascertain the overall effect of projects even though each system is implemented and operates on its own.

**Results**

The sequenced combination of cooperative projects was then implemented on a typical mine as a case study. Implementing all nine strategies in sequence allowed a 17 MW reduction in the Eskom evening peak period and a 132 GWh energy efficiency throughout the day as shown in Figure 10.

![Figure 10: Resultant change in energy profile of simplified typical deep level mine for sequenced combination.](image)

The implementation of the sequenced combination of strategies further resulted in an annual cost reduction of the mine ventilation and cooling system of R30 M. That is a saving of 38 % on the annual cost of the ventilation and cooling system, and 16 % on the annual costs for the entire mine for weekdays. Figure 11 shows the change in the weekday cost profile.

![Figure 11: Resultant change in 24 hour operational cost of simplified typical deep level mine for sequenced combination.](image)

An average project realises a 5 % annual saving on the annual ventilation and cooling cost. This 38 % saving shows that an integrated project approach delivers results that are greater than current ad hoc and uncoordinated implementations of projects.

**Conclusion**

This study listed all the sections of a mine cooling and ventilation system as well as all the associated energy and cost saving strategies. Each strategy was then analysed with regard to their yearly monetary savings, potential risks and other factors. The risk of each strategy was evaluated against service delivery, production, EHS, as well as overhead cost. Other factors (PAI) that were considered were the purchasing of new equipment, upgrading existing equipment, expanding the mine network and monitoring, implementation time, downtime and the interaction with other projects.

However, not all the projects could be implemented and the best combination of projects was determined. This combination was then sequenced by taking into account the factors mentioned above and looking at the project implementation steps. A simplified simulation was then used to determine the power usage of a mine’s cooling and ventilation system. The annual cost was calculated using the simulation model and Eskom’s tariff structure. These results showed that R30 M can be saved annually. In conclusion this study has shown that, by following the sequenced combination proposed, the maximum savings on all the systems will be realised.

**Acknowledgement**

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**References**


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