CONTINUOUS MONITORING FOR SAFETY, HEALTH AND OPTIMISATION IN SOUTH AFRICAN DEEP LEVEL MINING.

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Abstract

This paper describes the development of a monitoring architecture that allows for continuous monitoring of the process of mining, the underground environment, the state of the rockmass and its response to mining. The system is based on an open standard and is non-proprietary. It allows for dense sensor arrays in the workplace, wireless communication to the closest power line, and TCP/IP communication to a central server.

Continuous monitoring and quantification of the appropriate parameters allows a mine to optimise its mine process; to dynamically access the safety and health risk to people and equipment; and to quantify exposure to potential health hazards such as dust, gas or noise.

Current application examples of continuous monitoring include an application to optimise drilling and blasting thought fragmentation monitoring; an application of wireless sensor network-based monitoring in to provide early detection of potential rockfalls; and a trail to continuously assess the gold grade at the shaft through correlation with radioactivity.

It is unlikely that a single monitored parameter will provide adequate knowledge of the assessed risk or even an optimisation approach. Multiple parameters are being combined using cognitive science tools such as Bayesian theory and other statistical methods to improve the accuracy and relevance of, for example, risk quantification. The decision maker is not confronted with massive amounts of raw data but rather with a single knowledge statement such a probability of failure, a human physiological strain index or an optimisation index.

1 Introduction

A multidisciplinary team from the CSIR, South Africa has developed a scalable risk/hazard monitoring system, based on the wireless sensor network concept, to be applied in deep and high-stress mining environments. This system, called AziSA, is a non-proprietary and open standard specification that includes a mining environment data-acquisition, communication and decision-support system, with the internationally accepted concept of a wireless sensor network embodied in the system.

Three applications of real-time in-mine monitoring is described, namely the monitoring of rockfall hazard risk; fragmentation and on-line monitoring of gold.

AziSA’s first application is the backbone of a Mine Health and Safety Council sponsored rockfall research project. The range of sensor functions includes microseismic, acoustic, closure and differential movement,
infrared, support loading, and seismic velocity. The sensors have embedded wireless networking based on the Zigbee standard for in-stope data communication, and power line communication from stope area to the shaft. On surface the critical parameters are combined using Bayesian theory and other statistical methods to improve the accuracy and relevance of risk quantification and prediction.

An early implementation of continuous real-time monitoring for mining optimisation was the monitoring of reef fragmentation. This allowed for an optimisation of the blasting process and resulted in a significant reduction in gold losses.

A third AziSA application is described where the sensing of radio activity emitted from the hoisted reef and waste allow for the early detection of cross tipping and potentially an independent and continuous estimation of the amount of gold produced at the shaft.

2 Early recognition of rockfall hazard/risk

Rockfalls are a major contributor to fatal accidents in the South African mining industry (Adams, D.J., personal communication, 2007). A research project was awarded in 2006 by South Africa’s Mine Health and Safety Council (MHSC) to the CSIR to develop a measuring and monitoring methodology that could quantify the rockfall risk and allow for pro-active alleviation of such a hazard/risk. The project specified that the methodology should provide for the recognition of the precursory indications of rockfalls; interpret the predominant and critical mechanisms involved in rockfalls; and develop algorithms to combine the critical parameters in order to activate an alarm.

Rockfalls occur in environments of all the mining commodities in South Africa. Rockfall fatalities, however, occur predominantly in gold, coal and platinum mining environments. The 2004-2005 Mine Health and Safety Council annual report provided the information used in the following interpretation (MHSC, 2005). Information from this annual report was supplemented with information from an internal (CSIR) and unpublished database of all rockfall and rockburst accident investigations for the period 1990 to 2000. Figure 1 and Figure 2 show that gold mining bears the brunt of fatal rockfall accidents in terms of both risk and absolute numbers.

![Figure 1: Rockfall fatal incidents expressed in terms of fatality rate per million hours worked](image1)

![Figure 2: Rockfall fatal incidents expressed in terms of number of fatalities](image2)

With the understanding that the largest number of rockfall accidents occurs in gold mining, the following attributes are mostly observed with fatal rockfalls in South African mines.

These attributes can be summarised as follows:

- The Ventersdorp Contact Reef (VCR) experiences the most fatal rockfalls;
- The largest number of rockfall fatalities occur at a depth of around 2100 m;
The stoping area suffers 77% of rockfall fatalities;
Approximately 60% of fatalities occur between 06h30 and 12h30;
Around 80% of fatal rockfalls occur within 3.5 m from the face; and
A typical fall area is between 4 and 10 m².

It must be pointed out that exposure of the underground worker to a rockfall is dominating the above summary; the objective of which is the elimination or reduction of rockfall injuries/fatalities, i.e. the most severe consequence of rockfalls.

Given the above, the question remains: what parameters can be observed prior to instability? Existing knowledge limits the observer to the following measuring options of possible precursors:

- Direct measuring of movement or deformation (and specifically differential movement);
- Measuring of the rate of change of such movement;
- Sensing of the energy released in fracturing, friction on loss of cohesion;
- Sensing of the rate of the change in the fracturing, friction on loss of cohesion process;
- Observing of a differential change in temperature relative to the surrounding rockmass;
- Sensing of differential support loading;
- Quantification of rockmass rating and recognition of changes.

The objective of the earlier mentioned MHSC project is the development of optimal sensing and monitoring techniques that will allow for the recognition of these precursors and of decision-support systems that may provide early warning and/or continuous real-time risk assessment.

3 Application of AziSA for monitoring of rockfall risk

A multidisciplinary team from the CSIR, South Africa has developed a scalable risk/hazard monitoring system, based on the wireless sensor network concept, to be applied in deep and high-stress mining environments. This system, called AziSA, is a non-proprietary and open standard specification that includes a mining data-acquisition, communication and decision-support system, with the internationally accepted concept of a wireless sensor network embodied in the system.

3.1 Wireless sensor network concept

A sensor network in the AziSA system is a coordinated monitoring infrastructure comprising a distributed combination of resources, e.g. sensors, sensor platforms, communication infrastructure and, in the AziSA case, includes data management and decision support. In order to add meaning and value to a simple sensor measurement, certain attributes have to be associated with the specific measurement. Every measurement has to have information associated with the sensor such as identification; type of sensor; its sensing limits; time and date; and geographic position. Data without this associated information is of no value.

All in-stope sensors form a wireless sensor network (WSN), which is a computer network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical conditions. The sensors are also low power and battery driven (Römer, 2004).

The AziSA specification is intended to make it easier to integrate underground sensors and actuators into monitoring and data networks. It allows for four classes of devices, ranging from small wireless sensors to intelligent controllers. Typically these sensors are part of a low-power wireless network using the Zigbee protocol.

A system controller is storing data over a long time and presenting information for decision making to the outside world. Typically it will manage a database system and be situated on surface.
3.2 Positioning/localisation

As mentioned above, in order to add meaning and value to a simple sensor measurement that exists in AziSA, certain attributes have to be associated with the specific measurement. One of these attributes has been determined to be the location at which the measurement was taken. The battery-operated location device will operate in a noisy and enclosed space and it will be required to determine two-dimensional coordinates relative to a number of beacons with known locations. A study was conducted to gain insight as to which existing methods would be most applicable and practical for this particular application. Taking the requirements into account, it was decided to use a trilateration system to solve for the location of a measurement. A method is being developed in which at least three beacons are placed around the mining stope. Each beacon simultaneously transmits an electromagnetic pulse and an acoustic pulse. This allows the sensor to resolve the acoustic travel time and with similar information from two other beacons the sensor’s position can be resolved in two dimensions.

3.3 Communication

3.3.1 In-stope communication

Initial investigation showed that in-stope communication would have to be wireless. The environment is simply too hostile to consider wired sensors. Investigation into short-range low power wireless networks revealed two major players: the TinyOS system from UC Berkeley and Zigbee, which is an open standard. It was decided that Zigbee would be the protocol of choice for in-stope communication. The AziSA message scheme was implemented on the small wireless sensors so that they could interface with the rest of the AziSA network.

Figure 3 shows a schematic presentation of in-stope communication. Each sensor was converted to a wireless sensor, Zigbee, which allows for wireless sensor networking. Each sensor may act as a network router and network paths are dynamically determined and are automatically re-arranged should any sensor fail. At the nearest electrical power, an aggregator is placed that also functions as a bridging device between the in-stope Zigbee and the power line communication (or any other Internet Protocol communication) to the shaft area.

Figure 3 shows a possible sensor installation in a stope and the communication options. It also shows a mobile sensor, in this case a sensor carrier by a miner.
3.3.2 Stope to shaft communication

Extensive mining in a tabular orebody leads to long distances from stope to mining shaft. In many cases no fast communication (semi-broadband) cabling exists and it is envisaged that Power Line Communication (PLC) will be used. PLC essentially transforms the power grid into a network carrying broadband communication in the form of an IP (Internet Protocol) signal. Commercial equipment is to be used and an evaluation of such equipment in an underground environment is being undertaken.

3.3.3 Data management and decision support

An aggregator will be mounted at the closest power point to the stope. It is a relatively basic computing device, and will support no long-term data storage. The configuration of the sensors in the network for which it is responsible will be stored locally. Sufficient data reported by the sensors will be stored locally to enable an aggregator to make the necessary decisions with which it is tasked, and to buffer data for transmission to the surface controller, in case of communication difficulties necessitating resending the data.

The main data management focus is on the controllers, which are being implemented on standard computers and thus have more resources available to them. The controllers also respond to user queries by retrieving data from the data management system and presenting this to the user in an appropriately meaningful and useful form.

When a sensor joins an AziSA network, it registers with the system controller, and assigned a unique identifier for future reference. This registration will include the identification and position of the sensor and its component detectors. Each detector will be associated with a physical phenomenon concerning which
measurements are made, and with information relating to its calibration and for the processing of raw data values to derive information about the particular phenomenon. The detector will also be registered as reporting data in a particular form: a physically stationary device might send discrete measurements (e.g. single temperature or humidity values) or bursts of measurements (e.g. images or seismic waveforms), while a mobile device might report data from a different physical location on each occasion, and provision will be made for the storage of all such data.

Decision support is primarily based on a probabilistic risk assessment methodology. Similar methodology was used at Moonee Colliery for goaf warning (Brink and Newland, 2001) and in assessing rockburst and rockfall risk for the MHSC (Brink et al., 2002a).

### 3.3.3.1 Development of probabilistic risk assessment using an expert system philosophy

The Bayes' Theorem was adopted as an expert system philosophy for a rock engineering risk assessment project (Brink et al., 2002a). The basic concept of this philosophy is that a hypothesis should be developed that is tested against some evidence. In this case, the hypothesis states that a rock-related incident (rockfall or rockburst damage) would occur within the next eight hours. A prior probability, P(H), is set. This is the probability that such a rock-related incident may occur during the next eight hours (the probability of the hypothesis being true) without any associated evidence.

Evidence associated with the hypothesis being true is, for example, the observation that a high event rate is prevailing. The probability of observing such evidence, which is a high event rate, while the hypothesis is also true, \( p(E|H) \), is determined from previously observed information. Similarly, the probability of observing the evidence, but with a hypothesis that is not true, \( p(E|\sim H) \), is set.

On the basis of Bayes' Theorem, the probability of observing the hypothesis H if the evidence E has been observed is the probability \( p(H|E) \):

\[
p(H|E) = \frac{p(E|H)p(H)}{p(E|H)p(H) + p(E|\sim H)p(\sim H)}
\]

\( (p(H) \) is the prior probability of the hypothesis being true and \( p(\sim H) \) the prior probability of the hypothesis not being true.)

Similarly, the probability of observing the hypothesis H if the evidence E has not been observed is \( p(H|\sim E) \):

\[
p(H|\sim E) = \frac{p(\sim E|H)p(H)}{p(\sim E|H)p(H) + p(\sim E|\sim H)p(\sim H)}
\]

The initial importance (or Rule Value) of each item of evidence is given as:

\[
RV = | p(H|E) - p(H|\sim E) |
\]

A typical expert system will have a number of possible hypotheses and even more items of evidence that can be associated with these hypotheses. For the purpose of testing the hypothesis of a large rockfall and/or burst within the next eight hours, the expert system only considers this single hypothesis, tested against the available items of evidence.

The main advantage of employing an expert system approach is that it can cater for uncertainties. An expert system can also allow for the actual response to whether specific evidence is observed to between a 'yes' or a 'no'. (Naylor, 1998),

Initially, the hypothesis starts off with the given prior probability. This prior probability is updated by the application of one item of evidence, which may or may not be observed with a given degree of uncertainty, to produce a new posterior probability. This new posterior probability is then used as the new prior.
probability for a re-application of the same equation to the next item of evidence. The process continues in this way until all of the items of evidence have been accounted for.

In Figure 4 a single hypothesis, i.e. the probability of a rock-related incident happening during the next eight hours, is displayed. Any changes in the input parameters will trigger a re-assessment of the risk at all of the grid positions and a simultaneous display of the risk.

Each grid element has its own attributes describing the various static risk conditions (describing the vulnerability of the excavation) and the dynamic conditions (parameters relating to the seismicity as experienced at that specific grid element).

![Figure 4](image-url) **Figure 4** An example of a Bayesian-based risk output contoured over a tabular mine mini-longwall. The cross is a seismic event of Magnitude > 2

### 3.4 Monitoring strategy

The planned monitoring strategy to provide early warning and/or risk assessment of rockfalls makes a clear distinction between the early warning and risk approaches. Section Error! Reference source not found. listed the measuring options in the VCR geotechnical environment. This section describes the measuring/monitoring options that are to be implemented. The practical implementation of the monitoring strategy is also illustrated in Figure 3 above.

#### 3.4.1 Early warning sensing

Parameters that may provide short-term indications of a pending rockfall are the sensing of the energy released in fracturing, friction on loss of cohesion or the rate of change in the fracturing, friction on loss of cohesion process. A practical way to monitor the energy released in fracturing, etc. is the monitoring of the acoustic emissions or microseismicity. Differential movement of part of the hangingwall (or roof) and specifically the rate of change of such movement has the potential to be used as an early warning input.

#### 3.4.1.1 Microseismic monitoring

An established and proven technology in coal mining is the GoafWarn, a stand-alone microseismic unit with internal alarm condition recognition (Brink et al., 2002b). Application of this device is to provide a local alarm of imminent goafing. Figure 5 shows an example of precursive clustering of microseismicity immediately prior to the onset of a large goaf. The recognition of the precursive cluster is the basis of
operation of this device. The warning period ranges from approximately 2 hours to even less than a minute. This technology was recently tested in hard rock mining with promising early results.

![Peak particle velocities of the seismic events recorded at Section 56 around midnight on 26-27 July 2001](image)

**Figure 5  An example of the precursive clustering of microseismicity immediately prior to the onset of a large goaf**

3.4.1.2 Differential movement

An ability to monitor differential movement in the hangingwall of a tabular stope may greatly assist in the recognition of precursory movement or deformation prior to a rockfall. In open stopes or in slope stability, laser scanning is an ideal monitoring technique. The closeness of the laser scanner to the rock surface to be scanned, limits the effective scan surface and as such laser scanning is probably not practical in a tabular orebody.

3.4.2 Sensing for continuous risk assessment

The bulk of the monitoring options for precursors to rockfall are more appropriate for risk assessment rather than imminent early warning.

3.4.2.1 Electronic sounding

The electronic sounding device is a new development that allows for the cognitive decision-making process in sounding of the rock to be duplicated in an electronic device. Although the illustration appears to present a very unsafe act, the device is illustrated in Figure 6 and Figure 7. The sounding device will be part of the mobile human sensor as shown in Figure 3. It gives an immediate indication of the degree of detachment of the specific part of the rockmass to the miner and allows for immediate action in terms of 'making safe'. It is also an AziSA device in that frequency response as well as the two-dimensional position is transmitted to the central database. In principle, a supervisor of the dayshift (production shift) is in the position to have a full risk assessment contour, based on the sounding process, at his disposal prior to the start of the shift.
3.4.2.2 Infrared sensing

Infrared sensing has the proven ability to sense portions of the rockmass that might have cooled down faster from the virgin rock temperature to the temperature of the air ventilation. Similar to the sounding device, faster cooling is an indication of the degree of detachment of a specific part of the rockmass.

Stationary infrared sensing does not make much sense and a current development is the integration of infrared sensing with the sounding device. Each tap on the hanging will be associated with an infrared image of that particular part of the rockmass. Both sets of data, plus the geographic positioning, are to be transmitted to the central database and act as input parameters into the risk assessment process.

Figure 8 A greyscale conversion of an infrared image indicting a small difference in temperature on the hanging (from Oldroyd, 2006)
3.4.2.3 Closure measurement

Continuous closure monitoring is included in the monitoring strategy. A number of wireless closure sensors are to be installed in each panel in order to quantify the overall closure profile. Malan (2003) shows the value of continuous closure measurements for improved support design and hazard assessment. Again Figure 3 schematically shows the incorporation of closure measurement in the stop risk assessment. A relative inexpensive closure meter with a resolution of 0.01 mm was designed.

3.4.2.4 Support loading

Shield loading on longwall shearer in coal mining is routinely monitored. The loading on individual support elongates will be monitored. It is foreseen that differential loading of support will provide input in the rockfall risk quantification. The support loading sensing is an AziSA function and again will be wireless continuous monitoring.

3.4.2.5 Correlation between seismic velocity and rockmass rating

Sjøgren et al. (1979) state that their studies have confirmed earlier assumptions that there is a strong correlation between longitudinal velocity and fracturing and that the velocities can be used to give rather accurate predictions of the quality of rock masses. As shown in Figure 3, a seismic source and receiver are placed across the panel as close as possible to the face. Regular seismic velocity measurements are to be made and the quality of the rockmass is to be inferred.

4 Rock Fragmentation Monitoring

It is well known, in mining industry, particularly in the quarrying industry that fragmentation has pivotal role on downstream production outcome, cost and quality of the metal or mineral recovery. It is also very true in the gold mining industry were control of the fragmentation can play significant role in improvement of the gold extraction from ore body. Further the proper fragmentation distribution can impact in positive way on scraping, cleaning and trammaing and transport of the rock to surface. After arrival of the rock on surface rock is treated in the crushers and mills, here again properly distributed fragmentation can help to optimize treatment process and reduce cost. The crushing time, consumption of steel balls, water and energy highly depends on the fragmentation of the delivered rock.

<table>
<thead>
<tr>
<th>Fines &lt; 1 mm vs Explosives Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>% passing</td>
</tr>
<tr>
<td>+1.0 mm</td>
</tr>
<tr>
<td>+425µm</td>
</tr>
<tr>
<td>+150µm</td>
</tr>
<tr>
<td>+75µm</td>
</tr>
<tr>
<td>-75µm</td>
</tr>
</tbody>
</table>

Kopanag Mine Fragmentation Distribution

- Anfex
- Powergel
- Kubela 420
- R 100 G
- Rioflex
The results from earlier work by Zaniewski at AngloGold Mining Technologies during 2003 to 2004 showed that change in the explosives type and charge size used in the stope blasting have impact on the fines produced during the blast and amount of the liberated gold (indicated in Figure 9 and Figure 10).

This liberated gold during blasting tends to be lost during the cleaning operations and finally reduces the amount of gold delivered to the surface gold plant.

### Table 1  Gold content vs. explosives type in the fines smaller than 1.00 mm

<table>
<thead>
<tr>
<th>Explosives</th>
<th>Fines &lt; 1.0 mm, %</th>
<th>Au, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anfex</td>
<td>9.7</td>
<td>24.0</td>
</tr>
<tr>
<td>R100 G</td>
<td>7.9</td>
<td>17.5</td>
</tr>
<tr>
<td>Powergel</td>
<td>5.7</td>
<td>14.0</td>
</tr>
<tr>
<td>Kubela 420</td>
<td>4.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Rioflex</td>
<td>2.6</td>
<td>11.49</td>
</tr>
</tbody>
</table>

During 2003-2004 Kopanang Mine of AngloGoldAshanti in conjunction of CSIR Miningtek Division as a part of the Future Mine Project investigated various method of rock fragmentation measurement and monitoring. Physical sieving the most accurate and reliable method is not suitable for continuous measurement and monitoring due to high cost and time consuming. The optical digital imaging of the fragmented rock has been adopted for this purpose.

#### 4.1 System description

The fragmentation system installed on Kopanang Mine consists of an optical imaging device (a NIKON D200 camera) and WipFrag software from WipWare Inc., Canada, for automated image analysis system in real-time particle size distribution of unconsolidated material on conveyor belts. The original system was based on a video camera and frame grabbing. A required resolution of better that 1 mm could not been achieved with a conventional video system. A system accommodating discreet photographs from high quality digital camera was developed and implemented.

The NIKON digital camera is controlled by the surface PC and taking images of the flowing rock every minute, the image is converted to TCP/IP protocol and sent to surface computer running WipFrag software, where the image is processed and fragmentation curve is generated. The underground installation is shown in Figure 10.
Figure 10 Camera and lighting rig installation over conveyor belt on 74 level on Kopanang Mine

Figure 11 Captured digital image of the rock on the belt conveyor and fragmentation curve pertaining to the image.

After image has been processed and black and white copy of the compressed image has been stored for future reference if needed, the log is generated and date and time stamped. Further the daily, weekly and monthly profile of the fragmentation distribution is generated and posted on the mine web site. Based on the analysis of the fragmentation profiles and explosives efficiencies corrections to the blasting process are made on the monthly bases.

The average number of images processed by the system exceeds 1000 per day. The system does not provide for any immediate feedback for management decision support. A more automated system is required for further analysis, exception reporting and input for blasting optimization.
Lack of the continuous and automated analysis and optimisation is seen as a drawback of the system. Further co-operation between CSIR and mine will lead to the incorporation of continuous fragmentation monitoring into AziSA monitoring and optimisation system.

5 Application of an AziSA Geiger counter the estimate gold content on belt

In South African gold ore bodies, uranium is frequently deposited together with gold (Robb et al, 1998). In previous work by CSIR (Reef Detector) it was found that the presence of gold ore could be confirmed by the measurement of radioactive decay from radioactive uranium isotopes (Cole, D.I., 1998). This fact has been used in the past to confirm the presence of gold ore, but there has not been an attempt to use radioactive decay as a quantitative measurement of the amount of gold present.

The purpose of this task was to install several Geiger counters on the main reef and waste conveyor belts leaving a gold mine, and to correlate the amount of radioactive decay with the amount of gold produced by the gold plant in the long term. If such a correlation exists, such data could for example be used to determine how much gold is leaving certain areas of the mine, and will provide a different view of mine productivity than monitoring the ore volume.

The reason for installing Geiger counters on the waste belt is to determine if any gold ore is about to be discarded to the waste dump, and at a later stage to redirect gold-carrying waste to the gold plant.

This system was installed at Kopanang Mine in December 2007 and is currently collecting data for further analysis and calibration.

A Geiger counter consists of a Geiger tube and some electronic circuitry, shown in Figure 12. This unit is mounted underneath the conveyor belt transporting the hoisted reef from the shaft.

Figure 12 The AziSA Geiger Counter

The tube is filled with an inert gas such as helium, neon or argon, in some cases in a Penning mixture, and an organic vapour or a halogen, and contains electrodes between which there is a voltage of several hundred volts (mostly 400V to 1000V). The walls of the tube are either metal or the inside coated with metal or graphite to form the cathode while the anode is a wire passing up the centre of the tube.

Each time a gamma or beta ray hits the tube it creates an avalanche effect in the gases between the two electrodes, effectively connecting them together electrically. The voltage on the one electrode propagates to the other, which is connected to a voltage divider that clips down the pulses to a level that can be detected with common digital logic.
This system was installed at Kopanang Mine in December 2007 and is currently collecting data for further analysis and calibration.

Some initial processing and estimation of the calibration factors provided a daily estimation of gold produced at Kopanang Mine. (Figure 13)

Figure 13  An estimation of gold produced during one day. An accumulated gold output and an output per 30 minutes are shown.

6 Conclusions

This paper described the development of a monitoring architecture that allows for continuous monitoring of the mining process, the underground environment, the state of the rockmass and its response to mining.

Current applications of continuous monitoring include an application to optimise drilling and blasting thought fragmentation monitoring; an application of wireless sensor network-based monitoring in to provide early detection of potential rockfalls; and a trail to continuously assess the gold grade at the shaft through correlation with radioactivity.
Known technologies have been adopted and integrated in systems based on a sensor network concept. The validity of individual monitoring tools has been established but some system integration; the real-time and wireless sensing implementation of the system; and overall system effectiveness in providing early/risk assessment and continuous optimisation still have to be established.

Acknowledgements

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