School of Aerospace, Mechanical and Mechatronic Engineering

Intelligent Risk Mitigation System for Underground Coal Mine Explosions

Honours Thesis

Marcus Valastro

Academic Supervisor: Prof. Guodong Shi

Industry Supervisor: Mr Brad Waldon

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Declaration of Authorship

I, Marcus Valastro, declare that this thesis and the work within it is my own. Any information obtained elsewhere has been correctly acknowledged. My contributions consist of:

- I performed the research required to build an understanding of the context, background, and varying worldwide legislation surrounding UCM Explosions.
- I carried out the literature review.
- I performed the detailed investigation of the existing procedure for managing UCM explosions at the research mine, and personally travelled to the mine to better understand the roles, responsibilities, and cultural aspects of the workplace.
- With the support of my Industry Supervisor, Mr Brad Waldon, I designed the initial design framework and scope for the project to be completed at the research mine.
- I conducted business analysis and further research to create the detailed design requirements for the entire system, including the optimisation method.
- I project managed the entire system development and implementation. I did not directly write the software for the system however, I worked directly and frequently with the software developers to ensure the required system design and logic were followed.
- I did the initial testing of each system component against the detailed business requirements, and Quality Testers then completed the elaborate testing.
- I carried out the analysis and evaluation of the implemented system components for their functionality and performance against the system and thesis objectives.
- I completed the conclusions and suggested future work.
- I performed all work required to complete both case studies.

______________________	1/02/2023
Marcus Valastro	Date
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Prof. Guodong Shi	Date

Disclaimer: The views expressed within the thesis are those of the student and do not necessarily express the views of their supervisor or The University of Sydney.

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Abstract

A coal dust explosion is one of the most significant risks in the harsh and complex environment of an Underground Coal Mine (UCM). Reviewing literature, regulations, and existing systems surrounding explosive dust management shows that there have been few advancements in managing this risk over the past 90 years. Legislation has remained relatively stagnant, and minimal systems are implemented in the real world that can simplify, standardise, and improve the effectiveness of UCM explosive dust management.

To help bridge this gap, this thesis aims to design, develop, and implement an Explosive Dust Risk Mitigation System (EDRMS) utilising Business Intelligence (BI) that is capable of real-world use in industry. This thesis evaluates the existing explosive dust management process at an associated research mine to form high-level and detailed design requirements, focusing on digitally simplifying the procedure, not replicating it. This system is iteratively and incrementally developed and implemented at the research mine to commence real-world use. The developed BI platform is compared with the existing process to highlight the advancements in performance transparency, efficiency, and optimisation of UCM explosion mitigation.

This comparison and evaluation of the real-world system implementation at the research mine demonstrate its success in automating procedure steps, providing a readily accessible source of data, and enabling a proactive approach to planning and managing explosion risk mitigation. In addition to improvements just for the research mine, this thesis and EDRMS created within it directly address many Queensland regulatory audit findings. By finalising the total system and making the highlighted changes for standardisation, this BI system will have the adaptable capabilities for implementation across the UCM industry. As accurate data availability improves at UCMs, further work can be done to improve the systems' optimisation techniques, integration of other risks, and usability in other industries.

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Acronyms

API	Application Programming Interface
BA	Business Analytics
BI	Business Intelligence
BPM	Business Performance Management
CDEM	Coal Dust Explosibility Meter
DAR	Dust Application Rate
DcA	Descriptive Analytics
DgA	Diagnostic Analytics
DV	Data Visualisation
DW	Data Warehouse
EDM	Explosive Dust Management
EDRMS	Explosive Dust Risk Mitigation System
EDZ	Explosive Dust Zones
MDAR	Minimum Dust Application Rate
MG	Main Gate
MID	Minimum Incombustible Dust
MIT	Minimum Ignition Temperature
MLR	Multiple Linear Regression
NIOSH	National Institute of Occupational Safety and Health
PA	Production Area

PcA	Prescriptive Analytics
PdA	Predictive Analytics
RAD	Rolling Average Deviation
RMS	Risk Management System
SCT	Sample Compliance Target
SDC	Stone Dust Coordinator
UCM	Underground Coal Mine
UI	User Interface
WHS	Work Health and Safety

Executive Summary

Investigating the unique environmental and operating conditions within an Underground Coal Mine (UCM) surrounding coal dust explosions revealed that this significant risk is still ever-present. The risk is managed by frequently and systematically spreading incombustible 'stone' dust throughout the mine in sufficient quantities, which saturates the coal dust and renders it unable to combust and spread spontaneously.

This thesis aimed to rectify the rudimentary and convoluted risk management processes and systems surrounding Explosive Dust Management (EDM) by designing, developing, and implementing an Explosive Dust Risk Mitigation System (EDRMS) at the associated UCM. The system needed to be integrated, transparent, and enable proactive EDM while also promoting the further use of Business Intelligence (BI) systems in the mining industry.

Throughout the research and literature review, a more comprehensive understanding of the cause, prevention method, and significance of UCM explosions was developed, including its consequential accompanying legislative requirements. BI systems, their applicability and issues in the mining industry were evaluated, demonstrating the necessity for greater utilisation. Several technical methods and models are then briefly evaluated for their feasibility concerning the optimisation component of the EDRMS.

The methodology comprehensively evaluates the existing EDM process at the research mine to ensure the EDRMS is designed for real-world compatibility. From this evaluation, high-level and detailed design requirements are formed to address the existing limitations directly. The two core components of the process are stone dust application to an Explosive Dust Zone (EDZ) and ensuring the results of dust sampling within that EDZ are compliant.

Although there is a correlation between dust application and sample results, these are previously separate components of the existing process. To correct this flaw for the new EDRMS, a comprehensive methodology is provided to establish the relationship between these two components, allowing the amount of stone dust required for compliance to be optimised. To enable this, the methodology builds upon the existing research mine concept of a Production Area (PA), which refers to the location of an EDZ within the mine in relation to the type of, and distance to, mining production occurring. The rate at which dust must be applied to an

EDZ of a specific PA is then utilised as the manipulated variable of a basic feedback control loop, with the impacted and measured process variable being the dust sample results.

The thesis considers results as the successful real-world implementation of each component of the new EDRMS and its advantage over the existing process utilised at the research mine. A digital twin of the research mine was created that integrates with an AutoCAD file to automatically produce weekly sample plans and labels, a previously manual process with considerable potential for human error. An Application Programming Interface (API) was established with the external laboratory of the research mine to enable the direct integration of dust sample results into the EDRMS. Previously, these were emailed weekly in separate excel files.

Production Areas were formed as a distinctive, modifiable, and integrated component of the EDRMS, each with an associated Minimum Dust Application Rate (MDAR). These previously existed in procedures but were disconnected, limiting compliance assurance. Functionality was created for desktop and mobile to allow users to easily capture the routine stone dust application to EDZs, which is integrated with the MDAR to ensure compliance. Previously, stone dust applications were recorded and stored on paper with little consistency and compliance validation.

With the newly integrated data, interactive and informative digital dashboards were created to enable accurate visibility of historical data surrounding sample results, stone dust applications, and compliance. This enables users to effectively digest information visually and recognise patterns that may inform them why something may be occurring, which was previously not possible. Operational dashboards were also created, which display instantaneous live information on the failures of sample results and stone dust applications. This dashboard also allows users with sufficient authority to capture rectification dusting data directly rather than completing paper forms.

Due to the time constraints of this thesis, the EDRMS ability to suggest an optimal MDAR was only partially developed however, implementation will still occur post-conclusion. The expected component functionality far exceeds any functionality currently within the UCM industry. A brief theoretical scenario demonstrates that the functionality can achieve its purpose of adjusting the suggested MDAR until it is optimal for a given PA.

Based on the evaluation of the existing system, processes, and research, the EDRMS is notably superior in managing the risk of a UCM dust explosion. The aim of the thesis was satisfied, with the EDRMS considering BI to automate steps, provide an integrated and accessible source of data, and enable a proactive approach to explosion risk mitigation at the research mine. The evaluation and new system also highlighted several unforeseen flaws within their existing process and has challenged traditional views around optimal stone dust management. The system has received positive feedback, including that it has made the process more straightforward, transparent, and robust. Due to these advancements, the research mine (BHP-Mitsubishi Broadmeadow) desires to nominate the system for an underground coal mine industry safety award.

In addition to improvements just for the research mine, this thesis and EDRMS directly address many Queensland regulatory audit findings, which would apply to other UCMs. Despite the current EDRMS being solely applicable to the research mine, by finalising the total system and making the minor highlighted changes for standardisation, this BI system will have the adaptable capabilities for implementation across the UCM industry. Further work is suggested for when accurate data availability improves in UCMs, including improving the systems' optimisation techniques and ability to integrate other risks.

1 Introduction

The primary goal of an Underground Coal Mine (UCM) and the entire mining industry is to source usable material in the most economically viable and safe manner possible [1]. Thus, by accurately automating any previously manually completed tasks, a mine can decrease costs through efficiency while decreasing risk by removing the possibility of human error. This aligns with the thesis' focus of developing a system that reduces previously manual tasks surrounding UCM dust explosion risk management, and intelligently using newly integrated data to emphasise more optimal and safe processes.

1.1 Context

1.1.1 Underground Coal Mining

There are four main mining methods which include underground, open surface, placer, and in-situ [2]. This thesis will focus on UCMs using the longwall mining method.

1.1.2 Longwall Coal Mining Method

Unground longwall mining is a technique used to extract coal from tabular deposits below the surface. It involves shaping a long (100m to 300m) rectangular block of coal, which is done in the 'development' stage. Each defined underground block of coal is called a panel, which is outlined by driving a long set of tunnels from the main or tail roadways in the mine [3], which are MG and TG in Figure 1-1. These tunnel sets are joined with a smaller tunnel at either end.

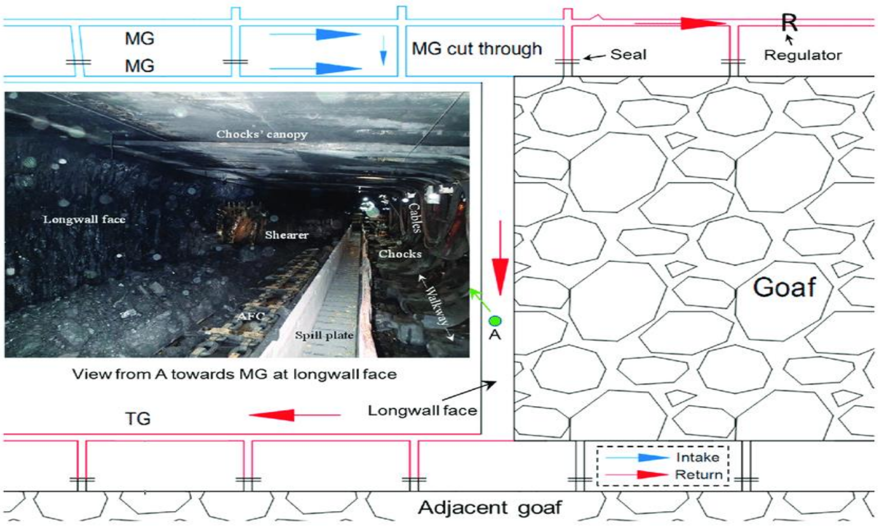


Figure 1-1 Layout of an Underground Longwall Mine [4]

A Longwall Miner is built within the tunnel along the coal face, which is a large and long miner that cuts parallel to the coal face. This continues to shear the longwall face, incrementally moving parallel from the Main Gate (MG) of the panel until it reaches the tunnel known as the Tail Gate (TG) at the other end of the panel [5]. The live longwall working area is protected by a moveable, powered roof support system which adjusts automatically to allow the roof to collapse behind the line of support and becomes goaf the face advances forward. As the mine progresses, the layout and structure of the mine continuously change, with new roadways being tunnelled and many existing roadways being completely sealed off and becoming goaf.

1.1.3 Key Hazards and Risks

Mishra et al. [6] details that the environmental conditions largely contribute to the production, efficiency, and safety of UCMs. The critical factors that impact the environmental condition are airflow, temperature, humidity, dust and gases. The operations produce various gases which are poisonous and inflammable, which by itself can lead to different vital hazards without the correct control procedures, such as ventilation. An additional significant hazard is UCM fires and explosions, which will be the focus of this thesis.

The risk types and some related event hazards affecting human health and safety include [7] :

- Geo-mechanical, such as flyrock occurrences and instability of immediate roof.
- Geo-chemical, such as coal dust explosions and gas emissions.
- Electrical, such as power disruptions and electrocution.
- Mechanical, such as slipping belt conveyor and stopping of the ventilation system.
- Chemical, such as unbalanced oxygen of blasting and hazardous fuels and chemicals.
- Environmental, such as a slippery floor, noise pollution, or asphyxiation.
- Social, Cultural and Managerial, such as inadequate training and lack of safety equipment.

This thesis will focus on Geo-chemical coal dust explosions and social, cultural, and managerial difficulties.

1.1.4 Explosion Prevention Using Stone Dust

The most considerable risk within a UCM is coal dust explosions due to the devastation they can cause. The explosibility of coal dust is influenced by its particle size, composition, the presence of inflammable gas in the air, its quantity and distribution, the strength of the ignition source, and many other surrounding conditions [8]. When an initial ignition suspends the coal dust, it continues to ignite and force further roadway coal dust into suspension, creating a chain reaction [9].

The most common method in industry to mitigate the risk of a coal dust explosion is utilising incombustible dust, or as primarily referred to in this thesis, 'stone dust' [10]. Stone dust is powdered limestone, an inert dust made up of stable oxides that do not undergo explosions, even when subject to high temperatures. The endothermic reaction during the decomposition of limestone dust in the atmosphere enables it to act as a heat sink and decrease the overall temperature to the extent that ignition of combustible dust such as coal does not occur [11].

Therefore, when stone dust is frequently and systematically spread throughout the mine in sufficient quantities, it saturates the coal dust and renders it unable to combust and spread spontaneously [12].

1.1.5 Standard Procedure and Regulations for Explosion Risk

Due to the high risk and harm of UCM explosions, extensive government regulations and standards worldwide surround the application and monitoring of stone dust to manage the immense risk. The standard procedure entails the following:

- Divide the mine into various Explosive Dust Zones (EDZ) of different categories according to the percentage of incombustible (stone) dust required in each zone, as per the level of explosion risk due to mining production in the vicinity at the time
- Systematically apply stone dust throughout each EDZ at a Dust Application Rate (DAR) which is deemed appropriate to manage the level of coal dust within the EDZ.
- Sample and test the EDZ for its stone dust content at a frequency determined by the level of explosion risk of the EDZ.
- Apply additional stone dust to the EDZ if the sample result reveals inadequate stone dust content.

Further regulatory requirements surrounding this include:

- The particle size of the stone dust used and layer thickness of the distributed stone dust.
- By what means should the mine be divided into EDZs.
- The minimum percentage of incombustible dust required and sample frequency per EDZ category.
- How the EDZ should be sampled and how the samples should be analysed.

Separately to the sequence and requirements above, an equally significant part of risk mitigation using stone dust includes passive barriers. These are typically bags of stone dust hung from the EDZs' ceilings in specific sequences. In the event of an explosion, the dust bags burst and significantly aid in reducing and halting the continuation of the explosion. The management of passive barriers is far less complex and subsequently raises fewer concerns in regulatory and site audits. Therefore, passive barriers will not be a focus of this thesis.

1.1.6 Research Mine – BRM Broadmeadow

The research mine associated with this thesis is BHP-Mitsubishi Broadmeadow Coal Mine (BRM), a UCM located in Queensland, Australia. The mine has a Standard Operating Procedure implemented for UCM explosion prevention. Additionally, a Principal Hazard Management Plan is in place to achieve an acceptable level of risk and meet the Queensland Recognised Standard requirements for mitigating UCM explosions.

The research mine has funded the system to see if it was possible to design and implement a digital system that could simplify the complex process and management of stone dust application, sampling, and analysis. Waldon Services has taken on this project which supported the research, design, and development of the UCM Explosive Dust Risk Mitigation System (EDRMS) detailed within this thesis.

1.2 Motivation

Over 290 people have died from UCM explosions in Australia [13] and many more worldwide, with the U.S. having over 10,000 UCM explosion-related deaths [14]. Over the past few decades, the increasingly enforced use of stone dust has decreased the frequency and severity of UCM explosions. Despite the improvement, the industry's management systems around stone dust procedures are incredibly rudimentary, convoluted, and reactive. This has seen incidents in Australia occur as recently as 2020 when five people experienced life-altering injuries from a UCM explosion in Queensland [13], and incidents worldwide, including 41 deaths in a UCM explosion in Turkey in 2022 [15].

Despite having an elaborate process that is likely above other mines in the industry, the research mine is no exception to these limited management systems and complicated procedures. Similarly, their current procedure is managed and implemented by disconnected and rudimentary tools, and reliant on paper-based tracking sheets. As a result, the process is complex, cumbersome, error-prone, and has a very limited ability to attain data. This makes it inefficient and difficult to effectively track the actual stone dust application across the mine and other vital data, which introduces the risk of not meeting compliance and, more importantly, increases the likelihood of a UCM explosion.

A Queensland regulatory audit on stone dust practices' adherence to regulatory standards at many UCMs revealed that many other mines were in similar or worse circumstances. They had a gross lack of understanding among various levels of management and supervision regarding legislative requirements for sampling, analysis and application of stone dust. These findings are further detailed in 1.6.

1.3 Problem Statement

While the regulatory legislation is strict in nature, it leaves much to the direct UCM in exactly how they decide to manage the risk of UCM dust explosions. Consequently, the industries' tools and procedures to manage this risk are complicated, reactive, and vary significantly from mine site to mine site, resulting in concerning findings from the regulatory audits. Further complicating the issue are the logistical limitations of UCMs due to the uniquely harsh environment, which results in ever-changing roadways, sensor and device constraints, and network issues. Therefore, there is a need for a standardised real-world digital system that can handle and simplify the complexities of both the regulatory requirements, and the physical and managerial variations in UCMs. From this data integration, the system needs to be able to aid in managing risk proactively rather than reactively.

There have been significant technological advancements in different divisions across the mining industry. However, there is still a growing disparity between the peak of technological use and the base. Research has revealed a lack of current literature on proactive risk management systems in UCM for mine dust explosions and other common risks. It has highlighted that within the relevant existing literature, there is little to no actual practical implementation of many suggested systems. Additionally, there is little to no familiarity and consideration of the strong bureaucratic culture and nature of mining work that inhibits the implementation and utilisation of even some basic digital systems that introduce change [16]. Thus, for successful implementation, not only is a comprehensive understanding of the current procedures, regulations, and operations required, but equally important is a comprehensive understanding of the complexities of typical roles, responsibilities, and workplace culture.

1.4 Aim and Objectives

The primary aim of this thesis and its associated project is to create a UCM Explosive Dust Risk Mitigation System (EDRMS) utilising Business Intelligence that is capable of real-world use in industry. By understanding and simplifying a complex problem, it aims to overcome the bureaucratic culture and hesitation to change in the mining industry in order to support the consistent achievement of an acceptable level of risk related to UCM explosions. In doing so, provide an academic and industry foundation of an EDRMS with optimal stone dusting procedures that have real-world implementation.

To achieve this aim, the key objectives of this thesis are to:

i. Identify the fundamental problems encompassed in managing the risk of a UCM dust explosion and investigate its cause, prevention, and regulatory requirements surrounding it.

ii. Evaluate the real-world capability of both implemented and theoretical systems that manage risks in a UCM and explore Business Intelligence to assess how it can be used in the mining industry for managing UCM explosion risk.

iii. Design a system that provides a more efficient and robust process for managing the required dust sampling, application, and re-treatment practices across the mine by:

    a. Automating steps in the procedures to reduce manual processing and minimise human error.

    b. Providing a single readily accessible source of data relating to stone dust application and sample analysis.

    c. Enabling a proactive approach to the planning and management of explosion risk mitigation.

iv. Develop and implement the designed system into the research mine to commence real-world use.

v. Evaluate the performance of the system and its capabilities for managing UCM explosion risk at other mine sites and how it addresses BI and the Queensland regulatory audit findings.

1.5 Thesis Outline

The thesis has the following content structure:

Chapter 2: Research and Literature Review

Explores UCM explosion causation and prevention, and in doing so, the relevance and variations of global legal and regulatory requirements. Relevant literature surrounding industry-leading risk mitigation systems and techniques is assessed for their applicability and feasibility in a real-world system. Additionally, Business Intelligence is introduced to understand how it can derive meaning from data and its applicability within the mining industry. Finally, several technical models are evaluated for their real-world feasibility to optimise explosive dust management processes.

Chapter 3: Methodology

Extensively details the existing UCM explosion prevention procedure used by the research mine. The procedure is evaluated to identify design considerations for the new system. Next, the new EDRMS design is proposed, and the required process to deliver the new system is detailed. Following this, more comprehensive methodology is provided for the optimisation component of the system.

Chapter 4: System Implementation and Results

Presents and discusses the new UCM EDRMS implemented and evaluates its performance. First, it outlines the functionality of each component of the EDRMS and then evaluates the components' performance against the existing system. From limitations identified during this evaluation, future considerations for the components are explored, along with what could be done to standardise the system for use at other mines. Additionally, the chapter will evaluate the overall EDRMS system for its utilisation of Business Intelligence concepts and how it addresses the Queensland regulatory audit findings.

Chapter 5: Conclusions and Future Research

This chapter summarises the work completed throughout this thesis with its original aim and the significance of the contribution made. Furthermore, future improvements and work that can build upon the EDRMS and thesis are discussed.

Appendix:

To satisfy the requirements of the Engineering Sydney Industry Placement Scholarship (ESIPS), this thesis must also complete a case study on each of the two units of study, which ESIPS formally replaced. A Work Health and Safety (WHS) report and practical experience logbook are also provided. The Appendix structure is as follows:

- Appendix A: Case Study 1 – AMME5520 Advanced Control and Optimisation
- Appendix B: Case Study 2 – AMME4710 Computer Vision and Image Processing
- Appendix C: Work Health and Safety Report
- Appendix D: Practical Experience Log

1.6 Queensland Regulations and Standards

The document, Quality of incombustible dust, sampling and analysis of roadway dust in underground coal mines by the Queensland Government has been compiled by the Department of Natural Resources, Mines and Energy under Recognised Standard 05, Coal Mining Safety and Health Act 1999 [17]. This governs and provides a technical standard for the application and monitoring of the use of stone dust or other explosion inhibitors in underground mine roadways to reduce the risk of dust explosion to an acceptable level. The selected following information is extracted from the standard.

1.6.1 Technical Guidance (Properties)

Stone dust used for explosion suppression in mines must be light in colour and contain no more than 3 per cent by mass of free silica as determined by an accepted method.

It must be of such fineness as determined by an accepted method that:

- Not less than 95 per cent by mass must pass through a 250-micrometre sieve.
- Of the dry dust which passes through a 250-micrometre sieve, not less than 60% and not more than 80 per cent by mass must pass through a 75-micrometre sieve.

1.6.2 Sampling

The mine should be divided into zones according to the percentage of incombustible dust required in each zone with a representative sample for the dust in each zone or sub- zone obtained at a frequency determined by the regulations.

- 85% - weekly. Face Zone
- 80% - monthly. Conveyor Roads and Return Air Roads. Gate road Barriers.
- 70% - three monthly. Intake Roads

There are also guidelines around how each frequency must be divided into sub-zones of a particular size and when these size restrictions may change.

Sample collection can be either by the strip sampling method or the spot sampling method of the deposited dust layer.

- Strip samples should be collected from a transverse strip around the periphery of the roadway
- Spot samples should be collected from a series of spots around the floor, roof and ribs, comprising an area not less than 0.1 m^2 of the roadway floor or sidewalls.
- Each sample of the deposited dust layer collected from the mine roadway should be taken from the layer to a depth not greater than 5 mm.
- If the sample material from any sampling zone or sub-zone is so wet that water can be squeezed from it, the sample should be discarded, but a record of the sample location and the fact that it was too wet should be kept.

1.6.3 Dust Sample Analysis

The dust collected from mine roadways shall be analysed by one or a combination of the following methods:

- **Laboratory method:** This is the most popular method: After specific heating and treating, the incinerated residue shall be weighed. The incombustible content is taken as the sum of moisture and incinerated residue, expressed as a percentage of the total mass of the sample. Where roadway dust samples were air-dried before analysis by the laboratory method, a correction shall be made to the incombustible matter content of the dust sample.
- **Portable instrument method:** A portable instrument may be used to analyse stone dust provided the instrument gives the same accuracy as would be obtained using the Laboratory Method. Each dust sample to be assessed using a portable instrument shall be prepared and evaluated by the method specified by the instrument.
- **Colourimetric method:** The colour of each dust sample is compared with a scientifically prepared reference colour sample of a known incombustible matter content. When using the visual method, reference colour samples shall be prepared

with an incombustible matter content of 70 per cent, 80 per cent and 85 per cent. Each sample of dust shall be analysed as soon as practicable after collection.

1.6.4 Review of Standards

In a review of Queensland underground coal mines [18], the audit revealed a gross lack of understanding among various levels of management and supervision regarding legislative requirements for sampling, analysis, and application of stone dust. Some relevant findings were directly extracted as below:

1. Gross lack of understanding of the intent and requirements of the legislation.
2. Standard Operating Procedure (SOP) lacked a detailed method of zoning and sub-zoning.
3. The SOP did not provide for the rate of application of stone dust in development panels, longwall panels and outbye areas.
4. Where a stone dust application rate was provided, the rate was based on past experience and sample analysis results, not on a scientific study.
5. No study on coal dust fallout had been carried out to decide the optimum rate of application of stone dust at different sections of mine roadways vis-à-vis source or generation rate of float dust.
6. The stone dusting method, dusting frequency, triggers for application of stone dust etc. were not detailed in the SOP.
7. The SOP did not provide for any sampling scheduling. A general work order for sampling was generated by the survey department. However, there was no spread-sheet or composite record for all the sample points and sampling date.
8. Date of collection and analysis of samples were not recorded on the analysis results.
9. There was no record maintained regarding the generation of coal dust at different locations and the required application rate of stone dust.
10. No record of re-dusting locations and results were observed.
11. There was gross inconsistency in the labels of samples, sample results from the laboratory and the work orders for sampling.
12. Sample locations were often not properly recorded on the analysis report.
13. No spread sheet was maintained to keep the records of each sample's analysis result except the hard copy of the report provided by the laboratory.

2 Research and Literature Review

This chapter will explore the causes of UCM explosions and how incombustible materials, such as stone dust, can prevent this. In doing so, the relevance and variations of global legal and regulatory requirements are explored. Relevant literature surrounding industry-leading risk mitigation systems and techniques is assessed for their applicability and feasibility in a real-world system. Following this, Business Intelligence is introduced, along with how it can derive meaning from data to make informed risk and business decisions, including currently within the mining industry. Finally, some technical models are evaluated for their real-world ability to optimise explosive dust management processes.

This chapter will support the following thesis objectives:

- Identify the fundamental problems encompassed in managing the risk of a UCM dust explosion and investigate its cause, prevention, and regulatory requirements surrounding it.
- Evaluate the real-world capability of both implemented and theoretical systems that manage risks in a UCM and explore Business Intelligence to assess how it can be used in the mining industry for managing UCM explosion risk.

2.1 Coal Dust Explosions

UCM explosions are the most significant risk within an underground mine, and there have been extensive studies on the cause of a UCM explosion and the effectiveness of stone dust as a prevention method. These studies have resulted in the extensive legislation and regulations in place worldwide today.

2.1.1 Cause of Propagation in an Underground Mine

Recent literature has commonly identified Rice et al. [8] as the first to allude to a scientific explanation of coal-dust explosion phenomena, along with a detailed evaluation of how various factors in prevention methods influence the propagation of coal dust. This foundational paper utilises more than a thousand experimental UCM explosions and commercial explosions to summarise and classify the conditions surrounding underground coal dust explosion and prevention. Rice extrapolates the explosibility of coal dust is influenced by: its size, composition, the presence of inflammable gas in the air, its quantity, the distribution of it on the perimeter of the passageway, the strength of the source of ignition, and the surrounding conditions. The paper is elaborate in evaluation and reasoning however, as the study is from almost 100 years ago, more recent studies will be researched to evaluate the current relevance.

Amyottee et al. [19] draw upon past literature to provide insight into the causation and prevention of dust explosions, unspecific to coal dust. Important dust explosibility parameters which are carried through this research are highlighted. These include minimum explosive dust concentration (g/m^3), minimum ignition energy of dust cloud (mJ), Minimum Ignition Temperature of dust cloud (MIT - ^oC), and minimum ignition of dust layer (^oC). The paper summarises that a dust explosion arises when a combustible dust cloud, with appropriate particle size distribution and formed by an adequate mixture of fuel and oxidants, meets a sufficiently energetic ignition source in a confinement that permits overpressure to develop.

This fundamental understanding from Amyottee et al. is carried by Mishra and Azam [9] in their experimental investigation of coal dust particle size, dust concentration and dust-dispersion-air pressure effects on MIT and its combustion process. A furnace was utilised with varying particle sizes and experimental factors. The paper elaborates that coal dust deflagrates through a homogenous catalytic reaction and rapid devolatilization. When an ignition suspends the coal dust, it continues to ignite and force further roadway dust into suspension, creating a chain reaction. The release of volatiles during devolatilization highly depends on the specific surface area.

The results concluded that the MIT of a dust cloud increased exponentially with an increase in particle size, emphasising that the coal dust particles less than 212 µm that are generally produced during mining are more prone to explosion. The MIT of finer dust particles (< 212 µm) was found to decrease with an increase in dust concentration up to 2000-3000 g/m^3. The MIT of a coal-dust cloud decreased with an increase in dust-dispersion-air pressure up to 60 kPa, suggesting this as the optimum pressure for a coal-dust explosion. Various real-life triggers of coal mine explosions, such as welding, cutting, electrical short circuiting, and any exposed hot surfaces, are also mentioned. Due to the consideration of the more common modern coal dust particle sizes in mining, the conclusions presented in this research provide a robust comparative measure than those of Rice et al. [8]. It also highlights the complexity of the conditions contributing to a UCM coal dust explosion, which may need to be considered for predictive purposes.

2.1.2 Prevention Using Inert Dust

As mentioned, Rice et al. [8] investigations hold high weight in literature and provide a detailed evaluation of how various factors in rock-dust (stone dust) prevention methods influence the propagation of coal dust. The paper defined coal dust to be "mine size" if it passes through a U.S. No. 20 sieve (850 µm), with 15-25% passing through a 200-mesh sieve (75 µm). It was also concluded that when other conditions are equal, the finer the size of the coal dust, the more explosive it is in the air. Moreover, it concludes that the size of stone dust particles has some effect on explosion prevention however, there is little difference for stone dust particles finer than 48-mesh (300 µm). After acknowledging that experimentally finer stone dust is still advantageous, the practical disadvantages of extremely fine stone dust are noted. These disadvantages include its caking/clumping tendency, the ease of dust displacement with movement and air currents, and making a dusty atmosphere for workers to breathe. This paper was crucial in establishing that at least 65% Incombustible Content (IC) is needed in non-return roadways of an underground mine and 80% IC in return roadways. Although these values were derived 94 years ago, they are still referred to and used today in some regulations, including in the U.S., highlighting the need to be considered in this thesis.

Mishra et al. [11] build on their previous investigation surrounding coal-dust properties' effects on MIT [9] by applying their research to the use of rock dust as an inert suppression in UCM [12]. This is conducted as rock dust is the most common method in industry to mitigate the risk of a coal dust explosion [10]. Rock dust is typically limestone ($CaCO_3$), which is made up of stable oxides, including silicates and carbonates. These do not undergo explosions, even when subject to high temperatures. These qualities enable the dust to act as a heat sink by thermally decomposing into CaO and CO_2.

2-1 Endothermic Reaction of Stone Dust

$$CaC0_3 + Heat \rightarrow CaO + C0_2$$

This endothermic reaction during the decomposition of lime-stone dust in the atmosphere consumes heat from the surrounding, decreasing the overall temperature to the extent that ignition of combustible dust such as coal does not occur. Additional to the understanding above, Mishra et al. [11] further detail how the rock dust required to inert the coal dust explosion proportionally increases with the decrease in the coal dust size and increase in the rock dust size. This is represented in the figure below as when the rock dust fineness decreases, the percentage of rock dust required to inert the coal dust increases. The lines represent the different coal fineness it was tested for, demonstrating that the finer the coal particle size, the higher the rock dust percentage required.

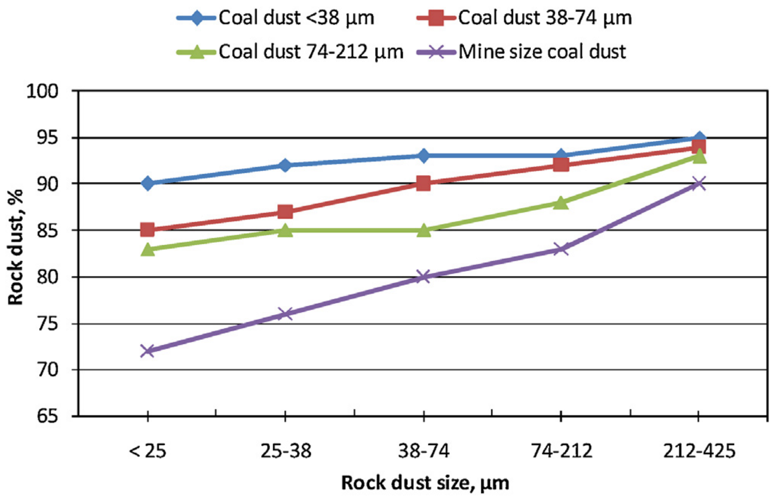


Figure 2-1 Dust Explosibility

The experiments were conducted in a controlled simulated environment very similar to a mine using a GG furnace, and many findings from this study were in line with other studies. The coarser coal dust particles were less susceptible to explosions, and the finer the stone dust, the less proportion was required. These results are helpful for this thesis as a comparative point for current regulatory requirements and other studies. The results showed that a minimum of 72% rock dust was required to inert mine-size coal dust, which is immediately evident to be above Rice et al. [8] initial findings of IC 65% to be satisfactory. Despites its use, the study did present a flaw that the "mine size coal dust" was the same standard as defined by Rice almost 100 years ago. This is a common flaw in literature and flows into federal regulations, as more recent studies have shown that with modern equipment and processes, the standard "mine size coal dust" is finer than in the past [20]. According to this and other studies, the finer dust suggests that the minimum percentage of stone dust required should be greater to inert the modern coal dust.

The limitations in stone dust fineness as a result of the negative implications it can have, including caking and the respiratory issues it can cause for miners, limit how much this factor can vary to account for the finer coal dust in modern mines. Therefore, the proportional percentage of stone dust applied should be the variable target for optimisation in the system created in this thesis.

2.1.3 Coal Dust Generation

Shahan et al. [21] conducted a detailed field characterisation study to determine quantitatively the sources, types, and amounts of dust produced during various UCM processes. The study covered the continuous miner section and longwall section. It confirmed that the primary dust sources were the continuous mining machine, longwall shearer and conveyor belt transfer points, which correspondingly occur at the development face, the longwall, and the belt roads. For each of these sections of operation of a UCM, dust samples were collected at different distances from the dust source and analysed using complex and custom methods, including a Multicyclone array and Gravimetric airborne float coal dust sampler. One of the purposes of the samples was to measure the varying concentration of float coal dust due to the dust source, which is a significant contributing factor to UCM explosions and the quantity of stone dust required to inert the generated float coal dust.

Although the investigation provides specific results, the main contribution to this thesis is the validation of how the different sections of a single UCM experience significant variations in coal dust content due to their relative exposure to the coal dust generating activities and variable conditions such as air velocity (caused from the UCMs ventilation system). Additionally, it was necessary to note that although some of these conditions can be measured once-off using complex equipment, the results are uniquely site and location-specific. These findings are essential to recognise for the system created in this thesis because it highlights the difficulty in attaining accurate data, which implies it is infeasible that live sensors can be used in the design and development of the new system. The uniqueness of different sections of the same mine suggests that the EDRMS needs a fundamental component that can differentiate and adapt to different mine sections. The incomparability of data from one mine site to another indicates that historical data from one mine can not be used to accurately dictate the exact stone dust quantity in different sections of another mine.

2.1.4 Existing Legislation and Standards

The findings by Rice et al. [8] in 1929 are still widely used as a base in government regulations worldwide. The National Institute for Occupational Safety and Health (NIOSH) identified this as an issue in 2009 for the United States Department of Labor Federal Coal Mine Health and Safety Act [20]. The document which applies to the Australian research mine and is detailed in this thesis is Recognised Standard 05, Coal Mining Safety and Health Act 1999 [17]. As previously detailed, this governs and provides a technical standard for the application and monitoring of the use of stone dust or other explosion inhibitors in underground mine roadways.

Issues with Stone Dust Procedures

The National Institute for Occupational Safety and Health (NIOSH) [20], as part of their research piece *Mitigating Coal Dust Explosions in Modern Underground Coal Mines,* investigated multiple areas in which current practices need to be updated. It is highlighted in their 2009 investigation that in the U.S., rock dust requirements have been essentially unchanged since 1969 and are based on the studies performed by Rice et al. [8] in the 1920s. Concerning the coal dust particle size, it is identified from extensive samples that the overall averages were 32% minus 200 mesh, and 64% minus 70 mesh, with a median dust particle diameter of 147 μm. These are significantly finer than findings from Rice which are used in the U.S. that defined "mine size" as dust that passed through an 850 μm sieve and just 20% passing through a 75 μm sieve.

The study then details their identified requirements to inert using stone dust, with the recommendation that based on the finer coal, a minimum of 72% rock dust is required, and thus, regulations should be updated from the 65% minimum IC to account for this. Based on the study, (NIOSH) recommended a new standard of 80% Minimum Incombustible Dust (MID) be required for all roadways, including in the intake airways [21]. In Australia, the requirements for UCM explosion prevention vary, with the MID content changing between 70%, 80%, and 85%, depending on the conditions surrounding the roadway. It is not the purpose of this thesis to evaluate and test whether current regulations are sufficient in Australia and globally. However, from these issues presented, it is evident there is still considerable variation and inconsistency in regulations and findings worldwide. The relevance to this thesis is the requirement for the new system to be configurable and adaptive to suit the standard in place.

2.2 Industry Leading Risk Mitigation for UCM Explosions

2.2.1 Sensor Networks

Muduli et al. [6] identify the need for continuous monitoring of the complex and hazardous mine environment, which is crucial for ensuring safe coal production. To find the vague areas needing further attention, they conducted a systematic literature review on the most advanced research on the application of Wireless Sensor Networks (WSN) in underground coal mines. Out of 762 articles identified from the search of digital libraries, just 52 primary studies were extracted and considered for the review. The resulting primary studies were classified into several UCM monitoring parameters, such as mine gases, temperature and humidity, air pressure, dust, fire, explosion, roof fall, mine personnel and equipment and other applications of WSN in mines. These results show the proportional amount of research that had been sufficiently conducted for each parameter in Figure 2-2.

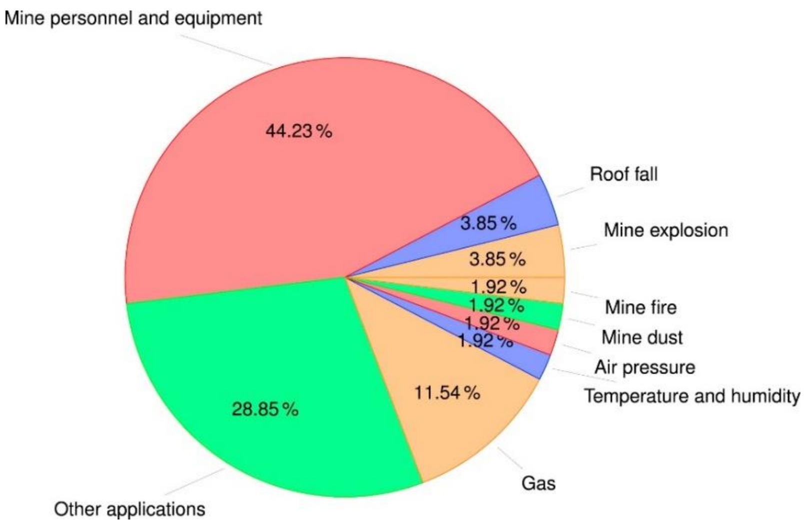


Figure 2-2 Monitoring of different environment parameters in underground coal mines [6]

The review concluded that despite monitoring various environmental parameters in UCM, the WSN technique had not been widely adopted for some of the most vital, including temperature and humidity, air pressure, mine dust concentration, fire, explosion, and roof fall. Thus, more emphasis should be given to these areas for effectively utilising the WSN technique or other advanced techniques, such as the Internet of Things, which can increase the efficiency and efficacy of monitoring systems and minimise the risks associated with a UCM.

This comprehensive review further identified what existing research had been conducted and provided additional in-depth analysis of the most prominent pieces of literature. The related papers, analysis, and conclusion by Muduli et al. support the aims and direction of this thesis by revealing the current lack of current literature on UCM dust explosions and other key risks. Additionally, highlighting minimal practical implementation within the existing literature supports the need for the new system to be capable of real-world implementation within this thesis.

2.2.2 Certified Sensors for Coal Dust Explosibility

A concerningly limited number of certified sensors are available to predict the explosibility of coal dust samples accurately. In their research on U.S. mines, the National Institute for Occupational Safety and Health (NIOSH) identified the lack of required updates to procedures and equipment regarding UCM explosion prevention [20]. To aid and modernise procedures, in 2010, they completed the development of the Coal Dust Explosibility Meter (CDEM) [22]. The handheld device uses optical reflectance to determine if the quantity of stone dust within a sample is sufficient and then shows a distinct colour (RED or GREEN) if the sample has passed or failed. The device has been federally approved for use in the U.S. so that UCM can use this in place of sending samples to external laboratories for analysis.

Therefore, the device can be considered an improvement by decreasing the time taken between taking an appropriate sample and determining whether it is adequate. While this is an improvement, the sensor is by no means live and still requires samples to be manually taken and prepared appropriately. It is currently not capable of being a stationary sensor that can provide data to a system and does not provide specific inert dust percentages. Therefore, there is little consideration for using this device in the EDRMS developed in this thesis.

Figure 2-3 NIOSH coal dust explosibility meter (CDEM) [22]

It is noted that there are many UCM dust samplers created however, these currently are not for the purpose or capability of monitoring the explosibility of the dust. They are primarily personal or stationary monitoring equipment that provides data on if there are dangerous levels of respiratory dust for personal inhalation.

2.2.3 Methods for Risk Assessment

Ray et al. [23] identify the scarcity of literature on monitoring hazards in UCMs compared to the vast amount of literature available for general risk assessment and modelling. Therefore, the focus of the study is to propose a methodology for identifying hazards at different locations in a given work system, characterizing hazards in terms of hazard rate and cumulative risk of occurrence, and monitoring hazard occurrences to determine the deterioration or improvement in safety. Initially, the paper explores this methodology for hazard evaluation and monitoring, with a hazard defined as something that has the potential to cause harm or a source of danger.

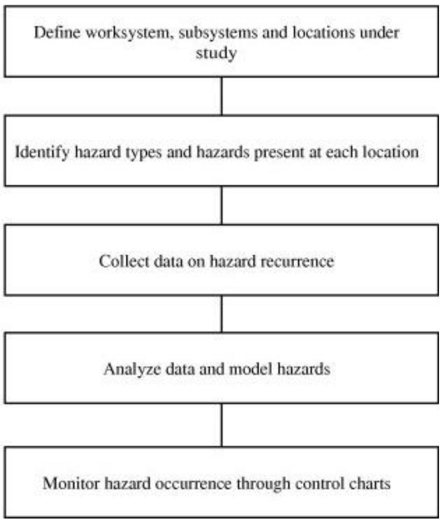


Figure 2-4 Methodology for Hazard Evaluation and Monitoring

The study offers a comprehensive analysis and utilises real-world data from a UCM over a 15-months. However, the methodology provided is only applicable to model the recurrence characteristic of hazard and leaves a significant gap in considering an event's severity while not providing an actual method around a monitoring scheme. By assessing the general structure of the methodology in Figure 2-4, it is evident that the current procedure of the research mine and industry lacks sufficiency in the last two steps of analysing data and monitoring occurrence through control charts. Besides the validation that the EDRMS should focus on improving these risk management steps to improve the overall procedure, this study offers little practical utility for this thesis. The methodology may apply to the potential future work of extending the system to integrate other risks.

Torrent et al. [24] propose a new simple methodology for evaluating explosion risk in UCM. The risk index used is the product of three-factor ratings, the Severity of Consequence (C), Probability of Ignition (P), and Exposure time (E). Based on the product's total, the risk is categorised into Unacceptable, High, Medium, and Acceptable. The aspect of each factor can be seen in Figure 2-5.

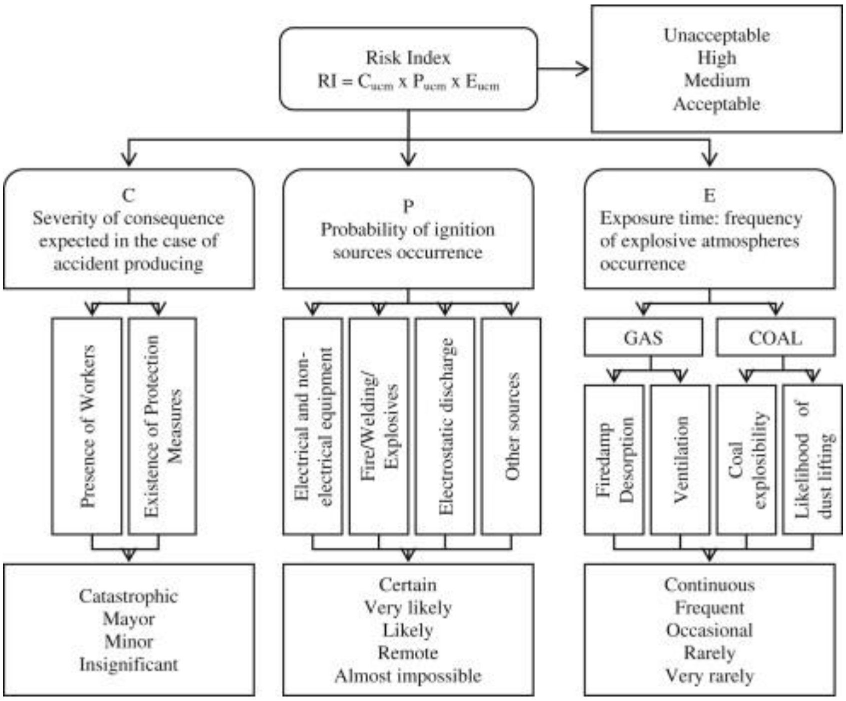


Figure 2-5 Methodology for Evaluation of Explosion Risk in UCM

The paper's analysis, methodology, and reasoning are comprehensive and consider most factors directly applicable to a UCM explosion. It has been simplified enough for real-world use and was applied to active mine conditions for demonstration. While the method is usable, it would only be implementable in difficult one-off instances at this stage, and there is no infrastructure yet to have comprehensive data for each. This paper does provide foundations for condition analysis which a system could use to determine an accurate category of risk however, the inability to adequately capture data on the conditions makes the methodology unusable for the real-world system created in this thesis.

2.3 Business Intelligence (BI)

Sharda et al. [25] comprehensively delve through the history of Business Intelligence (BI) and its continual development in industry, providing exposure to many analytical techniques. BI is the evolution of the Decision Support System (DSS), which was first articulated in 1971 as an "interactive computer based-systems which helps decision makers utilise data and models to solve unstructured problems". BI builds on this as a combination of architectures, tools, databases, analytical tools, applications, and methodologies, with the primary objective of enabling interactive access to data that can give business managers insights and analysts the ability to manipulate the data further to determine actions. Therefore, the overall process of BI is transforming data into information, decisions, and actions. Sharda et al. cover the four major components of BI architecture which include a Data Warehouse (DW), Business Analytics (BA), Business Performance Management (BPM), and a User Interface (UI).

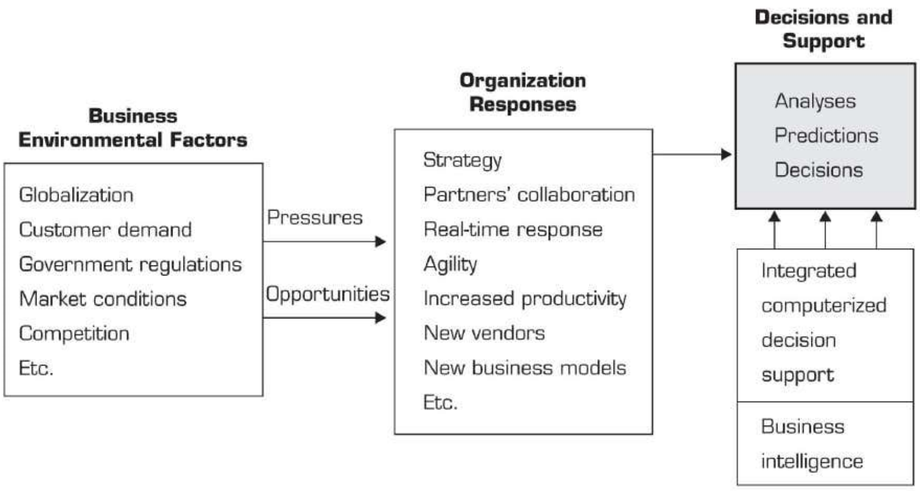


Figure 2-6 Business Intelligence Interaction with Organisations [25]

2.3.1 Data Warehouse (DW)

As detailed by Morr et al. [26], a Data Warehouse is a type of database that holds source data and is the foundation of BI systems. Any current or historical data that may be of significance to decision-makers is summarised and structured in a form suitable for analytical activities such as data mining and querying. A DW focuses on accessing, integrating, and organising vital operational data in a consistent, reliable, timely, and readily available form to aid decision-makers [25]. To process data from the real world to well-formed data, it must be consolidated, cleaned, transformed, and reduced, as detailed in Figure 2-7 [25].

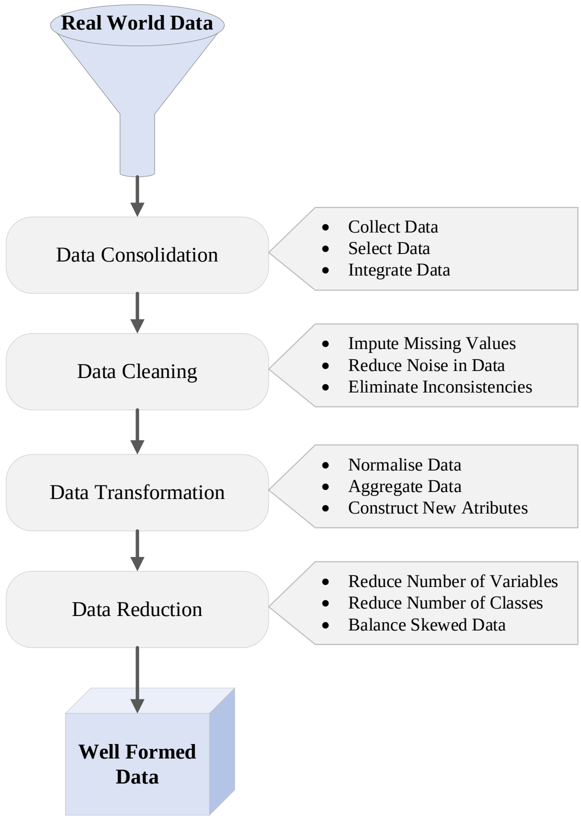


Figure 2-7 Key Data Processing Steps

The characteristics of a DW are separated into fundamental characteristics, including subject-orientated, integrated, time-variant, and non-volatile [25]. Organising data by detailed subject layers with only relevant information enables the users to extend beyond knowing how something is performing to why it is. Integrated data places data from various sources and subjects into consistent formats, meaning discrepancies between naming and units must be managed. Time is the one critical dimension that a DW must support because time-variant data enables insight into trends, deviations, and relationships among different subjects. Finally, data must be non-volatile, meaning it cannot be changed or updated after being entered into a warehouse. A change must be entered as new data, and obsolete data must be discarded. Some additional characteristics of a DW include web-based, relational/multidimensional, client/server, real-time, and metadata. The concept and implementation of a Data Warehouse will firmly apply to this thesis in creating the EDRMS.

2.3.2 Business Analytics (BA)

Sharda et al. [25] divide Business Analytics (BA) into the three categories of Descriptive Analytics, Predictive Analytics, and Prescriptive Analytics. Although this book comprehensively covers all technical information regarding analytical models and processes, the slightly different structure presented by Morr et al. [26], which separates Descriptive Analytics into the additional category, Diagnostic Analytics, is deemed more appropriate for the problem addressed in this thesis. This additional category is also frequently referenced by Cote [27], which supports its use.

The categories are presented as Descriptive Analytics (what happened), Diagnostic Analytics (why did it happen), Predictive Analytics (what will happen), and Prescriptive Analytics (how can we make it happen). Each has an increasing level of value provided to the end user and increasing difficulty in implementing.

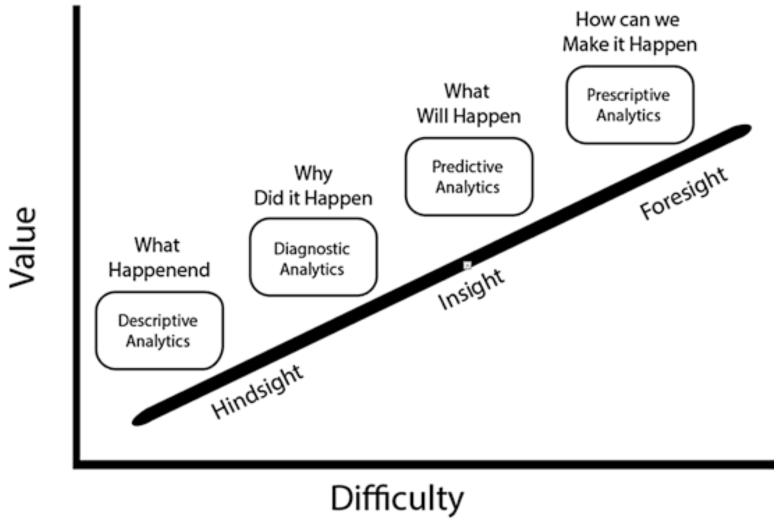


Figure 2-8 Business Analytics Types

Descriptive Analytics (DcA)

Descriptive Analytics (DcA) is often the primary link with BI by readily reporting data via a user interface on what has happened or is happening. Descriptive analytics displays past or current performance indicators to assist in understanding successes and failures and provide evidence for decision-making [26]. Organisations utilise descriptive analytics for replacing traditional reporting with interactive visualisation that provides insights, trends, and patterns in the data [28]. Accompanying DcA is descriptive statistics, which include measures of central tendency (mean, median, and mode), measures of dispersion (minimum, maximum, range, quartiles, and standard deviations), and distribution of variables (e.g., histograms) [26].

A benefit of DcA is that it can be leveraged on its own or utilised as the basis for the other three analytics types [29], making it ideal to utilise in this thesis. Despite offering no identification of the why, the specific target area of explosion risk mitigation within the UCM industry is relatively data-light with no current foundation for easily identifying trends. The development of this data infrastructure is part of the data warehouse [28], and then DcA will utilise this in the EDRMS.

Diagnostic Analytics (DgA)

The focus of DgA is to build on DcA to answer "why did it happen", which is done by identifying the relationship between the event and other variables that could constitute its causes [30]. This involves methods such as trend analysis, root cause analysis, cause and effect analysis, and cluster analysis [26]. This insight enables the ability to monitor performance indicators and improve procedures. Other notions presented around DgA are Hypothesis Testing (historically orientated), Correlation vs. Causation, and Diagnostic Regression Testing [31]. Once the data structure in the EDRMS as part of this thesis is established, DgA will be used to enhance decision-making.

Predictive Analytics (PdA)

PdA uses the past data of what and why from DcA and DgA to create a model that suggests what will happen [26]. This use of historical data to forecast potential scenarios can help drive strategic decisions [32], and the user can plan to implement corrective actions proactively before an event occurs. Some standard tools are what-if analysis, multiple regression analysis, predictive modelling, machine learning algorithms, and neural network algorithms [26]. It is unlikely PdA analytics will be utilised within this thesis in its standard implementation due to its data-light nature. The EDRMS will still enable users to be more proactive however, any algorithms used would need to be basic.

Prescriptive Analytics (PcA)

The final building block of PcA uses the knowledge of what will happen to prescribe specific actions or recommendations that increase the likelihood of a chosen outcome [33]. Encompassed within PcA is simulating, evaluating what-if scenarios, and advising how to maximise the possibility of a desired outcome. The techniques around this are graph analysis, simulation, stochastic optimisation, and non-linear programming [26]. Cote [34] details that most of these techniques can be conducted manually however, machine-learning algorithms are often used in PcA to analyse large amounts of data faster. Additionally, they highlight that while algorithms can provide data-informed recommendations, it is still essential to include human discernment. Although the system is data-light, the ability of the EDRMS to recommend actions will be explored within this thesis. Furthermore, Cote's view on keeping predictions to simply a suggestion rather than automatically implementing a change will also be followed due to the high-risk nature of the problem.

2.3.3 User Interface (UI)

Data Visualisation (DV) presents data to a reader in a way that helps them understand and interpret data to spot valuable information such as trends and exceptions. The User Interface (UI) component of BI extends from DV through more visualisation-rich tools such as infographics and dashboards. These techniques with information-rich designs without all the distracting details enable users to interpret and gain critical knowledge more efficiently [25], sometimes referred to as visual analytics.

Morr et al. [26] provided a valuable summary of the best graphical objects for specific relationships, as provided below.

	Graphical objects			
Relationship	Points	Lines	Bars	Boxes
Time series (categorical data on the *x*-axis and quantitative values on the *y*-axis)	Dot plot only when values were not collected at consistent intervals of time	For emphasis on the overall pattern	For emphasis on individual values	Only when showing distributions that change through time
Ranking	Dot plot when the quantitative scale does not start at zero; otherwise, use bar	Avoid	Horizontal or vertical	Only when ranking multiple distributions. Horizontal or vertical
Part-to-whole	Avoid	To display how parts of a whole change over time	Horizontal or vertical (e.g.,	Avoid
Deviation	Dot plot when the quantitative scale does not start at zero	Useful when combined with time series	Horizontal or vertical. Always vertical if combined with time series	Avoid
Distribution (single)	Known as a strip plot. Emphasis on individual values	Known as a frequency polygon. Emphasis on overall pattern	Known as a histogram. Emphasis on individual intervals	Avoid
Distribution (multiple)		Known as a frequency polygon. Limit to a few lines	Avoid	Known as a box plot (e.g., Fig.
Correlation	Known as a scatterplot (e.g.,	Avoid	Horizontal or vertical	Avoid
Geospatial	Different point sizes encode values	Used to mark routes (e.g.,	Avoid	Avoid
Nominal comparison	Use a dot plot if scales do not start at zero	Avoid	Horizontal or vertical. Use when the scale starts at zero	Avoid

Figure 2-9 Graphical Object use for Different Relationships [26]

A primary component of the UI component in BI is the dashboard which can be broken down into three roles: strategic, analytical, and operational [26]. Strategic dashboards tend to be simple, not interactive, and often do not need real-time data. This is because they tend to be at the executive level of a company to support long-term strategic goals and focus on high-level measures of performance. Analytical dashboards must offer data-rich comparisons with extensive history and often the ability of interaction to drill down for more details. They usually aid in detecting patterns and identifying the causes of problems. Operational dashboards are dynamic and must present real-time data in a simple way that is easy to interpret while ensuring they can attract immediate attention if an operation falls outside an acceptable threshold. The three different roles of the dashboard and their corresponding purpose will be strongly considered in creating the EDRMS in this thesis to comply with the system's focus of being utilised across different departments, roles, and responsibilities at the research mine.

2.3.4 Business Performance Management (BPM)

The component of Business Performance Management (BPM) refers to the processes, methodologies, metrics, and technologies used by enterprises to measure, monitor, and manage business performance [26]. BPM is more a product of rather than a requirement of BI. The principal addition of BPM is to be strategy driven, with the vital process to strategise, plan, monitor, act, and adjust [25], which is known as the closed-loop BMP cycle.

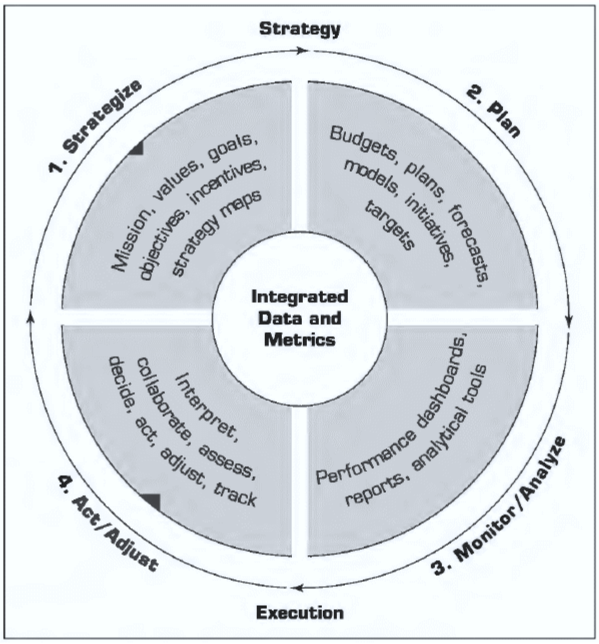


Figure 2-10 Closed-Loop BPM Cycle [25]

BPM aids companies in translating their strategies and objectives into plans, monitoring performance against those plans, analysing variations between actual results and planned results, and adjusting their objectives and actions in response to this analysis [28]. The concept of BPM will be important in this thesis as BPM and visual analytics have a symbiotic relationship (over scorecards and dashboards) where they benefit from each other's strengths [25].

2.4 Applicability and Issues of BI, Machine Learning, and AI in the Mining Industry

Anastasova et al. [35] highlight the benefits of BI and outlines the areas in the mining industry in which BI could be successfully implemented. These include monitoring and tracing various mineral aspects, general mine characteristics, and optimising mining, transport, administration, and compliance. It is agreeable that these areas could benefit from BI, however, the paper lacks much depth into the reality of the industry and lacks data in some key areas. The paper is more informative of BI than providing helpful information on the issues of how it can be used in the mining industry, and as such, it holds no weight in this thesis.

The paper presented by Eybers et al. [16] investigates factors that influence the adoption of BI Sytems by end users in the mining industry. The research included interviews at two operating mining plants with employees of different levels in the Business Improvement and Human Resource departments. The investigations analysis concluded that BI systems did not have the expected utilisation within the mining industry. This is primarily due to the strong bureaucratic culture and nature of mining work inhibiting job autonomy and the lack of senior management acknowledging or promoting the benefits of using the BI systems. The investigation lacked an adequate quantity of people interviewed to give it direct credibility however, it adequately addressed other investigations with similar findings to give it reliability. Although there was no technical implementation guidance, the primary recommendations around improving BI implementation at mines may be valuable in delivering the EDRMS associated with this thesis.

Hyder et al. [36] discussed the current implementation status of AI, ML, and autonomous technologies in the mining industry and conducted 20 interviews. Their paper will be reviewed in conjunction with Khan et al. [37] as they both came to similar conclusions. Khan et al. paper focused more specifically on safety measurements and risk assessments of the coal mining industry using AI and ML. Through their research, both papers appropriately identify that ML and AI can vastly improve productivity, efficiency, and safety. They also highlight that autonomous vehicles are currently the most significant use of intelligence in the mining industry. Hyder et al. and Khan et al. both similarly conclude from their interviews and research, respectively, that the main challenges are; reliable data availability, ambiguous data gathering, inconsistent existing systems, and difficulty in modelling design due to the ever-changing nature of the mining environment. Additional barriers include investment size, unavailability of skilled workers, and the uncertainty of success. These common themes and issues support the need for this thesis to target the real-world implementation of an EDRMS that utilises BI.

2.5 Feasible Optimisation Methods

Analytical methods and mathematical models require well-defined data and knowledge to represent information and scenarios accurately. The more comprehensive the dataset, the more advanced a model can be [25]. Due to a lack of data integration and sensor availability and utilisation, there is limited data currently available that can be used to accurately represent the processes and model the system surrounding explosive dust management. The focus of this thesis is to create a system capable and ready for real-world use, and in doing so, it can start breaching this data gap. As such, the initial analytical methods and modelling explored and utilised within this thesis will be basic compared to those possible with a more comprehensive dataset.

2.5.1 Regression Algorithms

A regression algorithm is practical when there is a need to predict the outcome of a time-driven event. It is commonly used to create a model that links the dependent outcome variable to the independent variables [26]. There are many different regression types, each serving different purposes with varying benefits. The foundational regression models are Linear Regression and Logistic Regression. Linear Regression can predict a dependent variable using a set of independent variables related to the dependent variable. The dependent output variable is a value on a continuous scale that varies based on the independent input variables [28], which may suit the purpose of the optimisation objective in this thesis. Logistic Regression is different as its output variable is discrete, such as 0 or 1. It uses independent variables to predict the occurrence or failure of a specific event through the binary outcome [38]. This would not be suitable to determine the optimal amount of stone dust to be applied given certain conditions, as the output should be a suggested value on a continuous scale. Therefore, only Multiple Linear Regression will be explored below.

Multiple Linear Regressions

A Multiple Linear Regression (MLR) model expresses the outcome prediction variable, known as the dependent variable, in terms of a linear function of predictor variables, known as independent variables. The independent variables each represent a causal factor that is selected as they have some form of correlation and relationship with the dependent variable [25]. With enough data to determine an accurate relationship, multiple independent variables can be mathematically combined to predict the dependent variable given a scenario of causal factors. The standard form of an MLR model is [39]:

2-2 Multiple Linear Regression Model

$$y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \ldots + b_p x_{ip} + \epsilon$$

Where, y_i = dependent Variable, b_0 = y-intercept, x_{ip} = independent variable, b_p = slope coefficients for each independent variable, ϵ = model error

Applying an MLR model to the problem addressed in this thesis of determining optimal stone dusting practices would be feasible with enough data concerning the exact mining conditions to create an accurate model. Suppose the prediction outcome dependent variable is set as the amount of stone dust required or the minimum stone dust application rate. In that case, there are clear independent variables that contribute to this. This may include the density of stone dust, the amount of coal dust generated in the production area that dust is being applied to, the width and height of the EDZ, the amount of stone dust previously applied with that EDZ, the ventilation airflow rate, and several other factors.

The independent variables mentioned, including coal dust generation, would vary significantly for each EDZ within the same mine and even more between different mines. Different equipment and coal dust control methods, such as wetting the coal and ventilation, significantly impact how much coal dust is generated [19]. Similarly, for the other independent variables, many conditions change, and there are not yet suitable sensors for these that can be feasibly used in the ever-changing conditions of an UCM. Therefore, although it would be possible to define and measure each of these conditions in one-off instances to create a MLR model, it would be impractical for real-world implementation due to the ever-changing conditions. As such, MLR will not be utilised in the EDRMS developed as part of this thesis.

2.5.2 Feedback Control

As explained by Kim et al. [40], feedback control is a control mechanism that uses information from measurements, usually live, to manipulate a variable to achieve a desired result. The purpose and goal of feedback control are to make the difference between the desired output Set Point (SP) and the actual output Process Variable (PV), known as Error (E), as close to zero as possible. The desired output is usually entered or set directly in a system, and the actual output is measured, usually by some form of sensor.

As seen in Figure 2-11 below, E is calculated as the difference between the SP and PV and is fed back into the system as a direct input to the controller, which determines how a variable should be manipulated. The manipulation is done within the Final Control Element (FCE) before being input into the overall process that results in the PV. This new PV is then measured to determine the new E, which is again fed back into the system. This undergoes the same process, with the system utilising the negative feedback loop until it approaches a steady state.

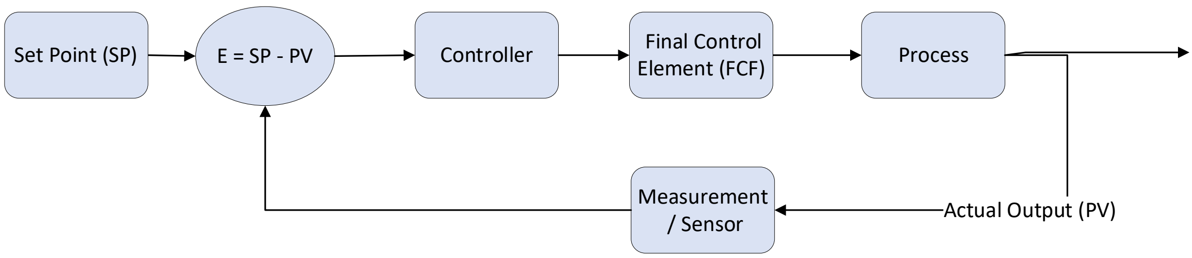


Figure 2-11 Basic Feedback Control Loop

In its typical sense, feedback control does not seem possible for UCM mining operations in its current state due to the lack of live sensors and actuators that can impact explosive dust control. Feedback control is commonly used for dynamical systems with sensors that provide live feedback for a controller to make suitable adjustments to actuators to achieve the desired SP. Feedback control is the foundation of automated systems and has advanced from on-off control to varying Proportional, Integral, and Derivative control combinations [41]. If there were live sensors to measure the conditions mentioned in MLR, and a programmable dust application actuator could be utilised throughout the EDZs, feedback control would appear more suitable for real-world implementation. As this is not the case, the advanced forms of feedback control will not be thoroughly explored for real-world use within this thesis.

However, the basic concept of feedback control may be practical by separating the overall operational process into receiving feedback through the weekly dust sample results (measurements) and the routine dust application completed by personnel using various dusting equipment. It is anticipated that the weekly dust sample result of EDZs and the amount of stone dust applied to an EDZ will be integrated into the EDRMS developed as part of this thesis. Using a Set Point that involves the sample result as a target, the calculated Error from the weekly sample result may be used as an input. Although there would be minimal manipulation of the error, it may be used to modify the Minimum Dust Application Rate, which personnel adhere to, until optimal sample results are received for an EDZ.

3 Methodology

This chapter extensively details the existing UCM explosion risk management and process used by the research mine. This is evaluated to identify what subsequent design considerations should be implemented for the new system designed and developed within this thesis. Next, the new EDRMS design is proposed and the required process to deliver the new system is detailed. Following this, more comprehensive methodology is provided for optimising the application rate.

This chapter will support the following thesis objectives:

- Determine the performance and weaknesses of existing systems that currently manage this risk and evaluate other existing risk mitigation techniques and systems.
- Design a system that provides a more efficient and robust process for managing the required dust sampling, application, and re-treatment practices across the mine by:
    a. Automating steps in the procedures to reduce manual processing and minimise human error.
    b. Providing a readily accessible source of data relating to stone dust application and sample analysis.
    c. Enabling a proactive approach to the planning and management of explosion risk mitigation.

3.1 Existing UCM Explosion System of the Research Mine

The research and literature review revealed that in order to implement real-world BI systems that end users in the mining industry would accept, an understanding beyond theoretical was required. Therefore, in-depth remote meetings were frequently conducted with the research mines Stone Dust Coordinator to complete this methodology in addition to reading and understanding the legislative requirements, standards, and existing literature. Furthermore, several days were spent at the research mine operating site to go through critical aspects of the process from start to finish, including going underground to get an appreciation for the environmental difficulties faced. It was also essential for understanding the different roles, responsibilities, and work cultures that may impact critical design decisions and end-user usability.

The current method employed by the research mine has taken on many recommendations from the regulatory review, including others not outlined in 1.6. Nevertheless, their method is still cumbersome and complex, and it has limited ability to attain data and plan proactively. Digitally integrating their system and processes will improve efficiency and enable the research mine to ensure their compliance with the recognised standards. The following process is completed weekly.

3.1.1 Management of Explosive Dust Zones

Managing the EDZ is the first major component of Explosive Dust Management (EDM). It encompasses:

- Dividing the mine into EDZs of sizes according to the percentage of incombustible dust required for that production area. This includes adding new EDZs as the mine expands and removing sealed or goaf EDZs.
- Updating the percentage of incombustible dust required in each EDZ as the mine advances, which is associated to the risk within that EDZ. The risk varies dependent on factors such as how close to live coal production and coal dust a zone is.

The physical location of an EDZ does not change however, its risk association does. At any stage, the EDZ is associated with either a Face Zone, Conveyor Road, Return Airways, Gateroad Barrier, or Intake Road. Depending on what Panel Area type of EDZ, it has the conditions outlined in Table 3-1 below. Note that a month is considered four weeks.

Table 3-1 Roadway Explosive Dust Management Requirements

Panel Area Type	***Face Zone (%)***	***Conveyor Roads***	***Return Roads***	***Gateroad Barrier***	***Intake Roads***
Minimum Percentage of Incombustible Dust Required	85	80	80	80	70
Colour	Pink	Cyan	Cyan	Red	Green

Detail	All roadways in each Subzone within 200m outbye the last completed line of cut-throughs	All conveyor roadways in each zone	All return roadways in each zone	All roadways in each gateroad barrier	All intake roadways in the zone
Sample Frequency	Weekly	Monthly	Monthly	Monthly	3-Monthly
Sample Method	1 x Composite sample made of 10 x strip (last week of each month) or Spot (first three weeks of the month) samples	1 x Composite sample made of 10 x strip samples or ONLY where the road is obstructed spot samples can be taken.	1 x Composite sample made of 10 x strip samples or ONLY where the road is obstructed spot samples can be taken	1 x Composite sample made of 10 x strip samples or ONLY where the road is obstructed spot samples can be taken	1 x Composite sample made of 10 x strip samples
Timeframe of Re-dusting Sample Failure	12 Hours of Notification	7 Days of Notification	7 Days of Notification	12 Hours of Notification	7 Days of Notification
Timeframe of Re-dusting Sample within 5% of Failure	7 Days of Notification	7 Days of Notification	7 Days of Notification	7 Days of Notification	7 Days of Notification
Timeframe of Re-dusting Sample within 10% of Failure	Monitor for trending	Monitor for trending	Monitor for trending	Monitor for trending	Monitor for trending

At the research mine, managing stone dust EDZ and their requirements are currently maintained using AutoCAD. They have a base model map of the mine (MP001) on which an EDZ management plan (MP1100) is built. This map can be seen in Figure 3-1. The associated legend of the map, which details what the colour roadways correspond to, is seen in Figure 3-2

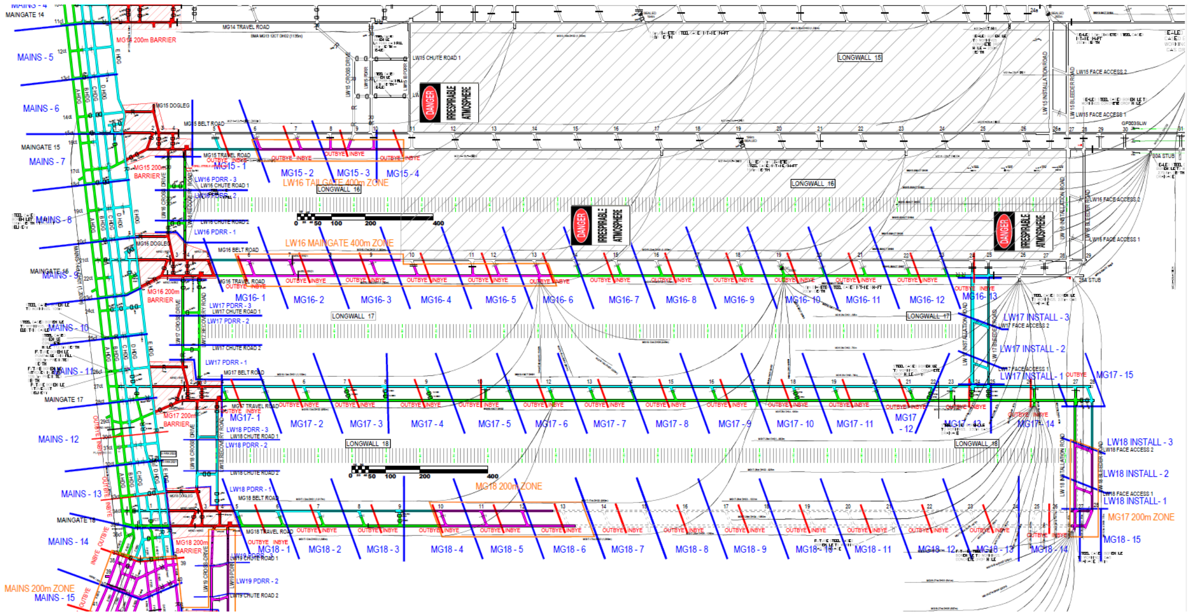


Figure 3-1 Research Mine Dust Zone Management Map (MP1100)

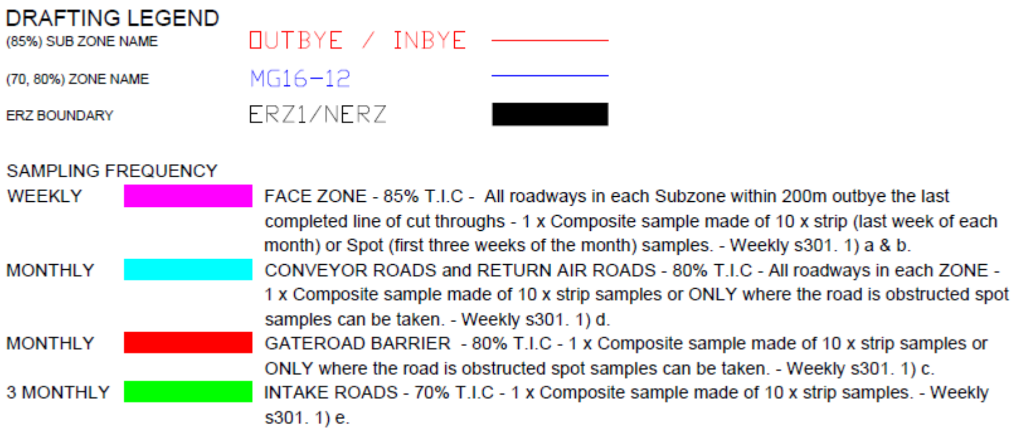


Figure 3-2 Research Mine Map Legend (MP1100)

Limitations of Existing System

Overall, managing the EDZ and their sampling requirements using the AutoCAD file and sharing as a PDF conversion is a visually rich way to view the data, allowing a representation of critical information which can be interpreted and digested by many users efficiently. Based on an understanding of processes at other mines, this method of management employed by the research mine is one of the more beneficial. It is still common that this part of the overall process is done in excel.

Although there are some positives, the critical limitation in its current form is that the AutoCAD file lacks compatibility and simple integration with the rest of the process and corresponding data. This lack of compatibility results in a data transfer required via visual interpretation into a compatible form, which will be detailed throughout the rest of the procedure. This issue introduces the possibility of human error when transferring data visually from this dataset into another form. Thus, even if the AutoCAD file is maintained accurately to represent the sample requirements, due to the manual data transfer, this may not be reflected in the data that controls what final samples take place.

Another issue realised from visiting the mine site is that the responsibility of managing these EDZ on AutoCAD was split between two departments, the Survey team, who creates it on AutoCAD and Compliance, who verifies it. Overall, this seemed to be managed well however, it does introduce inefficiencies and delays due to the double handling,

Subsequent Design Considerations

After understanding the vast intricacies involved and the disconnection between some concepts of the safety departments from the operational departments, it would be beneficial to create a Digital Twin as the foundation of the designed EDRMS. A digital twin is a virtual recreation of a physical object, area, process, or service. Establishing a digital twin enables a digital concept for real-world data to be associated and can be used to replicate the physical world or processes. Once a digital twin is established, it can continue to become more advanced as more data is gathered and is commonly capable of integrating the internet of things, artificial intelligence, and software analytics. Typical benefits of digital twins include increased reliability and risk reduction through monitoring, simulation and prediction, as well as cost saving through efficiency and optimisation [42]. Concerning the EDRMS, the digital twin would initially be a basic digital recreation of the mine using a map or image. From this, the digital twin will try to replicate the entire process digitally to collect data, improve monitoring, and optimise performance.

This would be beneficial as a common visual physical representation such as a map is more familiar and recognisable to different departments across the mine. The EDZs and the associated naming conventions are unique to explosive dust management and are not commonly used when referring to the physical location within the mine. For example, an operational worker applying stone dust may not be familiar with the names of EDZs but can relate to their visual location representation. It will also lay a foundation that more data can be associated with in a more meaningful and recognisable way. Therefore, having a digital twin as the foundation is the most efficient way to communicate the physical location of critical information regarding safety requirements such as sampling and failures. Additionally, if the management of EDZ is done on a digital twin integrated into the platform, the data is already in the system for other module components to draw upon and connect with.

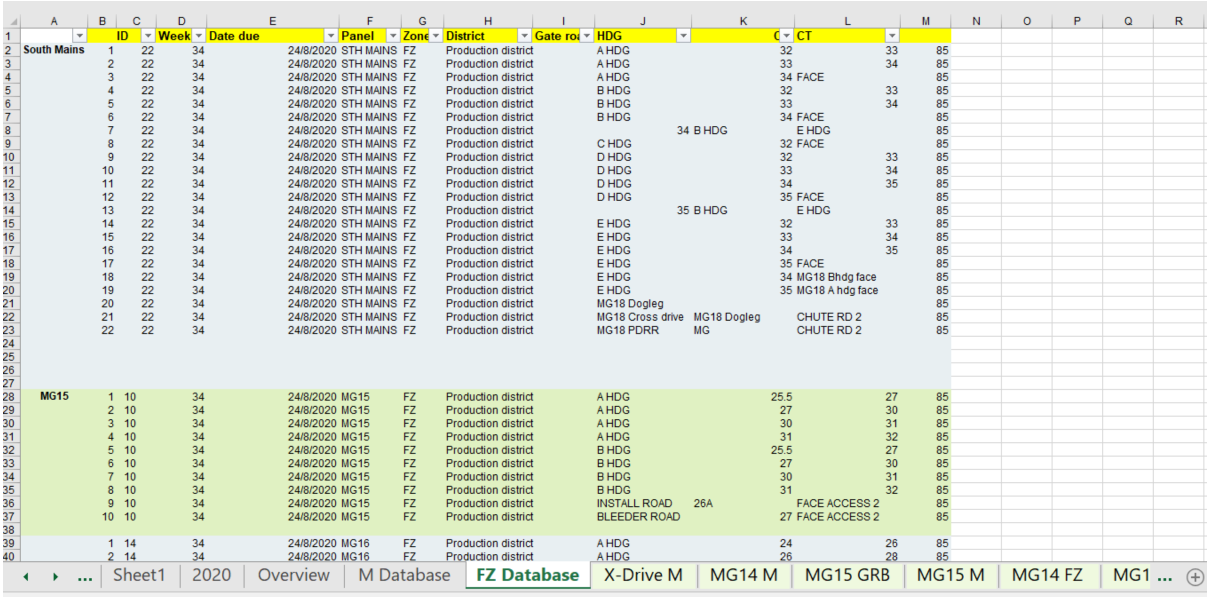
The preferred design would include the complete management of Explosive Dust Zones (EDZs) completed on the digital twin, which would include allocating sections as EDZ and setting their sampling requirements directly within it. However, part of the issue in implementing systems is not doing change incrementally, and if a significant change is enforced without sufficient consultation, it faces hesitation and conflict in adaptation [16]. With an understanding and consideration of the constraints of current roles and responsibilities at the research mine, it will be too large a shift to move responsibility from the survey team who manage their work on AutoCAD to managing this on the EDRMS platform. The primary consultation is completed with the Compliance and Production departments, and the new EDRMS will already impact many work processes, roles and responsibilities in these departments.

Therefore, to support the bounds of this project and thesis, the design and digital twin used for implementation must include functionality that can integrate with the current AutoCAD. This will mean that the Survey departments still make changes within AutoCAD, but the EDRMS will be able to read the layer colours within AutoCAD, which can then be associated with the sampling requirements of each zone. Following successful implementation and acceptance of the initial system, it would be the intention to change this to the desired design.

3.1.2 Preparing Sample Plans and Labels

The following essential part of the process is to translate the information decided upon in the management of EDZ into accurate Sample Plans and Labels. The Stone Dust Coordinator (SDC) will receive the MP1100 mine plan (Figure 3-1) and interpret it for sampling requirements via the colours as detailed in the map legend (Figure 3-2). As the SDC interprets the mine map, they will make any required adjustments to their stone dust management excel. This involves editing the existing database (Figure 3-3) in their excel by manually adding, removing, and updating any cells and rows where the requirement has changed based on the colour of the lines within the AutoCAD MP1100 plan.

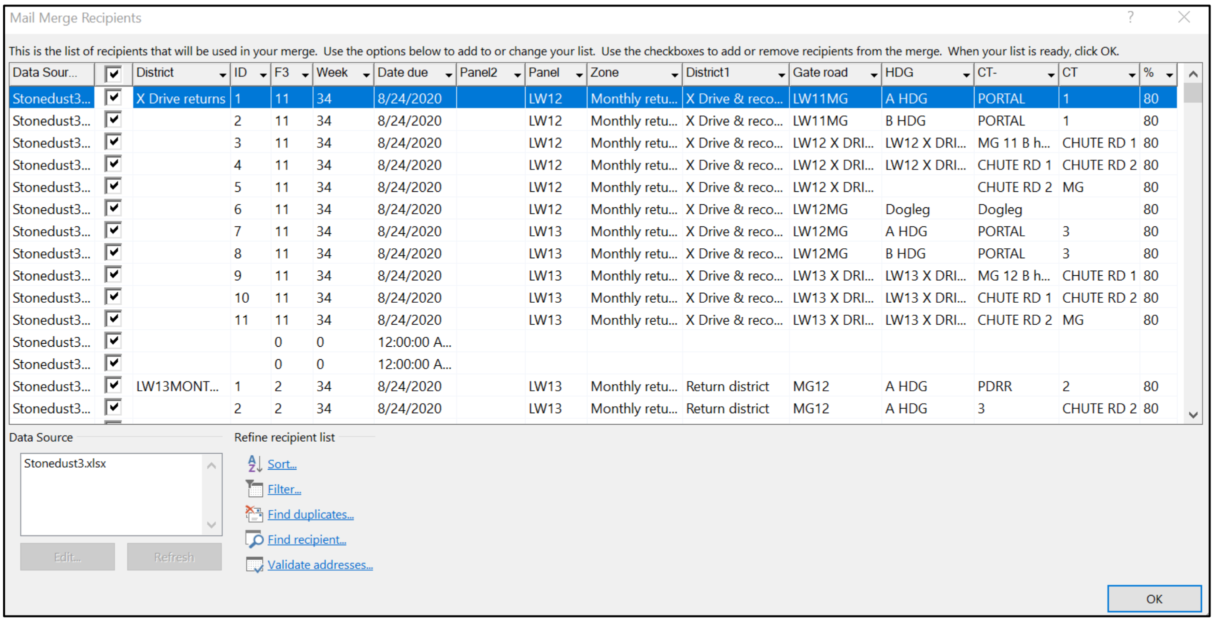
The updated information is then translated into other cells within other tabs of pre-templated report styles. The SDC will then edit the report templates based on the current EDZ AutoCAD. This includes taking screenshots of the related sections of the mine plan and pasting them into the templates. The SDC will then export the appropriate plans for that week as PDFs from the tabs which contain table templates.



	A	ID		Week	Date due	Panel	Zone	District	Gate roa	HDG	C	CT	
2	South Mains	1	22	34	24/8/2020	STH MAINS	FZ	Production district		A HDG	32	33	85
3		2	22	34	24/8/2020	STH MAINS	FZ	Production district		A HDG	33	34	85
4		3	22	34	24/8/2020	STH MAINS	FZ	Production district		A HDG	34	FACE	85
5		4	22	34	24/8/2020	STH MAINS	FZ	Production district		B HDG	32	33	85
6		5	22	34	24/8/2020	STH MAINS	FZ	Production district		B HDG	33	34	85
7		6	22	34	24/8/2020	STH MAINS	FZ	Production district		B HDG	34	FACE	85
8		7	22	34	24/8/2020	STH MAINS	FZ	Production district		34	B HDG	E HDG	85
9		8	22	34	24/8/2020	STH MAINS	FZ	Production district		C HDG	32	FACE	85
10		9	22	34	24/8/2020	STH MAINS	FZ	Production district		D HDG	32	33	85
11		10	22	34	24/8/2020	STH MAINS	FZ	Production district		D HDG	33	34	85
12		11	22	34	24/8/2020	STH MAINS	FZ	Production district		D HDG	34	35	85
13		12	22	34	24/8/2020	STH MAINS	FZ	Production district		D HDG	35	FACE	85
14		13	22	34	24/8/2020	STH MAINS	FZ	Production district		35	B HDG	E HDG	85
15		14	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	32	33	85
16		15	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	33	34	85
17		16	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	34	35	85
18		17	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	35	FACE	85
19		18	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	34	MG18 Bhdg face	85
20		19	22	34	24/8/2020	STH MAINS	FZ	Production district		E HDG	35	MG18 A hdg face	85
21		20	22	34	24/8/2020	STH MAINS	FZ	Production district		MG18 Dogleg			85
22		21	22	34	24/8/2020	STH MAINS	FZ	Production district		MG18 Cross drive	MG18 Dogleg	CHUTE RD 2	85
23		22	22	34	24/8/2020	STH MAINS	FZ	Production district		MG18 PDRR	MG	CHUTE RD 2	85
24													
25													
26													
27													
28	MG15	1	10	34	24/8/2020	MG15	FZ	Production district		A HDG	25.5	27	85
29		2	10	34	24/8/2020	MG15	FZ	Production district		A HDG	27	30	85
30		3	10	34	24/8/2020	MG15	FZ	Production district		A HDG	30	31	85
31		4	10	34	24/8/2020	MG15	FZ	Production district		A HDG	31	32	85
32		5	10	34	24/8/2020	MG15	FZ	Production district		B HDG	25.5	27	85
33		6	10	34	24/8/2020	MG15	FZ	Production district		B HDG	27	30	85
34		7	10	34	24/8/2020	MG15	FZ	Production district		B HDG	30	31	85
35		8	10	34	24/8/2020	MG15	FZ	Production district		B HDG	31	32	85
36		9	10	34	24/8/2020	MG15	FZ	Production district		INSTALL ROAD	26A	FACE ACCESS 2	85
37		10	10	34	24/8/2020	MG15	FZ	Production district		BLEEDER ROAD	27	FACE ACCESS 2	85
38													
39		1	14	34	24/8/2020	MG16	FZ	Production district		A HDG	24	26	85
40		2	14	34	24/8/2020	MG16	FZ	Production district		A HDG	26	28	85

Figure 3-3 Example of Stone Dust Excel Process

After these plans are exported and saved, the SDC uses a Word Document label template with a mailing list linked to the excel template (Figure 3-5). The SDC will edit the mailing list and manually check or uncheck EDZ selections extracted from the excel depending on what is required for sampling that week (Figure 3-4). Once they have checked or unchecked the appropriate zones, the word document template will populate with selected zones for sampling. The labels will then be printed off and ready for use.



Data Sour...	☑	District	ID	F3	Week	Date due	Panel2	Panel	Zone	District1	Gate road	HDG	CT-	CT	%
Stonedust3...	☑	X Drive returns	1	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW11MG	A HDG	PORTAL	1	80
Stonedust3...	☑		2	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW11MG	B HDG	PORTAL	1	80
Stonedust3...	☑		3	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW12 X DRI...	LW12 X DRI...	MG 11 B h...	CHUTE RD 1	80
Stonedust3...	☑		4	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW12 X DRI...	LW12 X DRI...	CHUTE RD 1	CHUTE RD 2	80
Stonedust3...	☑		5	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW12 X DRI...		CHUTE RD 2	MG	80
Stonedust3...	☑		6	11	34	8/24/2020		LW12	Monthly retu...	X Drive & reco...	LW12MG	Dogleg	Dogleg		80
Stonedust3...	☑		7	11	34	8/24/2020		LW13	Monthly retu...	X Drive & reco...	LW12MG	A HDG	PORTAL	3	80
Stonedust3...	☑		8	11	34	8/24/2020		LW13	Monthly retu...	X Drive & reco...	LW12MG	B HDG	PORTAL	3	80
Stonedust3...	☑		9	11	34	8/24/2020		LW13	Monthly retu...	X Drive & reco...	LW13 X DRI...	LW13 X DRI...	MG 12 B h...	CHUTE RD 1	80
Stonedust3...	☑		10	11	34	8/24/2020		LW13	Monthly retu...	X Drive & reco...	LW13 X DRI...	LW13 X DRI...	CHUTE RD 1	CHUTE RD 2	80
Stonedust3...	☑		11	11	34	8/24/2020		LW13	Monthly retu...	X Drive & reco...	LW13 X DRI...	LW13 X DRI...	CHUTE RD 2	MG	80
Stonedust3...	☑			0	0	12:00:00 A...									
Stonedust3...	☑			0	0	12:00:00 A...									
Stonedust3...	☑	LW13MONT...	1	2	34	8/24/2020		LW13	Monthly retu...	Return district	MG12	A HDG	PDRR	2	80
Stonedust3...	☑		2	2	34	8/24/2020		LW13	Monthly retu...	Return district	MG12	A HDG	3	CHUTE RD 2	80

Figure 3-4 Example of Stone Dust Word Process List

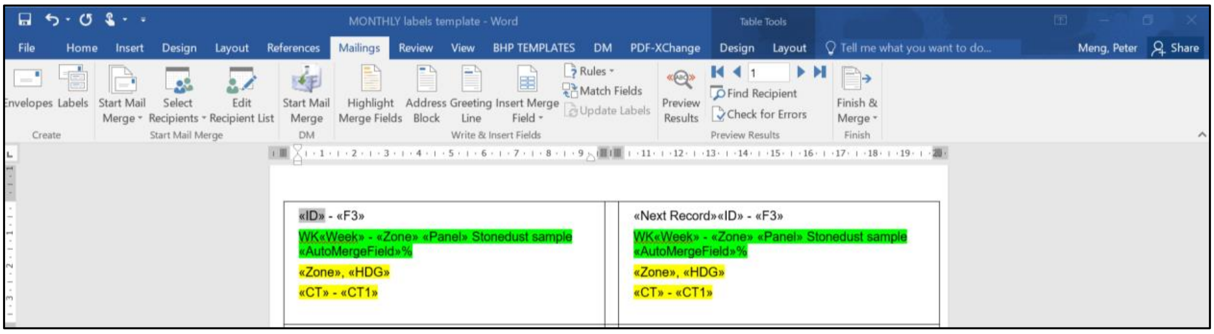


Figure 3-5 Example of Stone Dust Word Process

Limitations of Existing System

As mentioned, although the AutoCAD file and PDF conversion is a visually rich way to view the data, its key limitation is that it lacks compatibility with the other datasets. This part of the process introduces the possibility of error when transferring data visually from this AutoCAD file into the excel document. The excel document attempts to replicate and extend this data to determine the sampling requirements for that week. Consequently, if the data is transferred incorrectly, the determined samples may also be incorrect. Another opportunity for human error in transferring data occurs in the separate word label template, where the data samples for that week must be manually selected or unselected

Additional to the possibility of error in transferring data, another consequence of the visual interpretation, there is little consistency in EDZ naming conventions when translated into the excel document. Although the chosen names of EDZs make sense to the workers, the inconsistency in how a name is structured presents limitations in correlating and representing the data. Additionally, as the mine progresses or other users translate the data, some EDZs have multiple slightly varying names and structures. For example, the EDZ of "MG17, MG17 – 3, A HDG, OUTBYE" may additionally be in the form:

- MG17 – 3, OUTBYE, A HDG
- LW17, MG17 – 3, OUTBYE, A HDG
- MG17, LW17, MG17 – 3, OUTBYE, A HDG

Another example is variation in road names, such as the Longwall road labelled "Cross Drive", which may also be called XDRIVE.

Subsequent Design Considerations

From the 3.2.1 design consideration of managing the stone dust EDZs directly within the digital twin concept on the EDM system, all the data required to produce the stone dust plans and labels will already be available within the system. Therefore, the EDRMS can use the Last Sample Date of each EDZ (integration for this will be considered as part of 3.2.4) and the current Sample Frequency associated with the EDZs sampling requirement (e.g., monthly) to determine the Next Sample Date for all EDZs. Then, the EDRMS can determine what EDZs need to be sampled for the current sample week at any stage using all the Next Sample Date.

3-1 Next sample Date

$$Next\ Sample\ Date = Last\ Sample\ Date + Sample\ Frequency$$

As part of establishing the digital twin, a clear naming convention needs to be standardised for all EDZs to be consistently correlated. To cover these, the naming structure needs four layers, an Area, Zone, Road Type, and Subzone. The Area will encompass all the EDZs within easily relatable sections of the mine, including the Mains, the Main Gates (MG), and the Long Wall (LW). The Zones will be the segmented sections encompassing different roads and subzones, delineated by the blue lines in Figure 3-1. The Road Type will be the roads associated with the corresponding Area and encompass Subzones. If required, the Subzone will always be approximately equal halves of a Zone called Outbye or Inbye, with the outbye delineating the half closest to the mine exit. To allow for when a Subzone is not required for a Zone due to the Zone already being of a sufficiently short length, the entire Zone should default to Outbye.

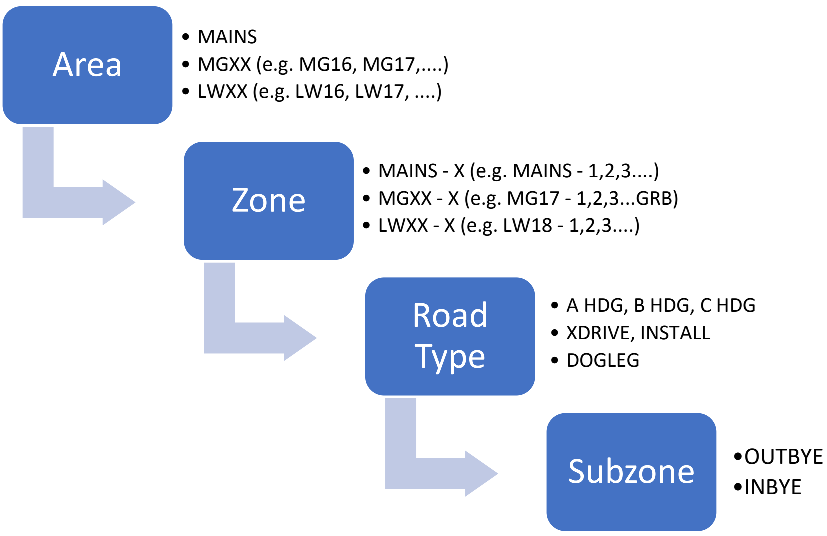


Figure 3-6 EDZ Naming Convention Structure

To extend beyond just imitating the existing process, layout, and style of the plans and labels, it would be ideal to enable digital editing and ‘checking off’ functionality of the forms, which users can complete once samples are collected. This would ensure that all the samples that needed to be collected were collected. When sample results are received, they could correspond directly with the collected samples, and if not, warn the users otherwise. Although complete digitalisation will be considered, it has been noted that many other stakeholders use these plans and labels throughout the mine and the external Laboratory which analyses the samples. Therefore, extending this part of the process further than the existing plans and labels may not be possible within this thesis and EDRMS due to the incremental change required.

3.1.3 Sample Collection

Once the sample labels and plans are printed, the samples need to be collected. The people responsible for collecting the samples are trained to attempt collection as consistently as possible and no deeper than 5mm from the surface. A paint brush is used to collect a representative sample every 10 metres of an EDZ, traversing the road from roof, rib and floor. It is captured in a container and then transferred to zip-lock bags.

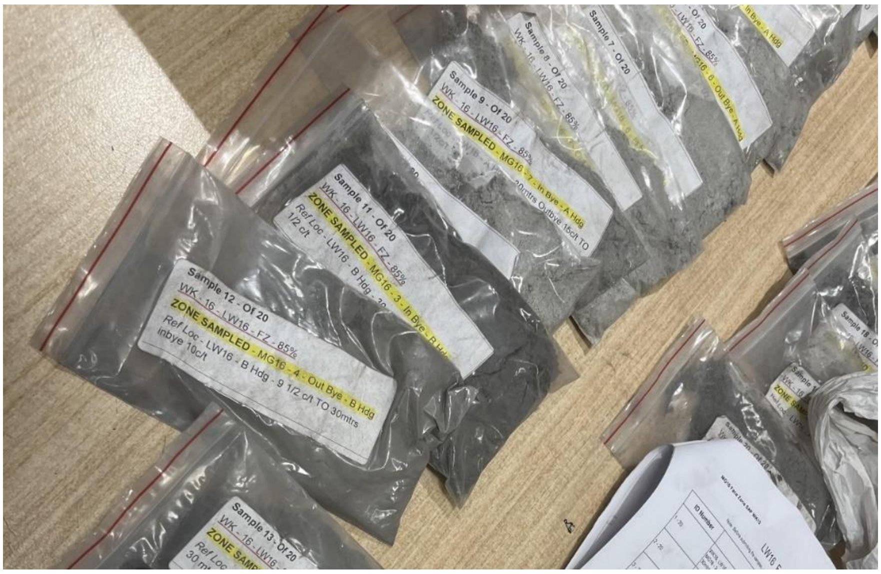


Figure 3-7 Dust Sample Collection Bags

Limitations of Existing System

One major and most evident issue is the uncontrollable sample variation due to the collection method. Despite their training and attempted consistency, collecting a sample of fine dust by hand introduces a higher probability of the sample being too deep or too shallow and, as such, not an accurate representation. This risk is minimised by combining the sample from multiple locations in the same EDZ. However, the subsequent data variation would still be present, which may lead to inaccurate, non-representative and nonrepeatable samples.

Standard research was conducted to find a collection device that may be suitable for stone dust sampling, but there were minimal real-world devices. Of the previous underground dust sampling and monitoring studies and devices found, the current focus on nearly all of them was respirable dust monitoring to prevent human dust inhalation.

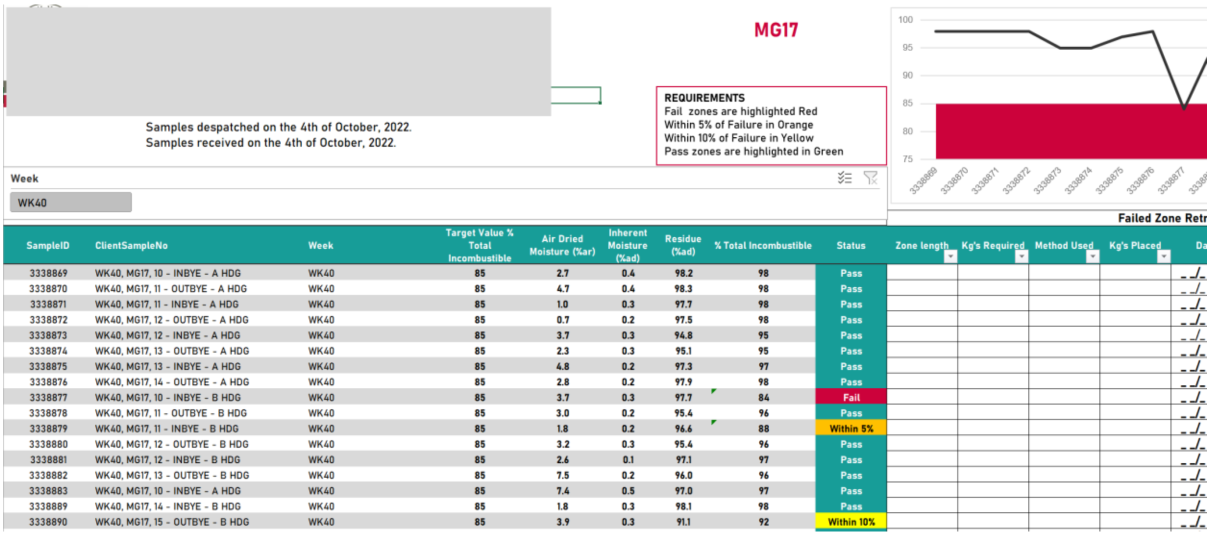
One of the best options was a sample collection working prototype developed in 2015. The sampling device applies a pulse of air to a testing surface and collects a representative sample of mine dust based on the pneumatic entrainment process during a mine explosion, which is supposedly more accurate and objective than conventional sampling [43]. Despite the promising results of the prototype, it appears there has been no commercialisation of the product or regulatory approval, such as from NIOSH.

Subsequent Design Considerations

The primary issue for sample collection is the collection method being by hand and introducing inconsistencies. An evident improvement would be to design and create a simple sample collection device that enables the collection of a sample of the same size from a consistent 5mm depth. Although these inconsistencies will be considered, there are no direct design considerations to encompass this. The design and testing required to create such as device are out of the scope of this thesis, however, it would be an extremely complementary study or commercialised device.

3.1.4 Sample Analysis and Results

Once collected, the samples get sent to an approved laboratory. The laboratory tests each sample to see the proportion of inert dust (stone dust) and coal dust. After approximately three days to analyse the samples, the laboratory emails an excel report that contains the results of all samples taken (Figure 3-8). The results include highlighting whether a sample failed, was within 5% of failure, or 10% of failure. Additionally, a basic graph per sample Area shows the results for that week. If an EDZ has not passed, the mine responds within a set timeframe, which will be explored later in the process.



SampleID	ClientSampleNo	Week	Target Value % Total Incombustible	Air Dried Moisture (%ar)	Inherent Moisture (%ad)	Residue (%ad)	% Total Incombustible	Status	Zone length	Kg's Required	Method Used	Kg's Placed	Da
3338869	WK40, MG17, 10 - INBYE - A HDG	WK40	85	2.7	0.4	98.2	98	Pass					_/_
3338870	WK40, MG17, 11 - OUTBYE - A HDG	WK40	85	4.7	0.4	98.3	98	Pass					_/_
3338871	WK40, MG17, 11 - INBYE - A HDG	WK40	85	1.0	0.3	97.7	98	Pass					_/_
3338872	WK40, MG17, 12 - OUTBYE - A HDG	WK40	85	0.7	0.2	97.5	98	Pass					_/_
3338873	WK40, MG17, 12 - INBYE - A HDG	WK40	85	3.7	0.3	94.8	95	Pass					_/_
3338874	WK40, MG17, 13 - OUTBYE - A HDG	WK40	85	2.3	0.3	95.1	95	Pass					_/_
3338875	WK40, MG17, 13 - INBYE - A HDG	WK40	85	4.8	0.2	97.3	97	Pass					_/_
3338876	WK40, MG17, 14 - OUTBYE - A HDG	WK40	85	2.8	0.2	97.9	98	Pass					_/_
3338877	WK40, MG17, 10 - INBYE - B HDG	WK40	85	3.7	0.3	97.7	84	Fail					_/_
3338878	WK40, MG17, 11 - OUTBYE - B HDG	WK40	85	3.0	0.2	95.4	96	Pass					_/_
3338879	WK40, MG17, 11 - INBYE - B HDG	WK40	85	1.8	0.2	96.6	88	Within 5%					_/_
3338880	WK40, MG17, 12 - OUTBYE - B HDG	WK40	85	3.2	0.3	95.4	96	Pass					_/_
3338881	WK40, MG17, 12 - INBYE - B HDG	WK40	85	2.6	0.1	97.1	97	Pass					_/_
3338882	WK40, MG17, 13 - OUTBYE - B HDG	WK40	85	7.5	0.2	96.0	96	Pass					_/_
3338883	WK40, MG17, 10 - INBYE - A HDG	WK40	85	7.4	0.5	97.0	97	Pass					_/_
3338889	WK40, MG17, 14 - INBYE - B HDG	WK40	85	1.8	0.3	98.1	98	Pass					_/_
3338890	WK40, MG17, 15 - OUTBYE - B HDG	WK40	85	3.9	0.3	91.1	92	Within 10%					_/_

Figure 3-8 Stone Dust Laboratory Result Samples Example

Limitations of Existing System

A primary limitation of sending samples offsite for testing is that it takes a long time to do sample analysis and creates a delay in getting results, which in this case, is three days. This means an EDZ could fail with consequential explosion risk without knowing for several days. In addition to the delay of sending and testing results, there is another slight delay of emailing results, requiring a user to see and read the email.

Limitations of how the results are communicated are that the excel sheet needs to be manually interpreted, it is not integrated with any other data or process, and there is no ongoing trend identification and insight over time. Upon receiving the samples back, there is also no comparison or mark-off to ensure all the samples sent have a matching result.

Subsequent Design Considerations

Similar to collecting the samples, changing the sample analysis method is out of this thesis's scope. As explored in the literature review and research, extremely limited approved and portable coal dust explosibility sample testing devices are available. The approved ones are still unable to produce live data once set up and still require specific sample preparation before testing. Additionally, they appear to work on a pass-or-fail system and do not give exact percentages of coal dust. There is still benefit if one of these is employed however, further research is required to recommend the CDEM for use in Australia, as its current approval is only in the US, where only a limit of 80% stone dust is enforced, and their consideration of how fine coal mine dust commonly varies [22] .

To reduce delays and manual processing consistent with the research mine's current sample testing and result process, the EDRMS will aim to integrate directly with the research mines external laboratory's result data system through an Application Programming Interface (API). The API created will facilitate the data sharing for each sample result.

By integrating this sample data and using consistent naming conventions, the EDRMS can correlate it to create insightful visual interfaces that can readily identify trends and overall performance. A graph can be created that shows Areas and all sub-layers of an EDZ, and their average sample result or failures can be easily compared across different time frames. As a digital twin of the mine map will be created, results can also be viewed on the mine map, such as a heat map of failed results overlaid on the mine map. This will allow users to digest the data to identify any problematic EDZs easily visually. The system can also use the integrated data to optimise key parameters.

3.1.5 Minimum Dust Application Rates

To determine the sufficient amount of stone dust that needs to be applied to a certain EDZ, the research mine utilises the concept of a Production Area (PA), with each having a different and distinct Minimum Dust Application Rate (MDAR). This is the minimum rate at which stone dust should be applied to an EDZ currently within a particular Production Area. A Production Area refers to the location within the mine in relation to the type of, and distance to, mining production occurring. Therefore, the rate should be set so that the combination of the resulting stone dust applied and coal dust produced in that PA would result in a proportional percentage that is satisfactory to the level of risk for that EDZ. Currently, the classed Production Areas of the research mine can be seen in the figure below.

Area	Minimum Application Rate
Development Face	20kg/m Advance (1 tonne/50m advance)
Development Return Longwall Belt Roads Trickle Duster (at Auxiliary Fan)	60kg per shift (at each trickle duster) 60kg per shift (at each trickle duster) Trickle duster rate -6kg per metre advance
Longwall Return	0.75t/shear (3t/4 shears) By combination of maingate and tailgate feeds

Figure 3-9 Minimum Dust Application Rates

Limitations of Existing System

The concept of a Production Area with corresponding MDAR is reasonable as it addresses the notion that the amount of stone dust applied should vary due to the conditions of mining production nearby. However, current PAs and their associated MDAR have been set by a mixture of “rule of thumb” and experience, which, as identified in the regulatory audit, is common across the UCM industry. Although the current PAs are distinct and appropriate for some Areas of the mine, many areas with varying levels of coal dust production exposure should have their own unique PA.

An additional limitation in how the concept is implemented is that, in theory, PA and their corresponding MDAR are set to account for the sampling requirements of an EDZ however, there is no actual relationship established in the current process that connects a PA to a sample category such as Face Zone or Conveyor Road and its associated sample requirements. Therefore, with the current rudimentary and paper-based systems in place, it is extremely difficult to correlate sample results to the PA, meaning it is currently near impossible to measure the actual suitability of the rates to that PA.

Subsequent Design Considerations

Noting that the PAs and their associated MDARs are a fundamental concept, the EDRMS needs to account for having these established as a concept in the system that is capable of changing.

Additionally, as the existing MDARs have little to no measurable suitability, the EDRMS will use the newly integrated data to optimise the MDARs to one that produces optimal sample results and compliance. This will be further explored and detailed in 3.3 Optimising the Application Rate.

3.1.6 Stone Dust Application

Stone dust is applied throughout the mine using various dusting methods, including Pod, Trickle, Silo, Fling, and Airo-Duster. Depending on the PA, the amount applied and method used should adhere to the MDARs (Figure 3-9). Each method distributes the stone dust differently, from the speed, method, and moisture. For example, stone dust poured into a Fling Duster is flung from the duster in an alternating pattern. In contrast, stone dust poured into a Trickle Duster is forced through a hose using air pressure and comes out dispersed from a stationary nozzle within an EDZ.

Figure 3-10 Fling Duster

Figure 3-11 Trickle Duste

Any time that dust is applied, it should be recorded using the paper stone dust application form. With it, the date, zone, amount of dust, shift production, and dust method are recorded (Figure 3-12). If the airo-duster is used, it is recorded using a separate paper form. Once it has been recorded, these paper forms are then stored in a folder.

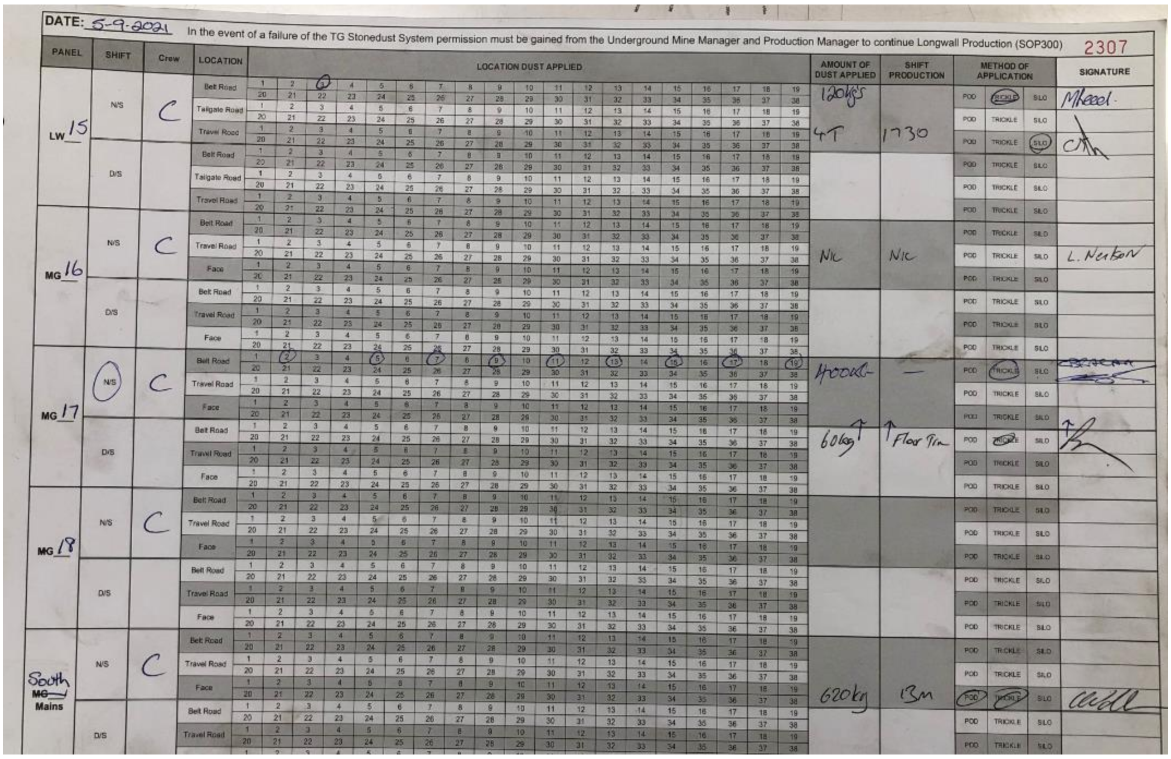


Figure 3-12 Stone Dust Application Paper Form

Limitations of Existing System

Many limitations exist surrounding this part of the process stemming from the records being purely paper-based. As it is a heavily manual process that does not require the direct calculation of the must application rate, there is minimal enforcement if the quantity applied for the shift production is above or below the MDAR. Additionally, there is much inconsistency in how and if all the information is recorded. Due to this, it would be easily possible that insufficient stone dust is applied and not realised, resulting in sample failures and higher risk. Furthermore, being paper-based results in no data integration. Consequently, it would be highly time-consuming and cumbersome to determine or visualise application trends and correlate dust application with sample results. There is also the risk of record loss if the paper form or folder becomes damaged.

There are also many limitations relating to the dust application itself and its variation amongst different methods. This may result in the quantity of dust being applied not being evenly distributed. As such, even if there were equivalent quantities of stone dust applied in different EDZs, one may not have sufficient coverage to a depth of 5mm when the other does. Exploring the dust methods and their relative suitability in depth is not within the scope of this thesis.

Subsequent Design Considerations

The system will allow stone dust application information to be captured as robustly and efficiently as possible. To do this, the EDRMS will establish an interface that easily allows the entry of the same data as captured by the forms and make the users select what Production Area the dust application was within. From this, the dust application rate can be automatically calculated and compared to the MDAR for that PA. This way, failures can be instantly visible to the user once the information is entered. The EDRMS can also use the newly captured data and visually represent it in an easily interpretable form. Additionally, the data can be correlated to sample results and used to determine whether the MDAR for the PA is sufficient, as further detailed in 3.3.

Although users will be able to capture this information on a desktop interface, this would still require the information to be captured on paper underground. Therefore, a mobile application must also be created to allow users to capture the dust application information on a handheld device underground. Another consideration is that underground, there is an unstable WIFI connection. Therefore, the mobile application will need to be able to capture data offline and automatically upload the data when re-connected to the internet.

3.1.7 Responding to Failed EDZ Samples

Another piece of the process is how to respond to an EDZ sample that has returned as Failed, Within 5%, or Within 10%. If a sample has Failed or Within 5% of Failure, then the EDZ must be re-dusted within the timeframes specified in Table 3-1. For example, when the research mine receives the results, if an 85% EDZ has come back as failed, they must re-dust the EDZ within 12 hours.

The quantity of dust re-applied for a failed result is set as the amount required in one application to the EDZ based on its Production Area. Once the re-dusting is completed, a re-dusting report of how much was applied and by what method is recorded and verified Figure 3-13.

ORIGIN BROADMEADOWUNDERGROUND MINE

REFERENCE NO M85035553

DESCRIPTION Underground Roadway Dust

REPORTED TO The Ventilation Officers

REQUIREMENTS Fail zones are highlighted Red
Within 5% of Failure in Orange
Within 10% of Failure in Yellow
Pass zones are highlighted in Green

Samples despatched on the 27th of September, 2015.
Samples received on the 29th of September, 2015

Page 1 of 2

Sample Identification	Target Value % Total Incombustible	Air Dried Moisture (%ar)	Inherent Moisture (%ad)	Residue (%ad)	% Total Incombustible
VK12, MG8-1, MG8, A HDG, PORTAL - FACE	85%	1.1	0.6	87.4	87.6
VK12, MG8-1, MG8, B HDG, PORTAL - FACE	85%	1.6	0.8	75.9	76.5
VK12, MG9-1, A HDG, PORTAL - 4 CT	85%	5.3	1.3	89.1	89.8
VK12, MG9-2, A HDG, 4 - 5½ CT	85%	3.9	0.6	91.7	92.1
VK12, MG9-1, B HDG, PORTAL - 3 CT	85%	2.6	0.6	87.1	87.5
VK12, MG9-12, FZ, MG9 A HDG, LW10 REAR ACCESS RD - 21 CT	85%	3.1	0.9	48.2	50.3
WK12, MG9XB-1, FZ, LW8 X DRIVE, MG8 TRAVEL RD - MID LW8 X DRIVE (BTWN CHUTE 1 & 2)	85%	2.2	2.1	68.6	69.9
VK12, MG9XB-2, FZ, LW8 X DRIVE, MID LW8 X DRIVE (BTWN CHUTE 1 & 2) - MG9 BELT RD	85%	0.8	0.9	81.2	81.5

Failed Zone Retreatment Record			
Re-Treated Date and Time	Amount & Method	ERZC sign.	SSUC sign.
/ / , :	FLINGER 100t		
/ / , :			
/ / , :			
/ / , :			
/ / , :			
/ / , :			
/ / , :			
/ / , :			
/ / , :			
/ / , :			
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/ / , :			

Figure 3-13 Re-dusting Failed Sample Report Example

Limitations of Existing System

The process presents limitations in data capture and visibility. The re-dusting report is yet another separate section of data disconnected from the rest of the process, which carries the same limitations previously explored. Currently, there is limited visibility of the urgency of dust applications. As the required timeframe of re-dusting varies from 12 hours to 7 days, it would be difficult for all users to know how much time to apply the dust remains.

As previously discussed, there is no referrable link between the sample results and PA. Therefore, having the amount of dust required to be applied for re-dusting based on the PA of the EDZ sample would be cumbersome to verify and ensure compliance.

Subsequent Design Considerations

Through laboratory integration, the EDRMS will immediately have access to the data of failed sample results. Using this, the system should contain easily accessible, interpretable, and accurate interfaces to view this critical information. From discussions with the research mine, it is possible to install a large monitor in an easy-to-view location for stakeholders. On this monitor, the EDRMS systems re-dusting interface can be displayed. An easily digestible way for users to interpret this is the failures overlaid on the digital twin map of the mine. Each failure can be a separate pin on the EDZ location of the map, and the pin can be a different colour depending on the time left to re-treat the failed EDZ. These would appear immediately as results are received from the laboratory via the API integration. Below the map, a list view of the failures will show, with each row detailing the EDZ, the failure category, a timer countdown to re-treat, and how much dust is required to be applied. From the list view, the system will allow users to select and capture how much dust was applied directly. This data will then be integrated separately and tracked as re-dusting.

3.1.8 Responding to Failed Dust Application Rates

Currently, due to the stone dust application forms being paper-based, there is minimum visibility of whether a dust application's dust application rate has been sufficient or failed the MDAR. As such, there is no standard response process as it is not readily known. Usually, this will only be known and responded to if the failed MDAR causes a failed sample result, and then the re-dusting process is completed as previously detailed.

Limitations of Existing System

The limitations of not determining whether the dust application rate is below the MDAR have been discussed in the stone dust application.

Subsequent Design Considerations

As discussed, by integrating the previously paper dust application forms, the system can automatically determine if a dust application has failed or passed the MDAR. If the dust application fails, the EDRMS system will treat it the same as a sample failure, and display it on the live digital twin map for instant visibility. As it will be rectified far quicker, the re-dusting quantity required can be the difference between the dust application of the stone dust application failed and the target MDAR.

3.1.9 Summary of Existing Process

A summary of the existing process at the research mine is depicted in Figure 3-14. The MP1100 Mine Sampling Plan is completed by the Survey team and passed to the VO Delegate (Stone Dust Coordinator) to complete the weekly procedure and produce labels. The sample labels will be handed to the SSUG and allocated to the ERZC and approved personnel to take the samples. The VO Delegate will then ensure all the samples have been taken and dispatch them offsite to the Laboratory. The Laboratory will complete the analysis and send the results back to the SSUG, who will work to check the results with the VO delegate for any failed EDZs. If any have failed, the work crews will re-dust the areas within the appropriate time frame. Once this is signed off by the ERZC and SSUG, the VO Delegate will review the other results for any concerns before finishing the process. Note that the figure excludes detail of the stone dust application of EDZ, which is routinely completed by crews and recorded on paper.

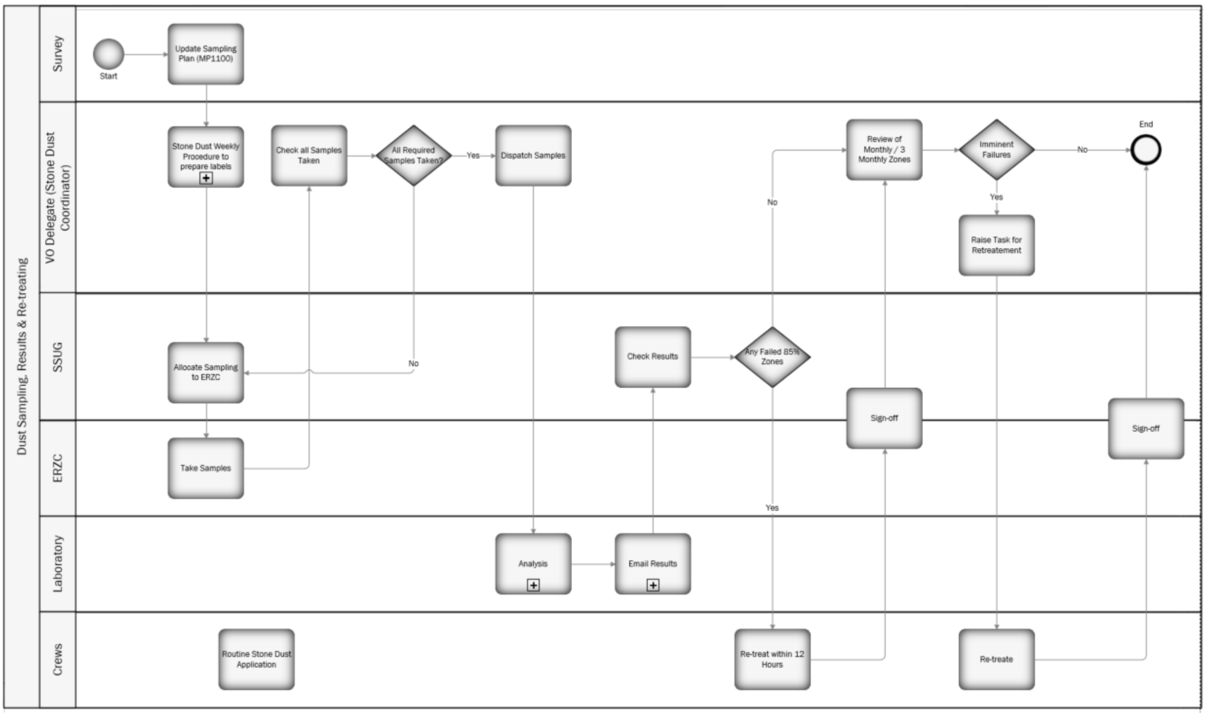


Figure 3-14 Stone Dust Sampling, Results, and Re-treatment Existing Process

3.2 Proposed System Design

After evaluating the issues and limitations of each part of the current process at the research mine, many subsequent design considerations were identified to create a system capable of real-world use. A detailed design is required to capture these considerations to create this system effectively. Wherever possible, the design will encompass the concepts within BI and will strongly consider how it will be compatible with the people, roles, and culture at the research mine.

To aid in workflow and conceptual understanding, the system is broken up into two scopes to be completed more simultaneously:

- Dust Sampling, Analysis, and Re-dusting Failed EDZ
- Stone Dust Application

3.2.1 Initial System Framework

The initial system framework outlines the high-level System Design (SD) requirements that need to be achieved to address the issues and limitations identified in the current process at the research mine.

1. Dust Sampling, Analysis, and Re-treatment

This component of the design will aim to replace, improve, and extend the functionality to address the issues and limitations within:

- Management of Stone Dust Zones
- Preparing Sample Plans and Label
- Sample Analysis and Results
- Responding to Failed EDZ Samples

The following functionality was determined to be required to support the achievement of a more efficient, robust, and proactive process for managing the required dust sampling, analysis and re-dusting practices mentioned above.

1. Enable the ability to establish a modifiable Digital Twin of the Mine.
2. Integrate with the AutoCAD Stone Dust Plan MP1100 (Figure 3-1) to import the EDZs and their associated sampling requirements into the system.
    - This was previously manually interpreted week to week.
3. System Integration with laboratory results.
    - Previously, laboratory results were emailed each week with no appropriate data integration between each.
4. Determine the Next Sampling Date of each EDZ based on the integrated sampling requirements from MP1100 and the integration with the laboratory results.
    - The excel management document previously handled this.
5. Generate the set of PDF Sample Plans that detail all EDZs which must be sampled that week and the requirements of each EDZ.
    - This was previously done by manually changing information within the excel file, and then exporting filtered information into PDFs and word documents.
6. Generate the set of Sample Labels associated with the sampling plans.
7. Create an interface for viewing and exporting historical sampling data.
    - Previously, there was no ability to view and filter through all historical results.
8. Create insightful graphical representations of sampling results.
    - Previously, there was minimal graphical representation.
9. Create a ‘heat map’ overlaid on the digital twin mine plan that visualises each EDZ relative failure frequency.

10. If a sample result comes back as failed or an EDZ requires re-dusting, automatically create an item with live and accurate detail.
    - Failed EDZ re-dusting records were previously paper-based and interpreted from the excel results.

2. Stone Dust Application

This component of the design will aim to replace, improve, and extend the functionality to address the issues and limitations within:

- Minimum Dust Application Rates
- Stone Dust Application
- Responding to Failed Dust Application Rates

This process is cumbersome and results in a limited ability to effectively track the actual stone dust application across the mine and ensure that it meets the minimum required application rates. The following functionality was determined to be required to achieve a more efficient and robust process for managing the required application of stone dust across the mine.

1. Create functionality to capture Stone Dust Application data digitally.
    - Previously, dust applied throughout the mine was recorded on a templated pieced of paper and kept in a binder.
2. Create dust application capturing functionality to be available on a mobile application (for both IOS and Android devices).
3. Extend mobile functionality to be available in the mobile application without being connected to a network and ensure data is synced when reconnected.
4. Create functionality to establish Production Areas with an associated Minimum Dust Application Rate (MDAR).
5. Automatically calculate the application rate of SDAs and highlight if it has met the minimum requirements.
    - Previously there was little accountability around if the SDAs were completed correctly and no comparison of it satisfying the MDAR of the Production Area.

6. Create functionality for re-dusting EDZs that failed from sample results. The associated items will be automatically created from the sampling scope however, this should track the amount & method of re-dusting.
    - Previously this was a form printed out and filled in when failures occurred.
7. Track stone dust application to each EDZ of the mine across time frames with the ability to export data.
    - Previously this was near impossible as all records were paper in a folder.
8. Similarly to failed sample results, automatically create an item if the MDAR has not been met.
    - Previously no set process for responding to MDAR failed as they were not visible.
9. Create a visual interface that graphically represents dust application for each EDZ and their MDAR fails.
    - There was previously no way to view this due to being solely paper-based.
10. Using the digital twin of the mine map, create a live map showing all failed EDZ, both sample and MDAR failures. List these with a timer countdown. It should constantly update.
    - There was previously minimal visibility around failures amongst roles.
11. Using all newly integrated data, create functionality that can display the performance and indicate the suitability of MDAR for each Production Area.
    - Previously, there was no way to audit MDARs in relation to sample failures.
12. Extend the data intelligence surrounding MDARs to determine and suggest an MDAR that will optimise the sample results associated with a Production Area.
    - Previously not possible. Previously within the industry and the research mine, there were no systems to optimise an application rate to specific EDZ conditions.

Summary

Once these requirements are implemented, the different departments' approximate workflow will be more integrated and transparent. An outline of the new and more integrated flow can be seen in the swimlane chart Figure 3-15 below, with each lane representing a different department or role.

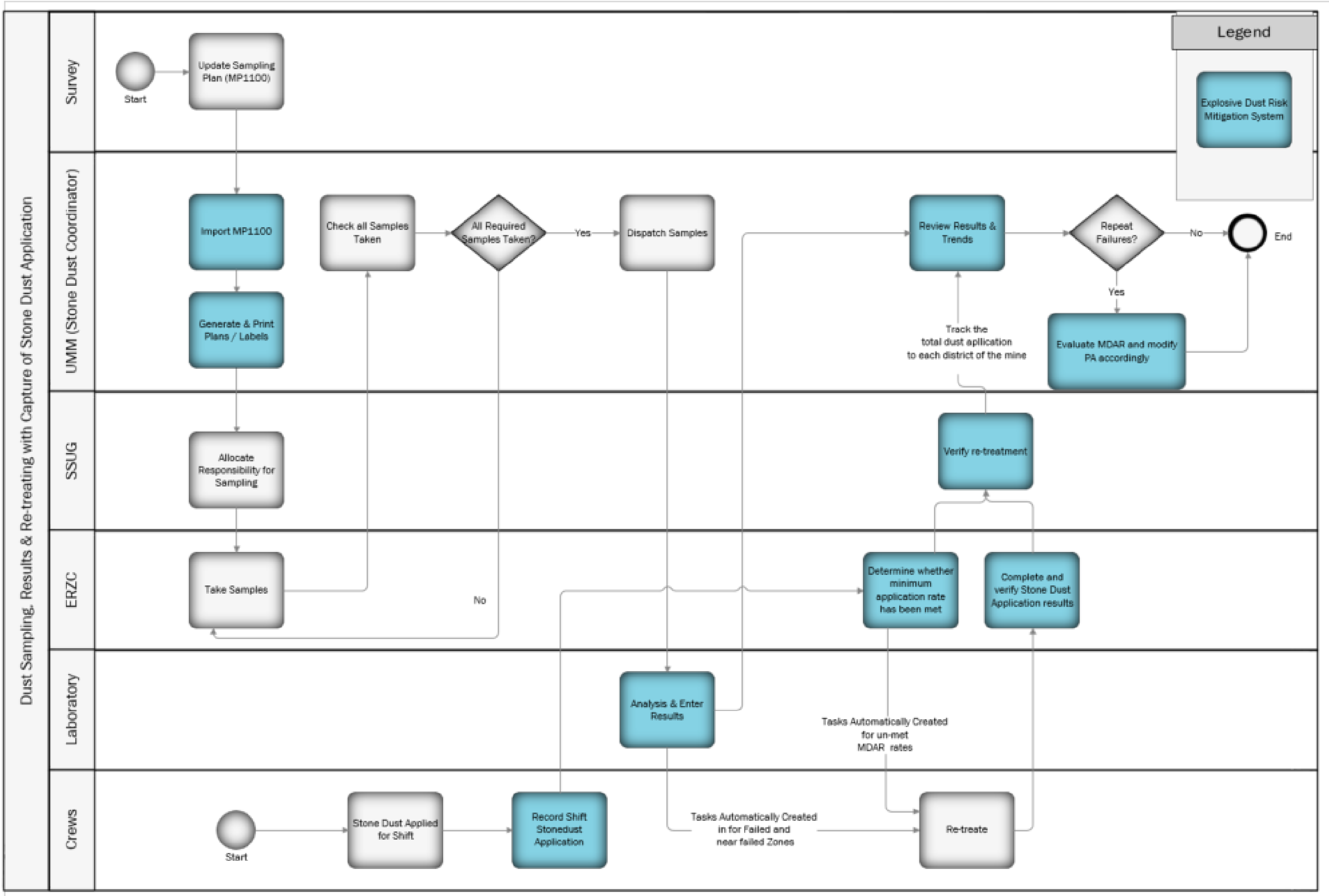


Figure 3-15 New System Design Stone Dust Application & Sampling

3.2.2 Detailed System Requirements for Software Development

To successfully implement as much of the system as possible within the timeframe of this thesis, there will be between 1 and 3 software developers working across these two scopes. A work module was created for each high-level SD requirement in the System Framework. Each work module has prescriptive and detailed design requirements written so that any software developer can develop a component without knowing the detail of the problem and the entire system. Additionally, there will be near-daily communication and feature assessment with each developer to ensure the developed system addresses the issues and limitations each requirement of the system framework is trying to solve.

3.2.3 Required Workflow

To deliver the system incrementally and sequentially, the workflow depicted in Figure 3-16 was determined to be the most effective.

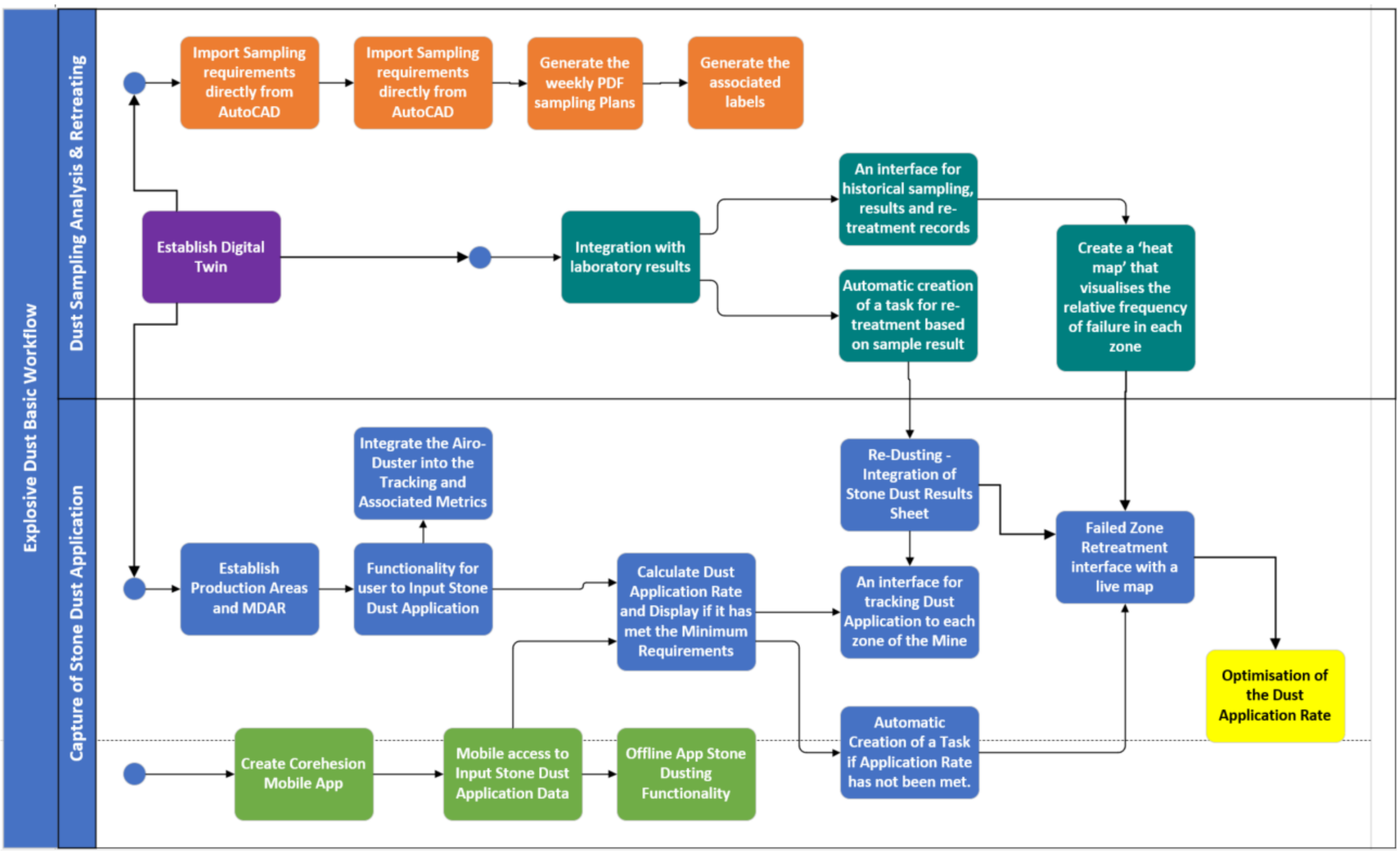


Figure 3-16 Workflow for System Creation

First, a digital twin of the mine must be established. Following this, functionality for the sampling requirements to be imported directly from the MP1100 AutoCAD file is required to generate the weekly sampling plans and labels. Separately, the system needs to integrate with the laboratory sampling results and create an interface for viewing this information. A heat map of these results is also desired as an extra visual aid. Next, with the integration, the system can automatically create a task if an area needs to be re-dusted after a failed result.

Production Areas need to be established as a core component with an associated Minimum Dust Application Rate (MDAR) for the stone dust application. Functionality is required to digitally capture the amount of stone dust applied throughout the mine, which is intended for both desktop and mobile with offline functionality. With PAs established as a central concept with an associated MDAR, the failure of digital dust applications can be determined, and failed tasks automatically created. These and the sample result failures can then be indicated on the failure interface and live map. This will replace the paper re-dusting sheets integrated from sample failures. With all this newly integrated data, an optimal stone dust application rate to mitigate failures and the risk of an explosion will be automatically determined.

3.2.4 Testing Process

Due to the real-world reliance on the system when implemented, once a work module of an SD requirement has been developed, before being released to the live production environment system that users can access, it undergoes an elaborate testing process. Firstly, once functional development is complete, the developer will write Unit Test Cases for the SD requirement piece and release it for technical code review. Then, the piece undergoes Smoke Testing to check its functional flow and ensure it was developed as intended. Following this, the piece undergoes extensive testing by designated Quality Test Analysts. Once it passes all test cases, it is released to the Production Environment, and users can begin using the functionality. Before any other release, the developer will complete automated UI test cases to allow for future regression testing.

3.2.5 Release

Once each feature within the EDM system is ready to be implemented and passed testing, it will be released to an existing online environment that different users from the research mine can access. Certain system features may be limited to some users, which will be managed by permission and role settings.

3.3 Optimising the Application Rate

Even with the new data available and integrated into the EDRMS, most of the optimisation methods researched would still require significantly more accurate and continuous data for acceptable use in a real-world system. Assumptions could be made which would enable experimental models to be created however, that is not within the scope or aim of this thesis. The primary intent is to design a simple optimiser that can be included to provide value in the real-world implementation of this EDRMS.

The method chosen will be a simple version of feedback control, which has no gain multiplier and does not manipulate the error. The simplicity is due to insufficient historical data surrounding the existing process, which is needed to determine an accurate gain multiplier and other advanced feedback control conditions. Furthermore, to account for the greater risk involved with any issue in the real-world implementation, the MDAR will not be continuously forced feedback. Instead, the continuously calculated optimal MDAR will be suggested to the user and rely on them to decide if it is suitable given all the new information presented from the EDRMS.

The system will use the Sample Results as the measured Process Variable (PV) and the Minimum Dust Application Rate (MDAR) of a Production Area (PA) as the manipulated variable that can impact the PV. In the existing process, there was no relationship between Sample Results and PAs and thus, no way to determine the performance of a PA MDAR. The new EDRMS will establish this relationship to determine the Error (E) and implement the feedback.

3.3.1 Measured Process Variable: Sample Analysis Results

The sample analysis results are selected to drive the feedback control because there is a clear Set Point target, referred to as the Compliance Target (CT), for each sample result which ensures the compliance and safety of that EDZ within the mine. Additionally, the results are some of the most accurate data from the entire process and are commonly available as part of risk management for all UCM across Australia.

The sample results are tested through laboratory analysis that must adhere to strict testing procedures, as detailed in the Queensland Regulations and Standards (1.6). They reveal the total incombustible (stone) dust percentage within a sample that has been representatively taken for each EDZ. Although individual data of each condition that contributes to the stone dust content in an EDZ is not accurately available, the total result of the sample can be assumed as the culmination of these conditions. Some of these contributing factors are detailed in Table 3-2.

Table 3-2 Contributing Conditions to the Result of an EDZ Sample

Amount of Float Coal Dust Generated from Mining Activities
Air Velocity of the Coal Face
Ventilating Air Velocities between Mining Face/s and EDZ
EDZ Distance from Coal Face
The density of Coal Float Dust Generated

The rate that Coal Dust Particles Subside on the Surface
The density of Stone Dust Applied
The Quantity of Stone Dust Applied
The uniformity that Stone Dust Spread Across the Surface
The frequency that Stone Dust is Applied
Dust Equipment Performance
Width of Roadway of EDZ that Stone Dust is Applied
Height of Roadway of EDZ that Stone Dust is Applied
The depth a Sample is Taken
Vehicle and Personnel Disturbance on the Roadway Surface

As seen from the table above, many conditions impact the amount of stone and coal dust on an Explosive Dust Zone (EDZ) surface. Many of the conditions above would greatly vary between each EDZ, such as the distance from the coal face, ventilating air velocities, rate of subsiding coal particles, surface disturbance, and others. Of all the conditions listed above, there is limited or no accurate, usable data available from the existing system and mining activities. As previously discussed, research can suggest snapshot parameters for some of the conditions of EDZs at particular mines however, research also reveals that the parameters vary significantly between UCMs. For instance, depending on the UCM mining equipment attachments and dust-wetting methods, the amount of float coal dust generated can vary above 80% and impact the density of the coal dust generated [19]. Additionally, the ventilation rates and physical layout of each mine vary greatly, which dramatically impacts the amount of coal dust that subsides on the surface of each EDZ. Therefore, a system that is designed based on the research conditions of a specific mine without live and accurate feedback is not robust when used for other mines or changing conditions.

As mentioned, even within the same mine, the contributing conditions to a sample result vary greatly from EDZ to EDZ. The other complexity is that even for a singular EDZ, the contributing conditions will vary significantly over time due to mining activities advancing, physical EDZs being sealed off, and ventilation changing to suit this. This change in operating conditions results in the Compliance Target (i.e. set point) for an EDZ also commonly changing over time. Therefore, each EDZ cannot be the relational comparison for the sample result, and a more adaptable concept must be used.

3.3.2 Manipulated Variable: PA Minimum Dust Application Rate

Of the variables listed in Table 3-2 above, the primary variable which can be tracked and manipulated to drive the sample result toward the CT is the amount of stone dust applied to an EDZ. However, due to the changing conditions, even within a singular EDZ, the optimal amount of stone dust applied within that EDZ to reach the CT should also change over time.

Thus, the system must establish and optimise the relationship between the EDZ operating conditions at any point in time and the amount of stone dust that should be applied due to those operating conditions. To do this, the EDRMS will build upon an existing concept within the research mine, the Minimum Dust Application Rate (MDAR) of a Production Area (PA). The MDAR is the minimum rate at which stone dust must be applied to an EDZ currently within a particular PA. A PA refers to an area within the mine in relation to the type of, and distance to, mining production. Currently, the classed Production Areas of the research mine are seen in the Table 3-3 below.

Table 3-3 Production Areas

Production Area (PA)	***MDAR (KG)***	***Comparison Unit (CU)***	***Details***
Development Face	20	Metre Mined	Metre advanced by mining new tunnel roadways using continuous mining machine.
Development Return	60	Shift	The return roadway near the development face
Longwall Belt Roads	60	Shift	The belt roads along the Longwall
Development Face Auxiliary Fan	6	Metre Mined	The duster located at the previous cut-through of the development face
Longwall Return	750	Shear Mined	The return roadways adjacent to the operating longwall miner machine.
Mains Airo-Duster	20	Metre Travelled	The Airo-Duster used along the existing Mains Roadways
Additional EDRMS Suggested Production Areas			
Mains Intake	20	Metre Travelled	The existing Mains Travel (Intake) Roadways, previously covered by the Airo-Duster

Mains Return	20	Metre Travelled	The existing Mains Return Roadways, previously covered by the Airo-Duster
Mains Belt Road	20	Metre Travelled	The existing Mains Belt Roadways, previously covered by the Airo-Duster

The existing concept of Production Areas having a different and distinct MDAR is reasonable as it addresses the notion that the amount of stone dust applied should vary due to the conditions of mining production nearby. However, current production areas and their associated MDAR have been set by a mixture of "rule of thumb" and experience, which, as identified in the regulatory audit, is common across the UCM industry. Although these rates may change, with the current rudimentary and paper-based systems in place, it is complicated to correlate sample results to the production area, meaning that it is currently near impossible to measure the actual suitability of the MDARs to that PA.

Although PAs are an existing general concept, the current PAs of the research mine are not specific enough. For the best optimiser performance, the PAs used should correspond to particular mining conditions as accurately as possible. The designed system will allow new and more suitable PAs with MDAR to be created by the users as new information is gathered and learnt from the new EDRMS.

An example of insufficient PAs is that the research mine currently uses an Airo-duster for all the existing Mains roadways and sets the MDAR for the Airo-duster equipment at 20 kg/m. Rather than having a classified PA for each roadway category, they apply the Airo-duster and its MDAR to all these roadways (A, B, C, D, & E HDG). Although it follows a similar concept, it is inconsistent as the MDAR links to a dust application method, not the PA. Inconsistencies in processes and management like this are common in managing UCM explosions, further highlighting the need for a standardised system. To standardise this, the Mains can be created as a Production Area with a MDAR of 20 kg/m, and the Airo-duster is simply the dusting method chosen for it.

Although the above is an improvement, the Mains roadways (Figure 3-17) contain intake roads, return roads, and belt roads, with each having different levels of exposure to the conditions that contribute to coal dust content. This variation is recognised by the sampling requirements however, it is not translated into the MDAR applied. As seen in Figure 3-17, the intake roads, A HDG and B HDG are green, and the return roads, C, D, E and F HDG, are blue. As mentioned earlier in this thesis, the colours correspond to the sampling requirements, which correspond to the mining conditions in those EDZs. The green roadways require 70% stone dust content, whereas the blue roadways require 80% to account for the difference in mining activity exposure. Therefore, having just one PA encompass all the Mains is still not specific enough because the 70% travel roadways should not require the same amount of dust (reflected by the MDAR) as the 80% return roadways. Additionally, although the belt road (E HDG) is also 80%, its exposure likely varies from the return roadways. Therefore, it is suggested there should be at least one PA for each as recognised by the “Additional EDRMS Suggested Production Areas” in Table 3-3 above.

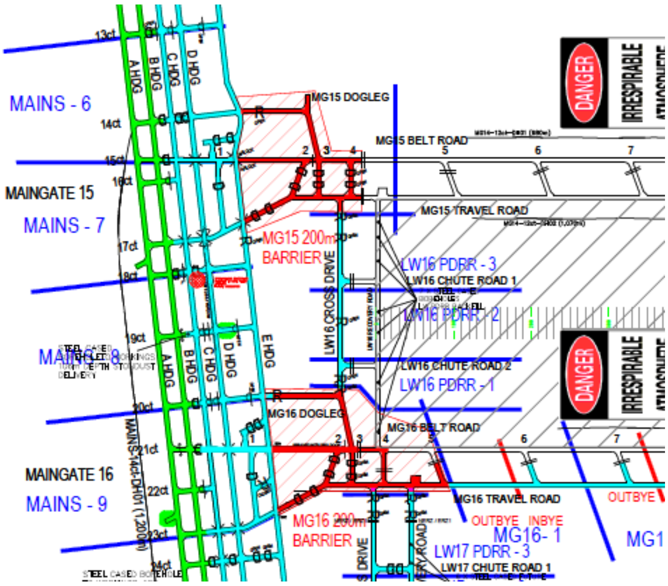


Figure 3-17 Classifying Mains Production Areas

Calculating Minimum Application Rates

In the current system, if the application rate of a stone dust application were desired, it would have to be manually calculated based on the paper records. It was not the standard to do this routinely when capturing the information, and thus, it is rarely confirmed if the MDARs are met. The new EDRMS digitally capturing the data will allow the application rate to be automatically calculated based on the inputs of the stone dust application and compared to the associated PAs MDAR to determine compliance.

Where Comparison Unit (Metres, Shears, or Shift) = CU, Stone Dust Applied (KG) = SDA, Minimum Dust Application Rate (KG) = MDAR, Shift Production (quantity) = SP, Number of Zones Applied = #ZA, the following can be used to determine compliance.

3-2 Equations to Determine Dust Application Failure

$$If\ CU = Metres, \qquad Pass = \frac{SDA}{SP\ (metres)} \geq MDR$$

$$If\ CU = Shears, \qquad Pass = \frac{SDA}{SP(shears)} \geq MDR$$

$$If\ CU = Shift, \qquad Pass = \frac{SDA}{\#ZA} \geq MDR$$

Note that the MDAR can be different for each Production Area, even if they have the same CU.

3.3.3 Creating a Relationship Between Measured PV and Manipulated Variable

Previously there was no clear relationship between an EDZ sample result and the Production Area associated it with for a given sample week. There was only a relationship between a sample result and that EDZ sampling requirement (e.g. 70%, 80%, 85%). In the designed system, a Stone Dust Application (SDA) record will be digitally captured and linked to a PA, an EDZ, and the date applied. Using this integrated information, for each EDZ sample result, it is possible to check all the SDAs to the same EDZ for the week before the sample is taken. Then, by checking the associated PA for those SDAs, a clear relationship can be established between a sample result and a Production Area.

The flow of this can be seen in Figure 3-18. For Week T, Sample Results 1, 2 and 3 relate to Stone Dust Applications 1,2,4 and 6 through their respective matching EDZs. These SDAs are associated with PA Y, making it possible to create relationships between results 1, 2, 3 and PA Y.

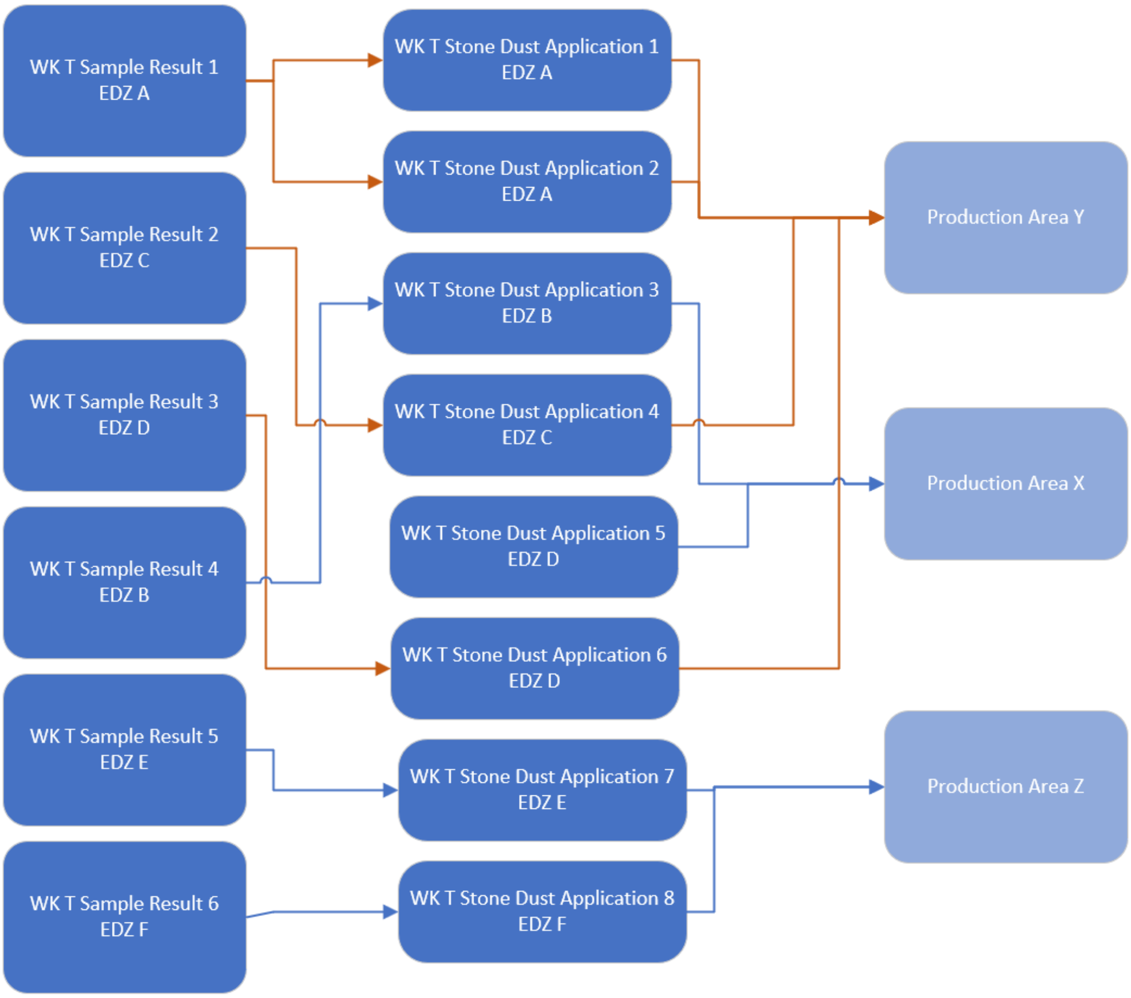


Figure 3-18 Creating a Relationship Between Sample Results and a Production Area

This relationship is critical because the amount of stone dust applied is dependent on the PA MDAR, and if the now-associated sample results are different to the expected Compliance Target, it is indicative that the MDAR should be adjusted, which in turn should change the CT.

3.3.4 Determining the Error

With a relationship created between the Production Area and the sample Results (R), it is now possible to calculate the Error (E) between each PAs sample result and the Compliance Target. As previously detailed, there are three categories for the minimum percentage content of incombustible dust required for EDZs throughout the mine, 70%, 80%, and 85%. When sample results are received, they are classified into Failed, Within 5%, Within 10%, and Compliant. The relevant parameters for each are presented in Table 3-4.

Table 3-4 Sample Result Status

Sample Category (%)	***Failed***	***Within 5 %***	***Within 10 %***	***Compliant***
70	R < 70.00	70.00 <= R < 73.50	73.50 <= R < 77.00	R >= 77.00
80	R < 80.00	80.00 <= R < 84.00	84.00 <= R < 88.00	R >= 88.00
85	R < 85.00	85.00 <= R < 89.25	89.25 <= R < 93.50	R >= 93.50

The proportional percentage difference between the Result (R) and the CT will be calculated to measure the error of each singular sample result, referred to as Result Error (RE). The proportional percentage difference is:

3-3 Result Error Deviation from Compliance Target

$$RE\ (\%) = \left(\frac{CT}{R} - 1\right) * 100$$

For example, if the weekly result for a particular EDZ was 79% and the CT was 88%, the RE would be 11.39%.

Each week the RE will be automatically calculated for each EDZ sample result received, which is usually around 50 – 100 at the research mine. Grouping these results based on their associated PA will allow the PAs average deviation from the CT for that week to be calculated as below.

3-4 PA Week Average Deviation from Compliance Target

$$(PA)Week_T\ E\ (\%) = \frac{RE_1 + RE_2 + RE_3 + \cdots .RE_x}{x}$$

In line with feedback control, the system will intend to make this error as close to zero as possible by manipulating the MDAR of the PA. Hence, it is expected that a single PA will have multiple MDARs implemented over time until the optimal rate that produces adequate sample results is determined. To account for this, the system will maintain the rolling average deviation from CT of sample results from week to week of a PA while the same MDAR is in place. This will be done by simply calculating the average of all the weekly errors since an MDAR is implemented.

3-5 MDAR,PA Rolling Average Deviation from Compliance Target

$$(MDAR, PA)\ E\ (\%) = \frac{Wk_T + Wk_{T+1} + Wk_{T+2} + \cdots .Wk_x}{\#Wk}$$

The overall flow of calculating this rolling average across multiple weeks is presented in Figure 3-19. Assume the current MDAR for Production Area Y was implemented in Week T. Each week, the deviation from the compliance target is calculated (Equation 3-3) for each related sample result. From these, the PAs week average deviation from the compliance target is calculated (Equation 3-4). Finally, for all weeks the MDAR of the PA has been implemented, the rolling average deviation from the compliance target is calculated (Equation 3-5).

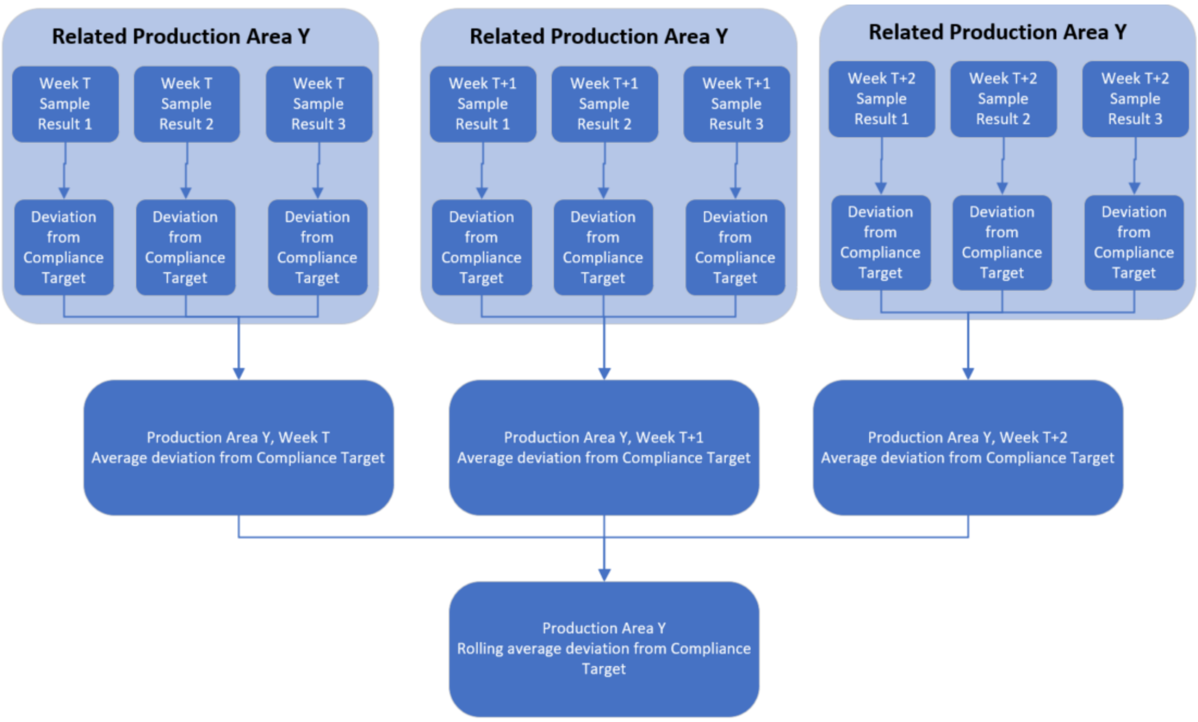


Figure 3-19 Calculating a Production Area MDAR Error

The rolling average deviation from the compliance target of a PA MDAR will be considered the Process Variable (PV) used to determine the feedback control Error. The Set Point (SP) will be 0% deviation from the compliance target.

3-6 Feedback Control Error

$$Error = Set\ Point\ (SP) - Process\ Variable\ (PV)$$

This means if, on average, the sample results are below the compliance target, resulting in a positive percentage PV, the Error calculated will be the negative value of the PV. If the sample results are above the compliance target, the Error calculated will be the positive value of the PV.

3.3.5 Implementing Feedback

As previously discussed, due to the lack of usable historical data, the controller process of the feedback control loop will be basic and not contain a gain multiplier or other advanced functions. To determine the suggested optimal MDAR of a PA, the Error will be multiplied by a negative before being summated with one and multiplied by the existing MDAR.

3-7 Suggested Optimal MDAR

$$Suggested\ MDAR = (MDAR, PA) * [(-)MDAR, PA(E) + 1]$$

For example, consider that the MDAR of the Development Face PA has been 20 kg/m for the past four weeks. For this time, the rolling average deviation from the compliance target of the associated samples is 12.5% (showing the stone dust content is less than required). The suggested MDAR would be:

$$Error = 0 - 0.125 = -0.125$$

$$Suggested\ MDAR = (20) * [(-) - 0.125 + 1] = 22.5\ \text{kg/m}$$

Despite the relationship between the PV and MDAR being not directly proportional, proportionally increasing or decreasing the MDAR and subsequent stone dust applied will still have some correlated impact on the stone dust content of EDZ sample results and, in turn, the PV. As long as the suggested MDARs continue to be implemented, the negative feedback loop should result in a rate that causes the sample result to plateau around the compliance target. It is expected that this will not be perfect, and thus, a 2% buffer will be set to either side of the Compliance Target. Any MDARs that produce sample results of average deviations within this 2% buffer will be considered optimal.

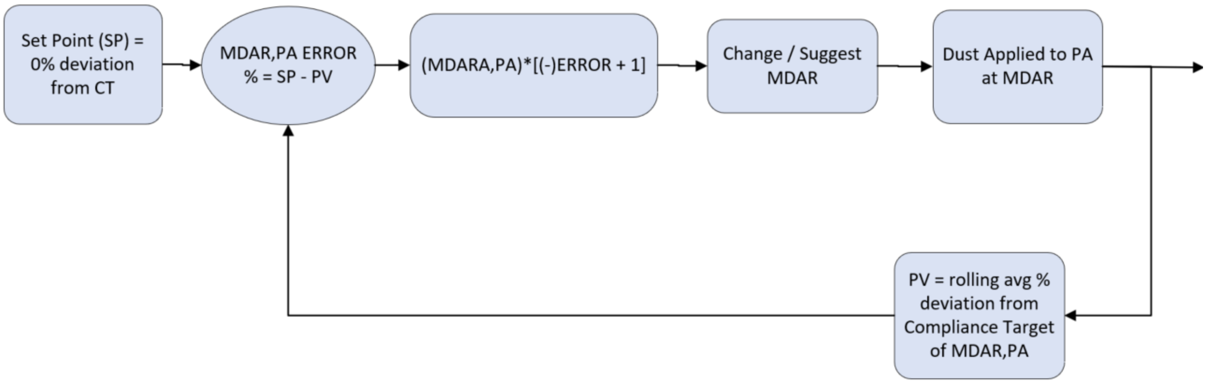


Figure 3-20 EDRMS Feedback Control

3.3.6 Limitations

The focus of the EDRMS design is to be the initial foundational system that enables reliable data capture and integration across the UCM explosion management process. As such, there are notably some limitations to how the optimiser can be designed without yet having access to the data. As previously discussed, the feedback system may take longer to reach the optimal MDAR without the gain multiplier however, it is still more desirable than the potential consequence of an incorrect gain multiplier. Following the results of the EDRMS implementation and gathering accurate historical data, it may be possible to determine an optimal gain multiplier. However, this will not be covered in this thesis.

Additional limitations and conditions discussed are:

- The optimised rate will only be suggested in real-world implementation due to the liability of the risk.
- The feedback from the results is not continuous because sample results are only received once per week for an EDZ.
- Although the result of a sample will be accurate for the sample taken, there is still the risk of outlier data due to unrepresentative samples.
- The system assumes that dust will be applied at the MDAR at a consistent frequency and has no check to ensure this and vary the expected sample results dependent on it.
- Due to human data entry of stone dust application, there is the risk of worker crew adherence of dust application (i.e. workers applying how much they record),
- There is no consideration of how well the stone dust-applying equipment performs (i.e. how much of the dust put through the equipment is wasted or not uniformly distributed), which could vary across different dust methods.
- There is no account for roadway surface disturbance caused by personnel and vehicles.

Accounting for all of these conditions is not feasible within the scope of this thesis however, once an EDRMS is established, their impact can be better determined. Although many of the conditions above affect the results, by averaging the sampling results and correlating the relationship over time, the suggested MDAR from the feedback control should encompass all these conditions and uniquely adapt to each mine.

4 System Implementation and Results

This chapter presents the implementation of the new UCM Explosive Dust Risk Mitigation System (EDRMS) and evaluates its performance. First, it will outline the functionality of each component of the implemented system, as created from the Methodology. It will then evaluate the performance of the components of the implemented system against the existing system and identity if any limitations still exist. Based on this evaluation, future considerations for the components will be explored along with what could be done to standardise the system for use at other mines. Finally, the current usage of the implemented system will be detailed with any further discussion surrounding the component. Additionally, the chapter will evaluate the overall EDRMS system for its utilisation of Business Intelligence concepts and how it addresses the Queensland regulatory audit findings.

This chapter will support the following thesis objectives:

- Develop and implement the designed system into the research mine for real-world use.
- Evaluate the performance of the system and its capabilities for managing UCM explosion risk at other mine sites and how it addresses the Queensland regulatory audit findings. Note the original system design objectives:
    a. Automating steps in the procedures to reduce manual processing and minimise human error.
    b. Providing a readily accessible source of data relating to stone dust application and sample analysis.
    c. Enabling a proactive approach to the planning and management of explosion risk mitigation.

4.1 Management of EDZ and Requirements: Digital Twin

This component involves the following System Design (SD) requirements:

SD1.1 Enable the ability to establish a modifiable Digital Twin of the Mine.

SD1.2 Integrate with the AutoCAD Stone Dust Plan MP1100 (Figure 3-1) to import the EDZs and their associated sampling requirements into the system.

4.1.1 Component Functionality

The system's foundation is the creation of a digital twin, a digital re-creation of the mine that enables critical information and data to be associated with an exact physical location. In its current implementation, this feature integrates directly with the AutoCAD map of the mine that users can easily interpret. The users can upload both a base mine map (MP001) which contains the layout of the mine, and then upload the explosive dust mine plan (MP1100), which contains additonal design and data relevant to the EDZs.

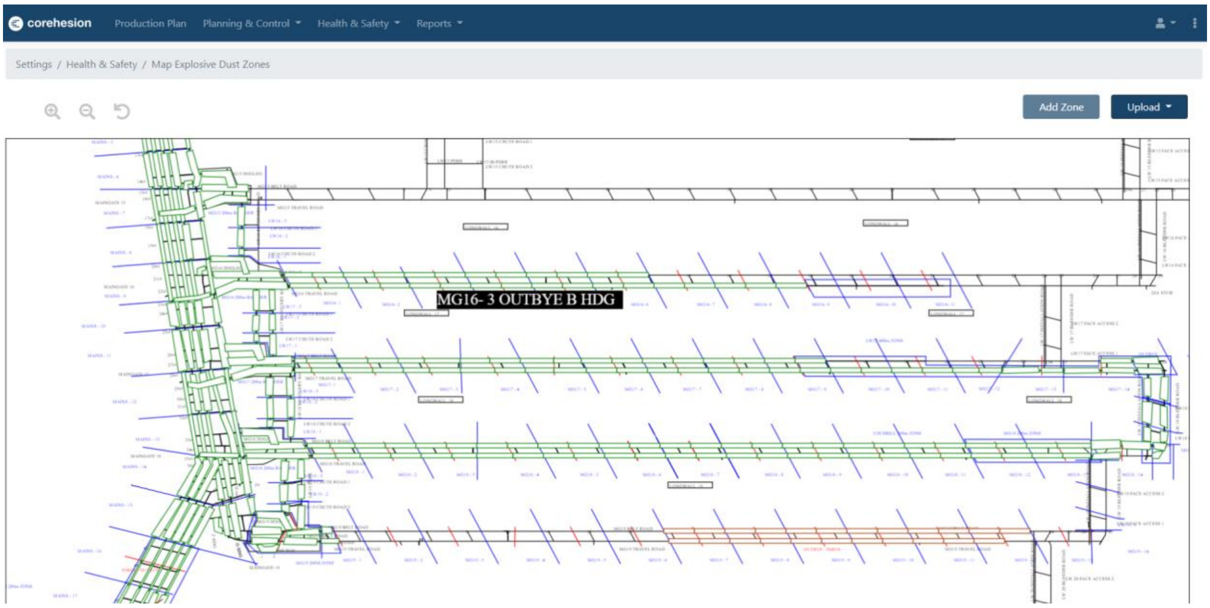


Figure 4-1 Digital Twin Creation of Mine

To define the location of an EDZ on the digital twin, a polygon must be created over each EDZ. The majority of these are automatically created upon uploading. To create or change any EDZ polygons, the user can place where each vertice should be around the outline of an EDZ Figure 4-2. They can then allocate the created polygon area to the corresponding EDZ from a list created using consistent naming conventions Figure 4-3.

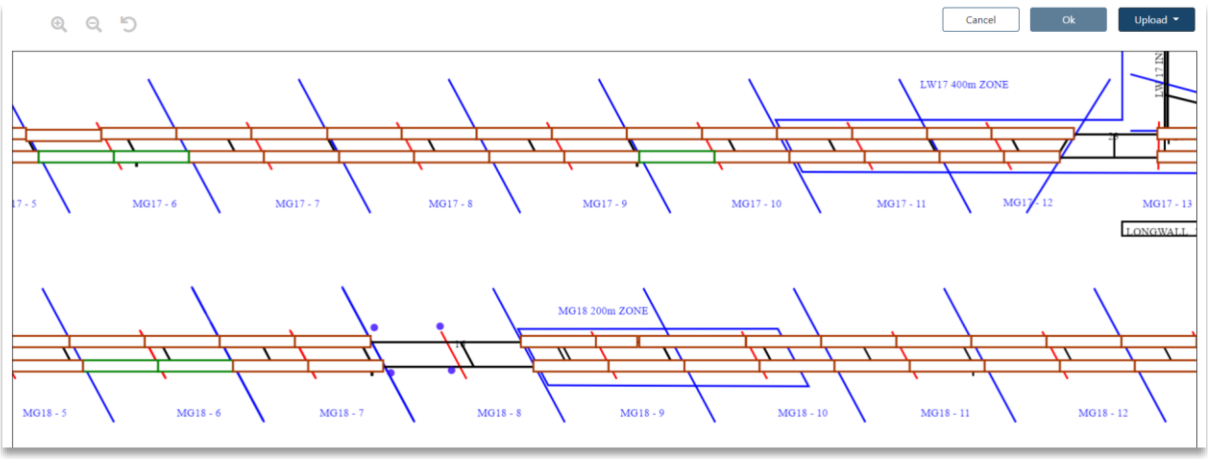


Figure 4-2 Creating a New EDZ

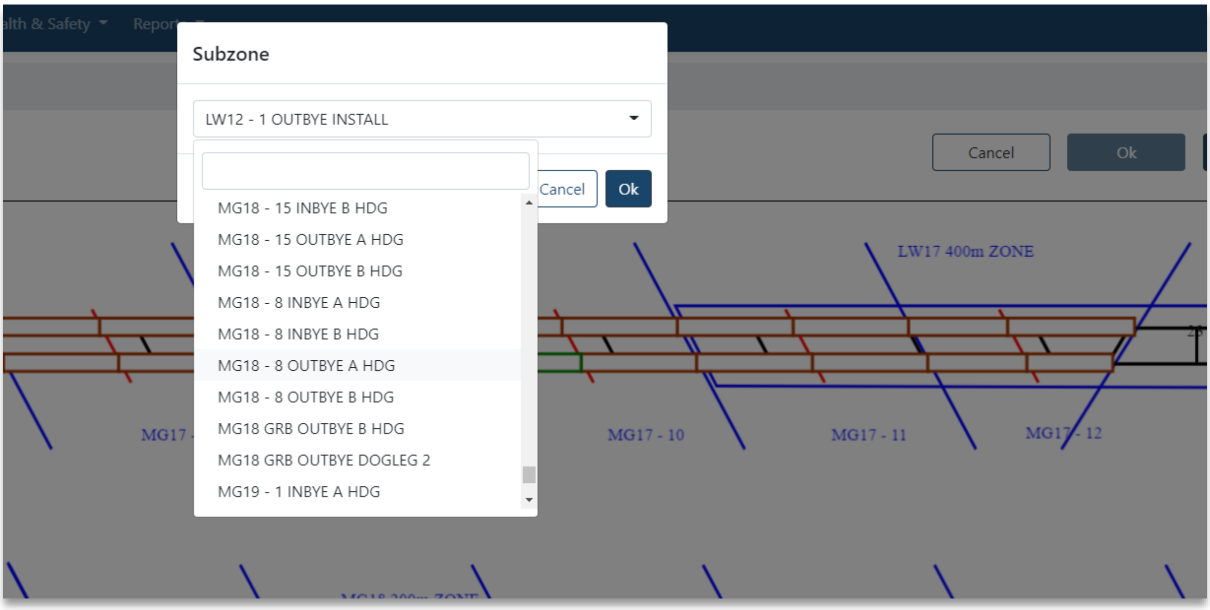


Figure 4-3 Naming a New EDZ

Once a polygon is created and associated with an EDZ, other information can easily be associated directly with that zone. This includes stone dust sampling and application data such as sample frequency, minimum stone dust content, sampling methods, production areas, failure response time frames, and any other valuable data. This enables historical tracking with comparative analytical abilities that can aid in pattern visibility.

After the EDZ digital twin has been accurately set up and the survey team has approved that the MP1100 file is sufficient for the sampling required for that week, a user will also upload the file on a separate interface. When uploading, the system will check the layer colour of the line that travels through the polygons for each EDZ defined on the digital twin. Then, it will link the associated sampling requirements of that colour to that EDZ for the current week.

Next, the system determines all the sampling requirements by comparing the current associated requirements with the previous sampling date, which the system identifies by integrating with the laboratory results. As detailed in Table 3-1, pink is weekly, blue and red are monthly, and green is three-monthly. For example, suppose the colour of the line within an EDZ has been updated from green to blue, and its last sample date was more than three weeks ago. In that case, it will determine the next sampling date to be the current week, and then once the laboratory result has returned, the following sampling date will update to the Monday four weeks' from the last sample date.

Additionally, the interface will display a list of all the EDZs that had their colour and associated sampling requirements updated in that sampling week (Figure 4-4)

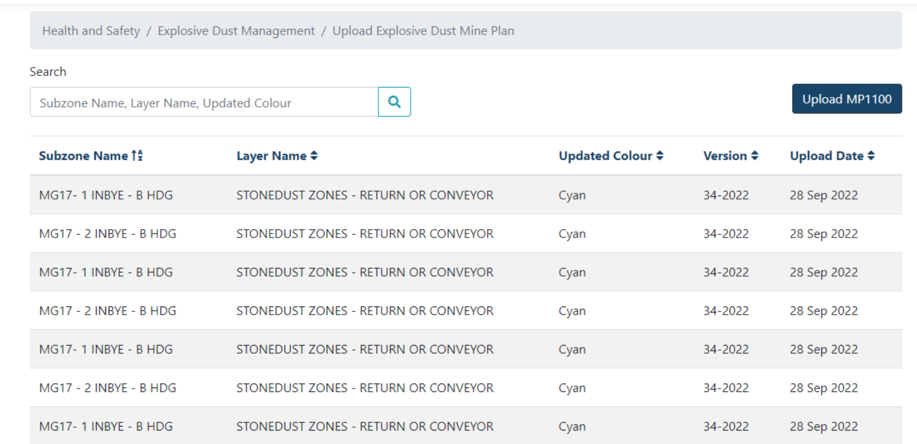


Figure 4-4 Determining Sampling Requirements

4.1.2 Evaluation Against System Objectives

Comparison with Existing System

The EDRMS component detailed above has replaced the need to translate the information read manually from the AutoCAD file into sample requirements. Instead of a user manually interpreting the AutoCAD file and its colours to input into an excel, they can simply upload the file into the EDRMS. This aids in addressing the objectives of automating steps (a) and providing an accessible source of data (b). This will save the user time and eliminate the risk of manually mistranslating the information. It has also not just been a digital recreation of the same process but has improved it to be more visually enriching and compatible with other functionality.

Limitations

Although this is a significant improvement to the existing process, it still has some limitations. Manual work is still involved with the Stone Dust Coordinator creating and managing the polygons on the digital twin associated with the EDZ. Despite being less time intensive for them than previously, there still exists a duplication of work, with the Survey team still managing and maintaining the sampling requirements in the AutoCAD file. Additionally, extracting detailed information from the AutoCAD file may take the system 5 to 10 minutes.

Future Considerations and Standardisation

Despite creating a slight duplication of work, the design choice to integrate with the AutoCAD file rather than creating functionality for the Survey team to mange all of the sampling requirements within the digital twin was intentional. As mentioned previously, research suggested much of the mining industries' hesitation to change and BI systems was due to them not being implemented incrementally with sufficient consultation. Therefore, it was decided it would be best to leave this responsibility and process with the Survey team until the remainder of the system has been successfully implemented and accepted.

For standardisation, it needs to be considered that not all mines manage their maps and EDZ using AutoCAD. Therefore, as the base for the digital twin, the system would need to allow the upload of an image, PDF, or be capable of converting other files to a standard type. The functionality to create polygons layered on the map would remain. Following this, to replace the management of EDZ in AutoCAD, new functionality needs to be implemented so users can allocate an EDZ polygon to either a Face Zone, Conveyor Road, Return Road, Gateroad Barrier, or Intake Road. This type would be associated with the sampling requirements detailed in Table 3-1. There would be minimal additional development to make this modification.

In the current implementation, the defining polygons created for which information can be associated are explosive dust zones that directly relate to managing the risk of UCM explosions. For standardisation to also manage other risks and hazards, modifications could be done to allow different layers of polygons upon the same base map of the digital twin. This way, the defining polygons created may be other recognisable locations of different types that can be associated with other risks. Then a standardised hazard concept could be created that integrated with the digital twin to capture hazards against different locations on the map.

Usage and Further Discussion

This was the first part of the EDRMS developed, and it has been successfully implemented for use at the research mine. There were issues initially faced with the system not recognising all possible EDZs due to some discrepancies within the AutoCAD file however, these have been rectified. Additionally, the system could not determine all of the sampling requirements as this component was implemented before the integration with the laboratory results, which is needed to know the last sampling date of the EDZ. To temporarily overcome this, laboratory sample results are directly uploaded into the system database, which will continue until the integration is completed.

Overall, initial user acceptance has been positive and enabled the Stone Dust Coordinator to already identify some gaps and inconsistencies in their existing excel management file

4.2 Sample Planning

This component involves the following System Design (SD) requirements:

SD1.5 Generate the set of PDF Sample Plans that detail all EDZs which must be sampled that week and the requirements of each EDZ.

SD1.6 Generate the set of Sample Labels associated with the sampling plans.

4.2.1 Component Functionality

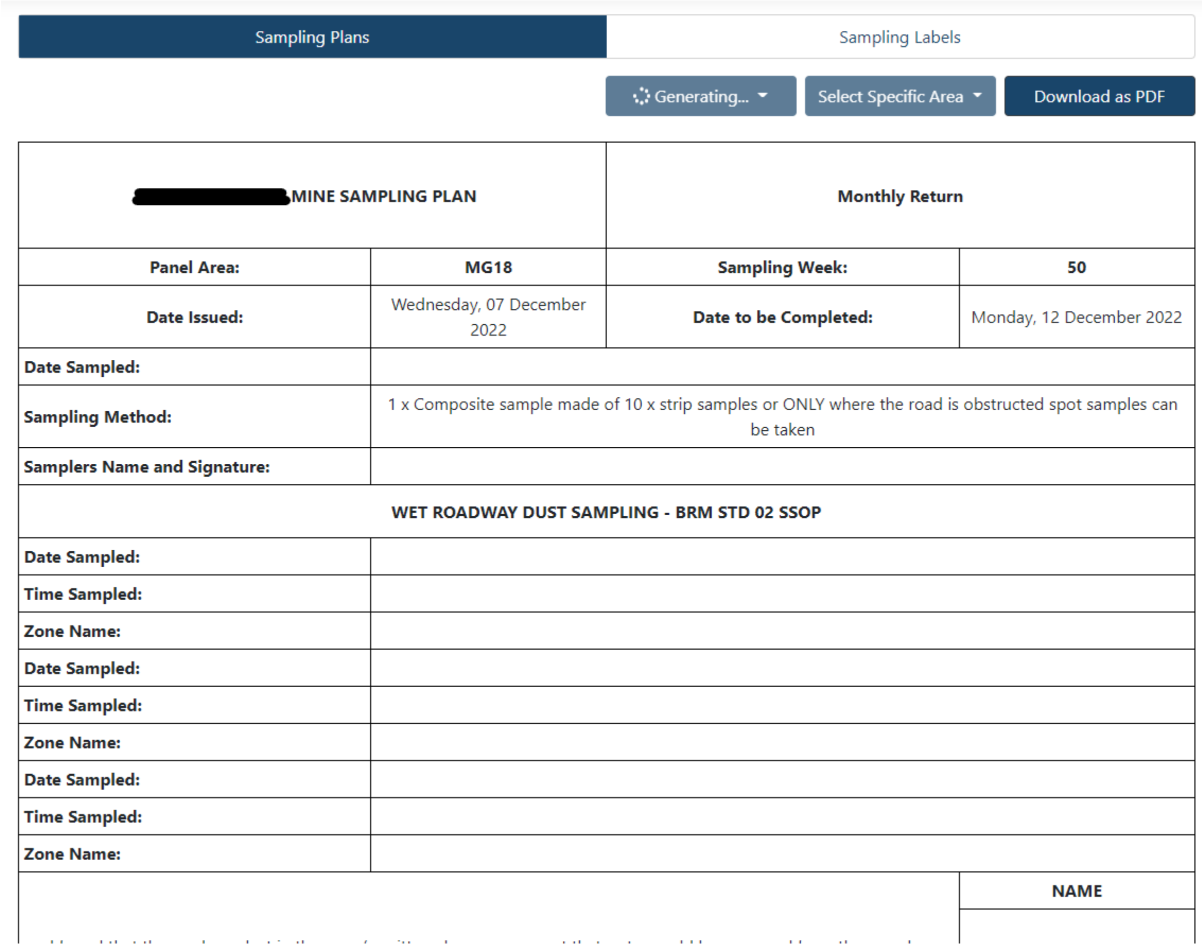
With the EDZ and their associated sampling requirements now integrated into the EDZ, weekly sampling plans and labels for each EDZ can be produced at the push of a button. As previously detailed, by integrating directly with the laboratory results, the system knows when the previous sampling date of each zone was. Based on this and the frequency of sampling required for that EDZ, the system can determine the next sampling date. This interface has two tabs, one for exporting the Sample Plans and one for exporting the Sample Labels.

Despite the intention of the sample plans to be exported as a PDF with blank fields, in anticipation of their future digitalisation, they can also be filled out and completed digitally before exporting. The plans are separated into their overarching Area and grouped into three categories, those that require weekly sampling (85% EDZs), those that require monthly sampling (80% EDZs) and those that require three-monthly sampling (70% EDZs). A user can select what category of plans they would like to generate and then select to download as PDF.

Page 1 of each Panel Area plan is an overview information sheet that details the category, the Panel Area, the date, the sampling method, and allows the users to record information about any wet roadway dust sampling.

Page 2 includes a basic image of the Panel Area of the map to offer visual location guidance when collecting samples. As the use of the digital twin improves, so can the visual representation of the map.

Page 3 is a sample checklist sheet that lists all the samples which need to be collected in that Panel Area for that week. This allows the users to confirm that all the samples were collected.



[redacted] MINE SAMPLING PLAN		Monthly Return	
Panel Area:	MG18	Sampling Week:	50
Date Issued:	Wednesday, 07 December 2022	Date to be Completed:	Monday, 12 December 2022
Date Sampled:			
Sampling Method:	1 x Composite sample made of 10 x strip samples or ONLY where the road is obstructed spot samples can be taken		
Samplers Name and Signature:			
WET ROADWAY DUST SAMPLING - BRM STD 02 SSOP			
Date Sampled:			
Time Sampled:			
Zone Name:			
Date Sampled:			
Time Sampled:			
Zone Name:			
Date Sampled:			
Time Sampled:			
Zone Name:			
			NAME

Figure 4-5 Sample PDF Plans Page 1

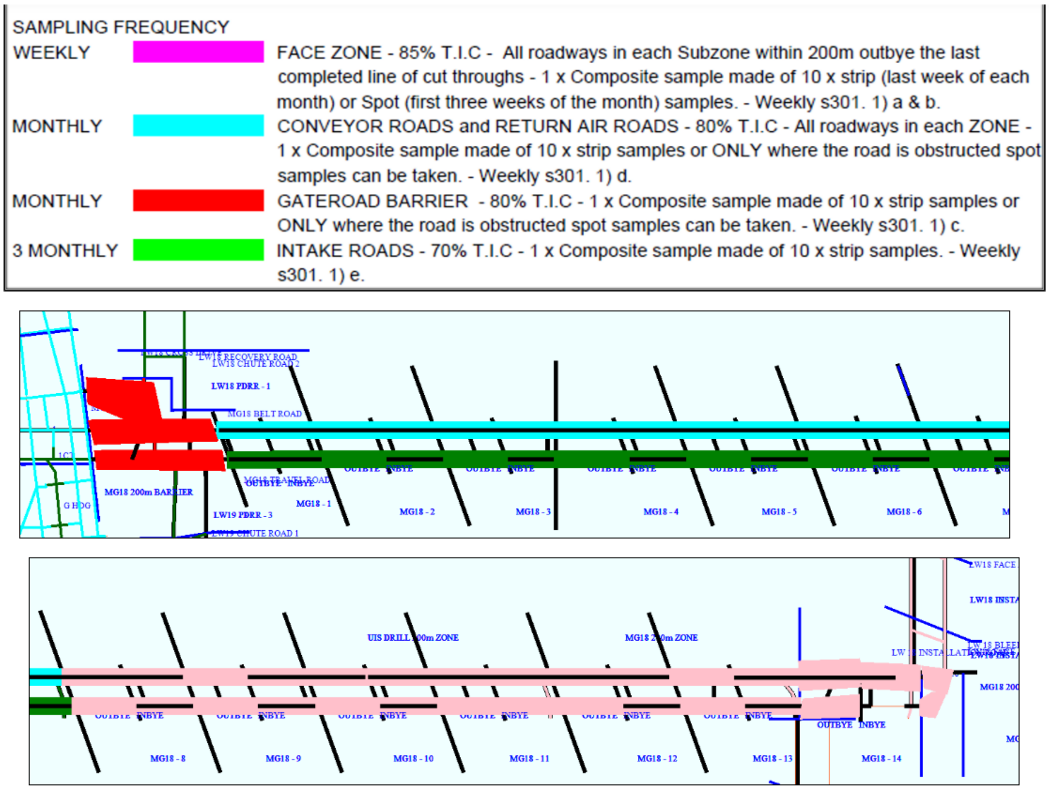


Figure 4-6 Sample PDF Plans Page 2

MG18 Monthly Return SAP WK50		Monday, 12 December 2022
Monthly Return		
Note: Before submitting the samples, use the checklist to ensure the total number of samples are in place.		
ID Number	**Location**	**Check**
1 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 1, OUTBYE, B HDG, *Ref Loc* - MG18 - 5 To 6	✓
2 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 2, OUTBYE, B HDG, *Ref Loc* - MG18 - 6 To 7.5	✓
3 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 3, OUTBYE, B HDG, *Ref Loc* - MG18 - 7.5 To 9	
4 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 4, OUTBYE, B HDG, *Ref Loc* - MG18 - 9 To 10.5	
5 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 5, OUTBYE, B HDG, *Ref Loc* - MG18 - 10.5 To 12	
6 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 6, OUTBYE, B HDG, *Ref Loc* - MG18 - 12 To 13.5	
7 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 7, OUTBYE, B HDG, *Ref Loc* - MG18 - 13.5 To 15	
8 - 14	WK50, MG18, Monthly Return, 80%, MG18 - 8, OUTBYE, B HDG, *Ref Loc* - MG18 - 15 To 16.5	

Figure 4-7 Sample PDF Plans Page 3

The Sample Labels can also be created and downloaded on the second tab using the same information as the sample plans. The user can select which category (85%, 80%, or 70%) of labels and then download these as a PDF. The size and layout of the labels were to fit the research mines existing label printing sheet. Each label contains the sample number of its Panel Area, a unique Sample ID, the sampling week and category, the EDZ sampled, and a reference location. Once printed, the labels are individually used on each dust sample before being collected and sent to the laboratory.

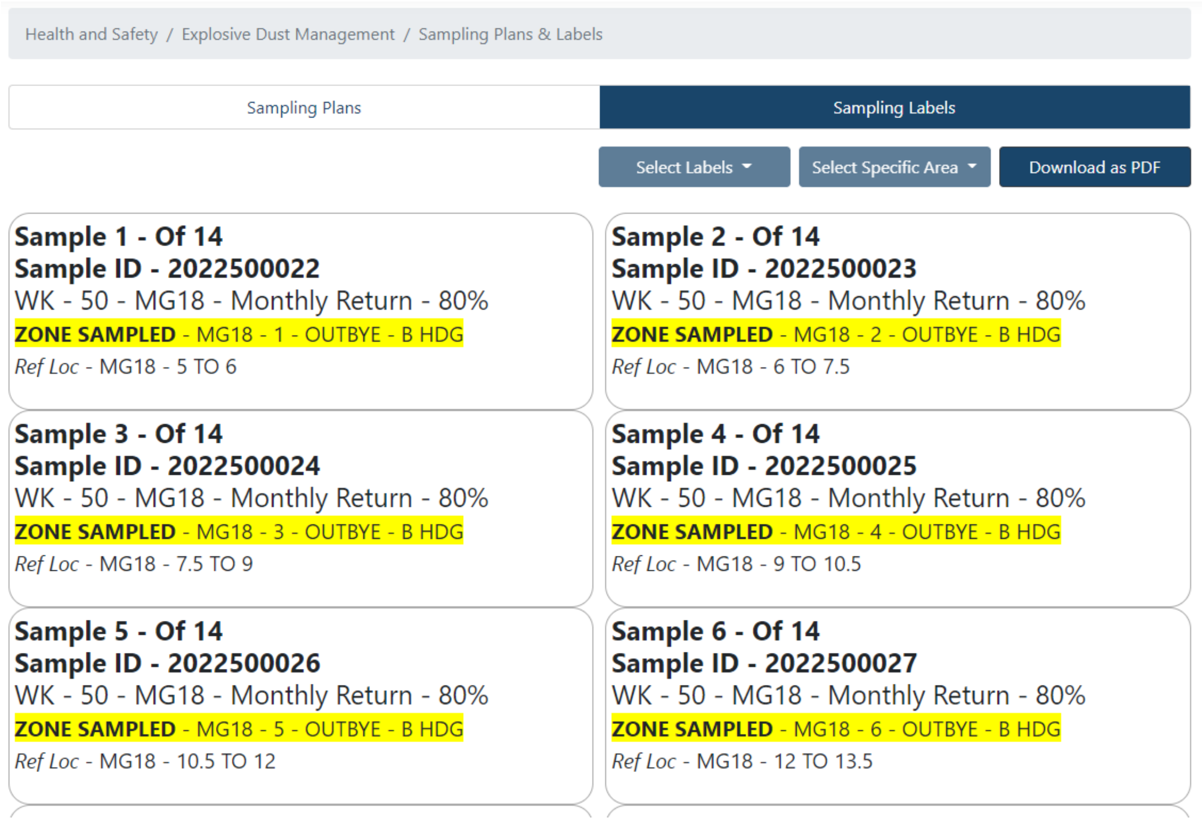


Figure 4-8 Sample Labels Generated

4.2.2 Evaluation Against System Objectives

Comparison with Existing System

This implementation of this system component replaces the remainder of the need for the previously used user excel file and word document to create the plans and labels. This supports the objective of automating steps to reduce manual processing (a). When exporting the labels previously using the word document, there was a risk of a user not directly selecting all of the labels even if they had translated the information correctly into the excel document, whereas now this risk is eliminated. Also, label content is slightly improved with the introduction of the unique Sample ID. Previously, there was not a unique Sample ID associated with each label that could be related from week to week, making it difficult to correlate data from the laboratory results. Introducing the Sample ID will make the system more efficient when integrating with the laboratory. The remainder of the content within the sample plans and labels is essentially a replication of what was included previously.

Limitations

Despite the components' superiority over the existing process, there are still general limitations. When completing the sample plans digitally, such as typing information in the blank fields and checking off a sample as collected, the digital editing shows upon immediate export to the PDF however, the system does not yet save or use this data in any way. There is still a limitation when the laboratory receives the samples from the research mine that they need to read and record the information from the labels manually. Additionally, for the system to generate the labels, it must have a previous sampling date for each EDZ, which requires three months of sample history to ensure no three-monthly sampling EDZ are missed.

Future Considerations and Standardisation

To improve digitisation, the sample plans and data within them should be stored by the system each week. Additionally, making them available on the mobile application to be used on a handled device would be helpful as they do not need to be printed, and users can check off each sample as it is taken. To reduce the manual processing of the labels from the laboratories' side, QR codes or label barcodes could be used as an alternative. This and the ability to send them a digital list have been discussed with the laboratory, and minimal development would be involved.

The layout of the forms is currently a replica of the research mine existing forms. For standardisation, this feature could utilise modifiable forms functionality so that each different mine can modify the standard layout of their sample plans to one that suites their needs,

Usage and Further Discussion

This component has been implemented at the research mine. Overall, the initial feedback was positive. There was some understandable dislike for Page 2 of the sample plans, which shows the visual location guidance. The current image of the mine map is quite pixelated, and the colours do not look similar to what the users are previously familiar with. Additionally, the lines and colours hide the location cut through markers which offer guidance. As a solution, the mine has agreed that the line colours can be removed to reveal better location notation.

Although this component is implemented, the mine is still generating the plans and labels alongside its existing plans and labels. This is because a Management of Change process is required before the system can be solely used, which is near completion. To aid in the transition, the new and old labels are commonly used on the same sample so that the laboratory can adjust to the new naming conventions.

4.3 Sample Analysis and Results

This component involves the following System Design (SD) requirements:

SD1.3 System Integration with laboratory results.

SD1.6 Create an interface for viewing and exporting historical sampling data.

4.3.1 Component Functionality

For this component, an interface was created that enabled all historical results to be viewed in one place with easy filtering functionality to view certain date ranges or specific EDZs. Additionally, export functionality was added so that, if required, a user can provide regulatory authorities with evidence of historical samples.

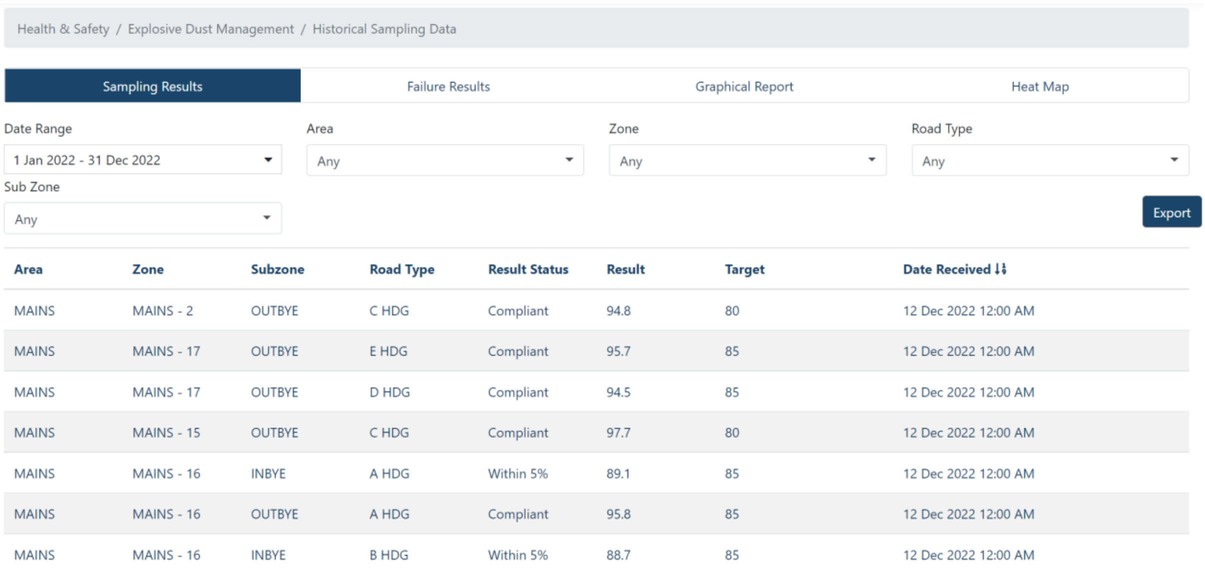


Figure 4-9 Laboratory Integration

As part of the system, there are two integration methods, automatic and manual. The automatic is the system's primary method, which is done through an application programming interface (API) integration directly to the research mines utilised laboratory. The API created facilitates the data sharing for each sample result. The critical data required for each sample is the unique Sample ID, the result, and the target. The system can then relate the unique Sample ID to the samples sent and determine the result status based on the result and the target. As previously detailed in Table 3-4 Sample Result Status, a result will be either Failed, Within 5%, Within 10%, or Compliant.

Due to some discrepancies between the research mines previous sample naming conventions and the current system naming conventions, along with the absence of a unique Sample ID, this API can only be utilised once the research mine is solely using the generated sample labels. The manual integration method must be utilised until systems-generated labels are used and if there were issues with the API for any reason. The manual method can be done by extracting the sampling results from the weekly excel results emailed weekly to the research mine.

4.3.2 Evaluation Against System Objectives

Comparison with Existing System

Previously, there was no way to access all historic sampling records in one place, and a user would need to go through separate excel files and collate them. Additionally, weekly excel records would not be accessible until they are emailed. This automatic integration with the laboratory has replaced these drawbacks by having one integrated interface. There will be other interfaces to provide quick data insights however, by standardising the naming conventions, this interface alone provides better usability than the existing method. This aids in addressing the objectives of automating steps (a) and providing an accessible source of data (b). Although the users will no longer need to use the excel result emailed from the laboratory, at this stage, they will still be emailed as part of the laboratory's own process to provide a record.

Limitations

Compared to the existing system, this component has little to no limitations. This current interface does not indicate action is required if a stone dust sample has failed however, this is covered in a later component. A general limitation of the existing process used by research mine, as well as this current component, is that there is no validation done to ensure that there are sample results for all the samples sent. Although unlikely, this means that it may not be realised if the laboratory does not record a sample.

A limitation in the initial process of implementing the system is the manual integration required until the mine uses the labels with standardised naming conventions and a Sample ID. There are minimal changes that can be done to avoid this, as it is a consequence of the previously inconsistent and unstandardised naming conventions.

Future Considerations and Standardisation

To ensure no sample results are missed, it would be beneficial to add a validation in the system which identifies any samples sent that do not have a matching result. This could be a row within the same interface with a Result Status of “Missing” and a red row.

Standardisation is achieved for naming conventions of the EDZs however, if this system was to be used at other mines, a new API would need to be explicitly created for the laboratory that the mine utilises to analyse its sample results. Currently, there is still regulation that the laboratory needs to provide a monthly report to the mine (which is commonly done within an excel file) however, once established and permitted by the authorities, a standard monthly report could be generated from the EDRMS.

Usage and Further Discussion

As mentioned within the sample planning, the old sample labels and process are still being used alongside the new labels and system until a Management of Change is complete. This means that the API has not finished its final development, and most results are still being integrated through a manual upload into the database.

This part of the process has been far more complicated than initially anticipated due to the significant discrepancies and general inconsistencies in the existing naming conventions of EDZ. Due to no common standard and the complexity of the existing management excel, it was common that a single EDZ may have one, two, and sometimes three different names that had been used over the past three months. Therefore, to allow these existing sample results to be uploaded into the new system database, an equivalent EDZ list needed to be created that could be used to compare what an existing EDZ name would match in the new system. To do this, there was extensive manual reading and comprehension involved.

4.4 Production Areas and Dust Application Rates

This component involves the following System Design (SD) requirements:

SD2.4 Create functionality to establish Production Areas with an associated Minimum Dust Application Rate (MDAR).

4.4.1 Component Functionality

The next foundation of the system required to provide a new level of insight is capturing stone dust application and maintaining Minimum Dust Application Rates (MDAR). Before stone dust application can be captured, the Production Areas (PAs) and their associated MDARs need to be established. To manage this, an interface was created that displays all current and previous PAs and their application rates. It also allows users to update the MDAR or add a new PA.

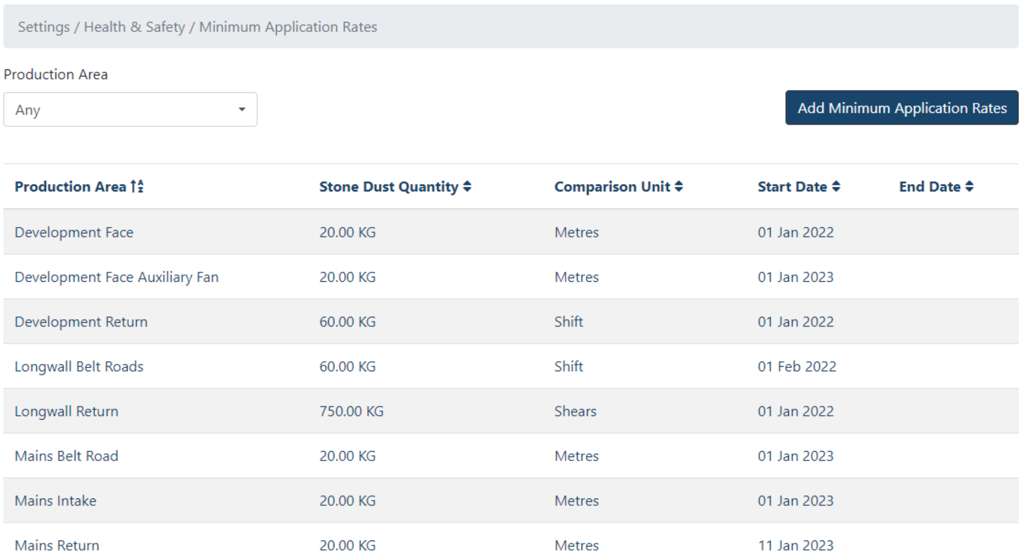


Figure 4-10 Interface for Managing Minimum Application Rate

Production Areas were created to match those previously used by the research mine (Figure 3-9). Additionally, the existing Mains Airo-Duster has been replaced with Mains Belt Road, Mains Intake, and Mains Return to improve accuracy and consistency within the system (Table 3-3).

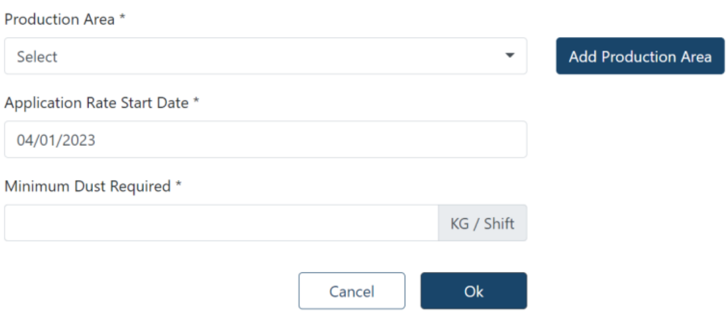


Figure 4-11 Adding a New Application Rate

When creating a new PA, it must have a Comparison Unit of either Metres, Shears, or Shift. Then, the minimum dust required is entered to be equated per Comparison Unit to achieve the MDAR. Additionally, a rate must have a Start Date associated with it of when it must be enforced. If a new MDAR is defined with a new start date for an existing PA, the MDAR of that PA will automatically be associated with an End Date, and the new rate will come into effect.

4.4.2 Evaluation Against System Objectives

Comparison with Existing System

Previously, MDARs existed in writing in standards and procedures however, it was challenging to ensure dust applications compliance with this, and it was not frequently verified. These PAs and their associated rates will be utilised throughout the remainder of the EDRMS to determine the failure of Stone Dust Applications in real-time, something previously not possible. Additionally, this component has standardised the concept of a Production Area by removing the existing processes ad-hoc Mains Airo-Duster, which jumbled the concept of a PA with a dust method. By establishing PAs and MDARs within the system, this component aids the objective of providing an accessible source of data (b). Additionally, this will begin supporting a proactive approach to UCM explosion risk management (c) by determining if the rates are sufficient and efficient.

Limitations

There are no limitations encompassed with this component for the direct functionality above. It can be noted that an existing PA cannot be directly deleted by the user however, this was desired and, if needed, can be deleted through the database.

Future Considerations and Standardisation

It is anticipated that as the system is further established and utilised, new Production Areas will be created that are more closely related to the conditions of an EDZ that stone dust is being applied. Additonal and more suitable PAs will improve system accuracy when optimising the application rate (4.9).

In its current implementation, there is no direct relationship between the EDZs created in the digital twin and a PA. This was to adhere to the existing process at the research mine, where an EDZs sampling requirements and a PA were two disconnected concepts. However, after gathering a more comprehensive understanding of how coal dust varies in production and this relationship to sampling requirements, there is no doubt that having a clear relationship between a PA and EDZs would be beneficial and sensical to the entire system and the EDZ management process.

It was mentioned in 4.1.2 that for standardisation in managing the EDZ polygons, they could be directly allocated to an Area Type (Face Zone, Conveyor Road, etc.) which could be associated with the rest of the sampling requirements. To standardise and integrate a relationship for PAs, when creating a new PA within this component, it could be associated with an Area Type such as Face Zone, which would then be linked to the rest of the sampling requirements. If this was set, users could manage the EDZs and their requirements on the digital twin by allocating the polygon to a PA, and altering the allocated PA of a polygon to suit the coal production exposure in the EDZ over time. By doing this, not only is there a relationship from a PA to an EDZ for a given timeframe, but also a clear relationship to the sample results for that EDZ, which would be helpful when gathering data to optimise the application rates.

Usage and Further Discussion

This has been successfully implemented and is being actively used at the research mine as part of capturing stone dust application. Managing and changing the minimum dust application rates will be restricted to the Stone Dust Coordinator and Compliance Superintendent due to the risk involved with missed compliance.

Although there is no direct relationship between the PAs and EDZs in its current implementation, through dynamic data analysis, a relationship can be created between a sample result and a PA, as explored in 3.3. This will be utilised for optimising the application rate in the current EDRMS implementation, as covered in 4.9.

4.5 Capture and Record Stone Dust Application

This component involves the following System Design (SD) requirements:

SD2.1 Create functionality to capture Stone Dust Application data digitally.

SD2.2 Create dust application capturing functionality to be available on a mobile application (for both IOS and Android devices).

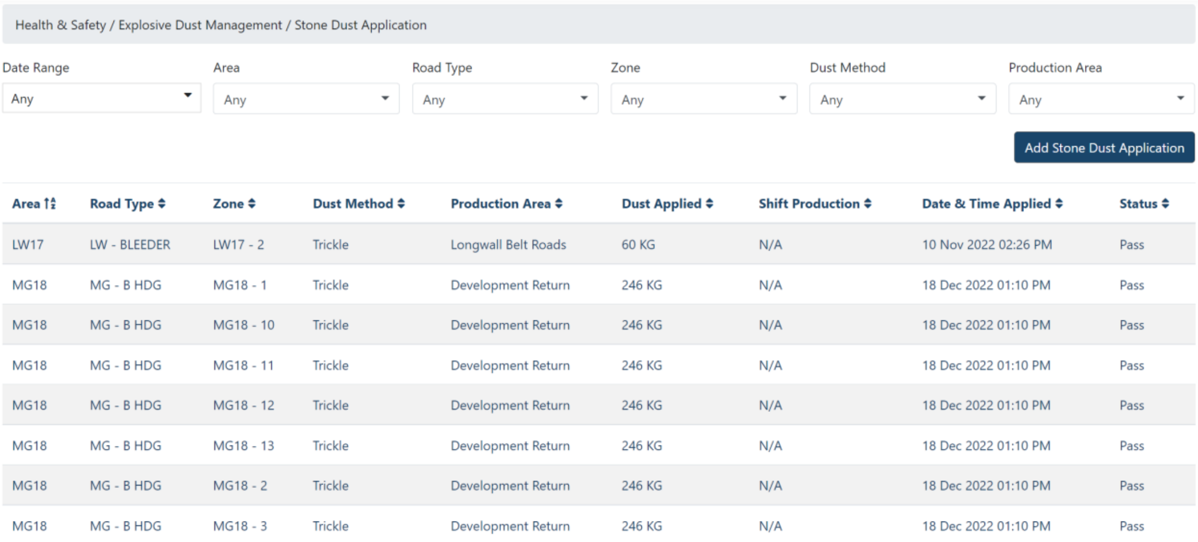
SD2.3 Extend mobile functionality to be available in the mobile application without being connected to a network and ensure data is synced when reconnected.

SD2.5 Automatically calculate the application rate of SDAs and highlight if it has met the minimum requirements.

SD2.7 Track stone dust application to each EDZ of the mine across time frames with the ability to export data.

4.5.1 Component Functionality

The stone dust application can be captured in two different ways, both on a desktop application and through a mobile application. To do this on the desktop, a simple interface was created that allows users to add new stone dust applications and see previous dust applications that have been added.



Area	Road Type	Zone	Dust Method	Production Area	Dust Applied	Shift Production	Date & Time Applied	Status
LW17	LW - BLEEDER	LW17 - 2	Trickle	Longwall Belt Roads	60 KG	N/A	10 Nov 2022 02:26 PM	Pass
MG18	MG - B HDG	MG18 - 1	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 10	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 11	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 12	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 13	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 2	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass
MG18	MG - B HDG	MG18 - 3	Trickle	Development Return	246 KG	N/A	18 Dec 2022 01:10 PM	Pass

Figure 4-12 Interface to View and Add Stone Dust Application

When selecting the button to capture a new dust application, a user can select the button, an interface will open that requires the user to select and enter the following information:

- **Area:** Drop down of all panel Areas that have corresponding approved EDZs in the Digital Twin.
- **Production Area:** Drop down of all pre-defined Production Areas that have different associated Minimum Application Rates.
- **Shift:** Drop down of Day or Night for selecting the shift in which the dust was applied.
- **Crew:** Drop down of all the available work crews.
- **Road Type:** Drop down of all the Road Types associated with the selected Area.
- **Zone:** Drop down of all the EDZs associated with the selected Road Type and Area. Multiple zones can be selected at a time.
- **Dust Applied:** Numeric entry of the amount of stone dust applied in kg across all selected zones.
- **Shift Production:** This will either be Metres, Shears, or Shift, depending on what Production Area was selected. A numeric entry is required for the number of Metres and Shears, but nothing is required for Shift.

- **Dust Method:** Drop down of pre-defined dust methods.
- **Date & Time Applied:** A calendar selection of the date and selection of time that the dust was applied, not the date and time of entering the application into the system. This time is what the system uses within failure compliance.

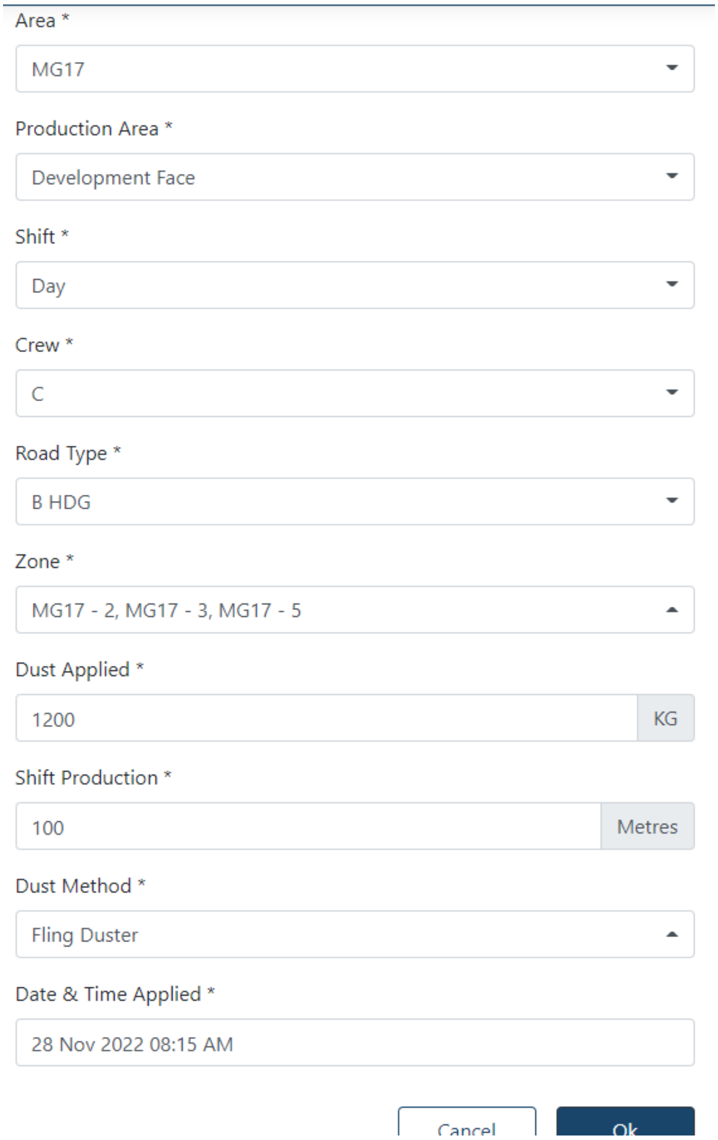


Figure 4-13 New Stone Dust Application

When the above information has been saved, it shows as a new dust application for the EDZ. If more than one EDZ was selected, it will divide the dust applied evenly amongst the EDZs. Now that dust application data is being captured and integrated directly, the system can actively determine whether an entered application is acceptable or failed. As previously discussed, this is done based on MDARs that are previously defined within the system. Currently, the system handles the application rates of kg / Metre, kg / Shear, or kg / Shift. Once a dust application is saved, the status of the application (last column on the interface in Figure 4-12) will be determined based on the calculations identified in 3.3.2. This failure status will be further utilised later in the system for the Failed Zone Retreatment.

To make the process of capturing dust application easier for the users applying the dust and closer to real-time, a mobile application interface has been created that users can access on their phone or underground tablet. Users can see the most recent dust applications on the interface and enter new dust applications. The same selection parameters are available on mobile as the desktop version. Once added, the users can see the dust applications on the desktop version and vice versa.

Additionally, the system has an offline mode for the mobile application in anticipation that although mines have some Wi-Fi underground, connections could have inconsistencies or problems. This is automatically enabled when there is no internet available. When in this mode, the users can still add new dust applications that will automatically upload when the device is reconnected to the internet.

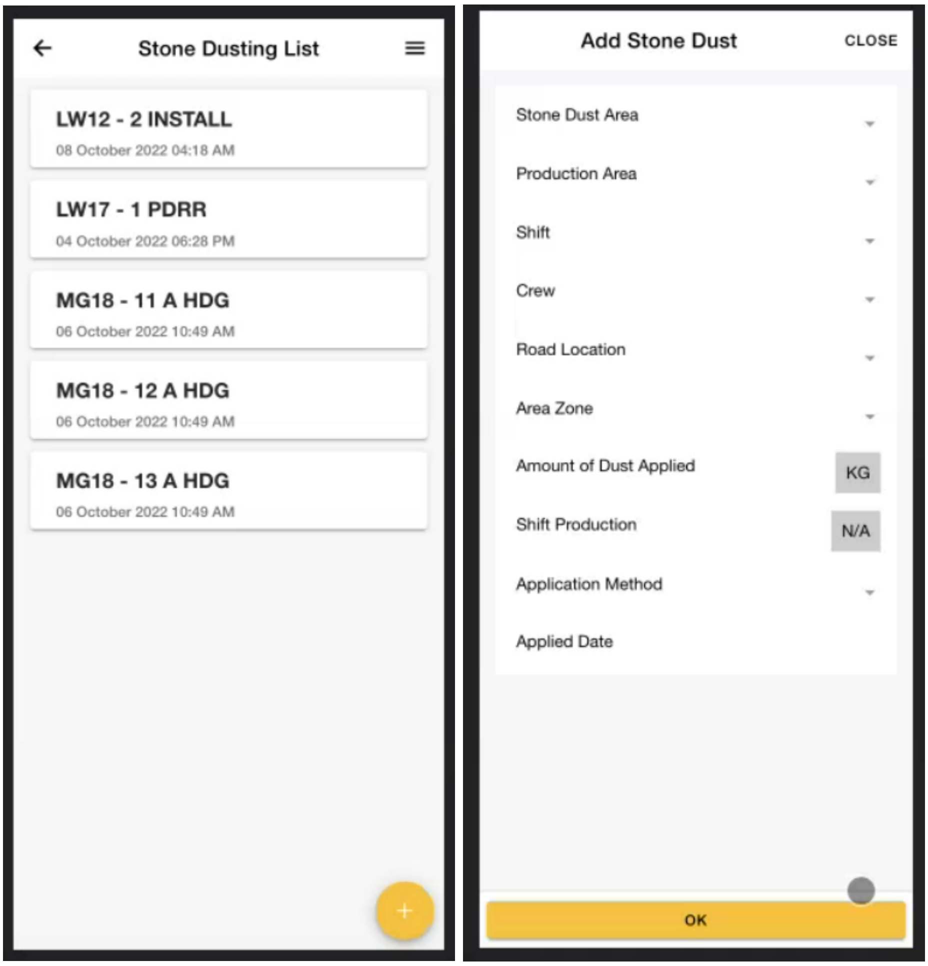


Figure 4-14 Mobile Interface for Capturing Dust Application

4.5.2 Evaluation Against System Objectives

Comparison with Existing System

Previously at the research mine, capturing stone dust application was entirely paper-based, with records of stone dust applications kept in a folder. When a new stone dust application was previously captured on a paper application form, there was no enforcement that the information was accurate or that the MDAR was sufficient. By enabling the users to capture this information digitally, along with the integration of MDAR to determine compliance automatically, it helps address the objectives of automating steps (a) and providing an accessible source of data (b). Having digital records of this information with filtering functionality makes searching for previous dust applications far more efficient than turning pages of a record folder.

Although it is still beneficial and robust having a desktop interface for capturing dust applications, if this were the only option, it would create a duplication of work. This is because dust records would likely still need to be written on paper in the UCM, and then when workers return to the surface, they would have to input this information into the desktop version. However, this duplication is removed with the additional mobile application interface that enables workers to digitally capture the same information when underground, even if offline. Therefore, this component will eliminate the need for any paper stone dust application records.

Limitations

This system component offers a far superior approach to capturing stone dust applications and determining their failure with little recognisable limitation. This current interface does not indicate action is required if a stone dust application has failed however, this is covered in a later component. In the previous and current processes, there is a general data accuracy limitation by averaging dust application across multiple zones. This is because much of the dust application equipment is mechanical and either the same equipment is used in a single sequence or different equipment is similarly used across multiple corresponding EDZs. Therefore, it is more efficient for workers to capture the total applied across the multiple corresponding EDZs and have the system average this out per EDZ. To ensure data accuracy, it would be ideal to have these captured separately and individually however, at this stage, it was more critical for workforce acceptance and ease of use.

Future Considerations and Standardisation

For its current purpose of capturing dust application, minimal changes need to be made to the system for standardisation at other mines. While it is currently not consistently possible with the dust application equipment being used, it would be more efficient if the system could directly integrate with a form of dust weight sensor that was compatible with the equipment.

The primary information to add a new dust application is drawn from the digital twin and Production Areas. Therefore, as long as these have been sufficiently set up, it should be possible to use this component as is at other mines.

Fort standardised to manage other risks and hazards, another mobile interface could be created with more flexible data entry fields so that users could capture hazard information while underground. This could relate to the standardised hazard concept created with the digital twin to capture hazards against different locations on the map. Additionally, photos of these hazards could be easily captured and directly integrated against a hazard using the mobile application.

Usage and Further Discussion

This has been successfully implemented, and the desktop interface is being actively used at the research mine to capture and record new and existing stone dust applications to begin building a data record. At this stage, the mobile application is not being actively used due to the Management of Change required to show that the EDRMS is sufficient for replacing the existing paper process. It is expected it will be used shortly. Therefore, although it is being used, not 100% of dust applications are currently recorded in the system.

Most of the feedback surrounding this system component and the new process of capturing dust applications has been positive. There have been some initial confusion from workers due to changes in EDZ naming conventions from what they are commonly familiar with. Overcoming this has been a consultation exercise with many examples to ensure workers understand not only the functionality but the reasoning why the naming conventions have changed and are being standardised for data consistency. There was also feedback after initial usage concerning capturing the dust applied using two different methods within the same EDZ for the same dust application. The system is being slightly adjusted to allow for this easily.

4.6 Sample Result and Dust Application Historical Data Visibility

This component involves the following System Design (SD) requirements:

SD1.8 Create insightful graphical representations of sampling results.

SD1.9 Create a 'heat map' overlaid on the digital twin mine plan that visualises each EDZs relative failure frequency.

SD2.7 Track stone dust application to each EDZ of the mine across time frames with the ability to export data.

SD2.9 Create a visual interface that graphically represents dust application for each EDZ and their MDAR fails.

4.6.1 Component Functionality

With the previous components integrating and capturing stone dust samples and application data, the EDRMS can offer visual insights that may aid the users in identifying issues. The primary Graphical Report interface contains four graphs, two on one row for sample result information and two below them for dust application information. There is an overall graph date range filter that impacts all the graphs, and then each graph has its own relevant filters. Additionally to this graphical report is a heat map to view the failures for the sample results. If more detailed and exact information is desired for either of these, the exact data can be exported from the list view interfaces explored in the earlier components.

Sample Results

For the selected time frame, the left sample results bar graph depicts a summary of the average sample result for each Explosive Dust Area. Simultaneously for the same time frame, the right multi-bar graph shows three separate bars for each area: the total number of failures, the total number within 5% of failure, and the number within 10% of failure.

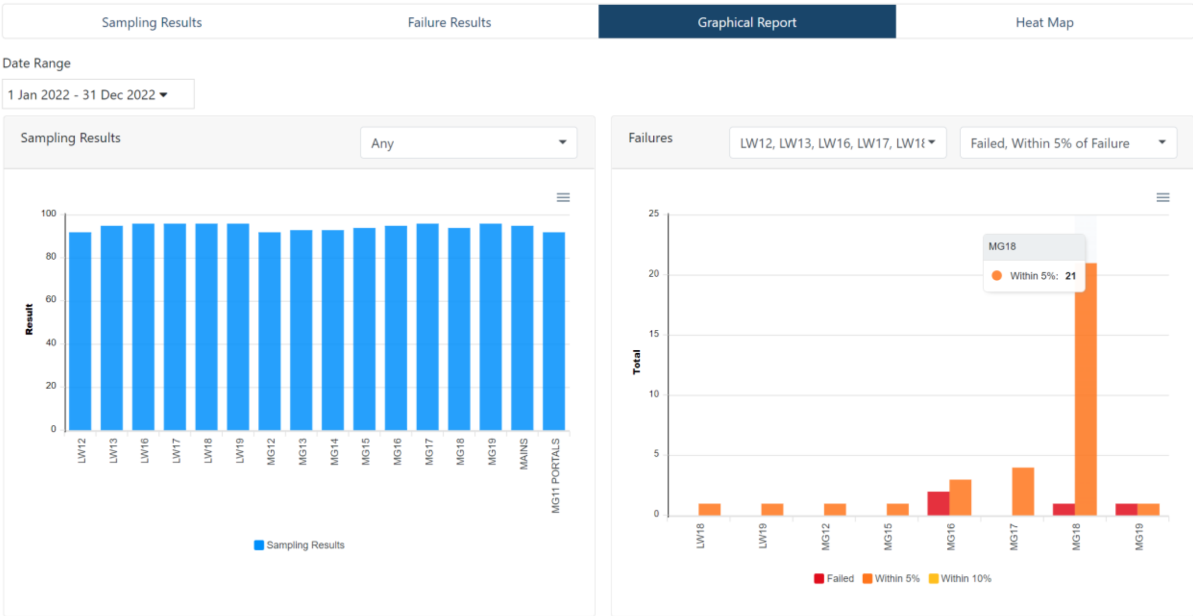


Figure 4-15 Graphical Interface for Sample Results

Each graph has drill-down functionality to see more detail. This means that clicking on any Area bar will drill down into each Zone encompassed within that Area. Similarly, the user can drill down further into the Road Type and Subzone of each EDZ. Each time the user drills down, the graph will narrow the average sample result or total failures to be more specific to the depicted EDZs. Additionally, if the user hovers their mouse over a bar, it will show information about the result or failures.

Figure 4-16 Sample Results Drill Down Graph

While the bar chart graphical interface is helpful for users to identify relationships and problems, to further aid users in visually digesting critical information as efficiently as possible, a secondary visual interface of the failure results was created, containing a Failure Heat Map.

This utilises the polygons created in the digital twin to view the mine map with a heat map overlaid upon it. The user can select a date range and a Failure Type (Failed, Within 5%, or Within 10%), and the colours of the EDZs will automatically scale to show which EDZs have had the most failures for the selected time frame. This indicates where the most prominent problem EDZs have been for that time frame. By hovering over any coloured EDZs, a user will see additional information, including the EDZ name, how many fails had been recorded for that Failure Type, and when the most recent failure occurred.

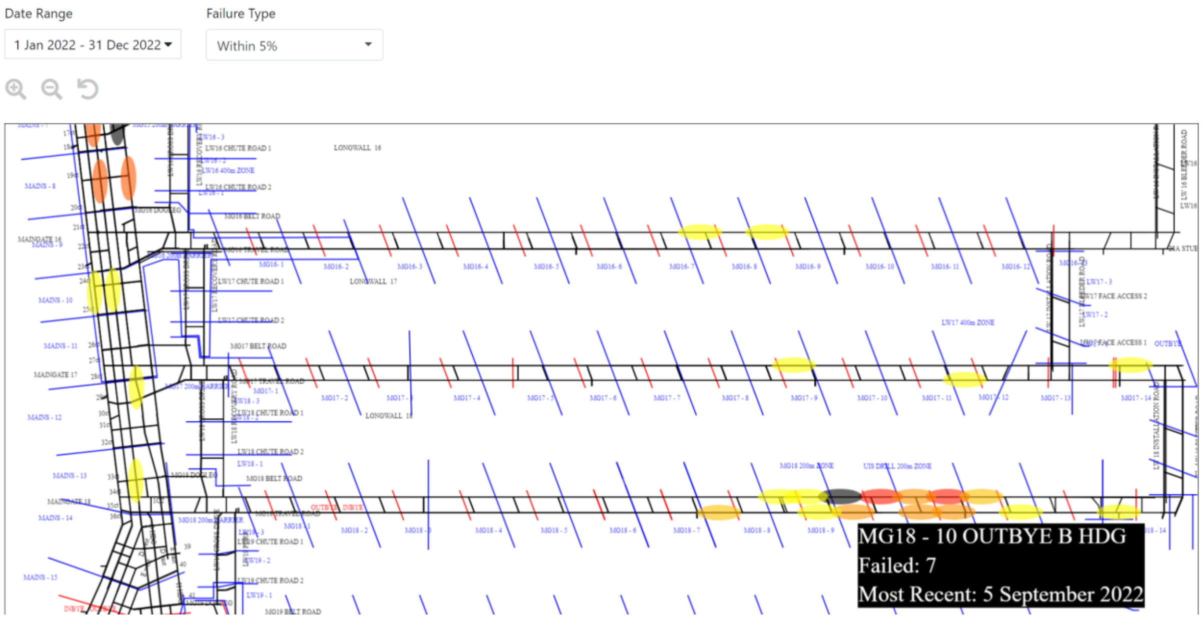


Figure 4-17 Sample Failure Heat Map

Stone Dust Application

Below the sample results graphs on the Graphical Report, the Stone Dust Application and MDAR failure compliance can also be viewed. The left graph shows the total amount of dust applied in kg for each Area, and the right graph shows the total MDAR Area failures.

Figure 4-18 Graphical Interface for Stone Dust Application

Similarly, to sample results, the user can then drill down into the detail of Zones and Road Types by clicking on the bars. However, specific to stone dust application graphs, the final level of detail in the drill down is the dust method used. This was added as it may offer insight into what method has the most failures and enable the users to identify if this is a problem.

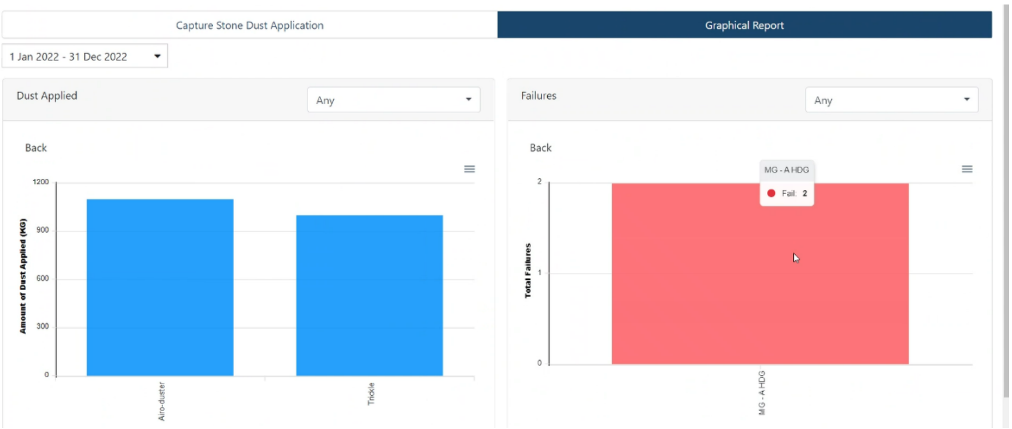


Figure 4-19 Stone Dust Application Drill Down Graph

4.6.2 Evaluation Against System Objectives

Comparison with Existing System

Previously, there was no way to easily view and find relationships from the raw information of sample results and stone dust application across different time frames. The laboratory provided the best previous representation, which was a graph for each group of results each week. While this was useful for showing overall if sample results for the week were above the target, it offered no comparative visual analytics which could aid in identifying ongoing issues. As the dust application was previously paper-based, this had no historical data visibility.

Therefore, the current system provides far more insight into this historical data and supports the objective of enabling a proactive approach to planning and management (c). The four graphs were all intentionally included on the same interface so that a user can identify any relationships between sample failures and how they might relate to stone dust application for a given area. This identifies to the user ‘what happened’ and leads them into the ‘why did it happen’. The additional failure heat map interface places this information onto a more familiar context for users. Placing the data on this map context, which is used across the mine for planning and other purposes may lead users to realise previously unrelated concepts. There will be further insight provided in optimising application rate component.

Limitations

This user interface is a vast improvement from anything previously available. As such, there are no direct limitations but only future considerations for continuous improvement. There is a current limitation to the usefulness of data shown as the incomplete Management of Change means not all stone dust application data is being captured, and some manually integrated historical sampling data may be missing. However, this is not a system limitation.

Future Considerations and Standardisation

As mentioned, this interface provides insight into what happened and provides users with easily interpretable data that may highlight why it happened. This will be further built upon in the optimisation of the MDAR module, which will show another graphical interface that displays the failures related to Production Areas.

Currently, this component leaves it to the user to interpret the data and identify relationships. It is evident that a relationship exists between components, such as total dust application and sample failures, however, no system previously had the EDZ sample results and stone dust application data integrated, making it impossible to derive a quantitatively comparable relationship. This means the system can not yet accurately suggest to the user why a failure may have happened and can only provide a platform for insight. This will be considered in the future once more data is gathered. Another helpful feature for the heat map would be to additionally show failures for stone dust application MDARs.

No modification is required for standardisation at other mines once their digital twin and data integration has been successfully established in the previous components.

Usage and Further Discussion

This interface is successfully implemented and available for the research mine however, as previously discussed, some data is still incomplete while the system is being introduced. Despite this, the feedback has been positive, with the graphs and heat map already clearly revealing that some EDZs are clearly problematic areas.

4.7 Failed Zone Retreatment

This component involves the following System Design (SD) requirements:

SD1.10 If a sample result comes back as failed or an EDZ requires re-dusting, automatically create an item with live and accurate detail.

SD2.8 Similarly to failed sample results, automatically create an item if the MDAR has not been met.

4.7.1 Component Functionality

With the previous components integrating and capturing critical compliance data, the system can now indicate the action required to rectify failed dust sample results and dust applications. If a failure is determined from a sample result returned from the laboratory or MDAR failure from a stone dust application, it will immediately appear on this failure interface Figure 4-20.


Health & Safety / Explosive Dust Management / Failed Zone Retreatment

Type	Area	Zone	Road	Subzone	Target Result	Actual Result	Date & Time Fail Recorded	Time Left to Retreat	Dust Required
Sample Result	MAINS	MAINS - 5	C HDG	OUTBYE	85.00%	69.40%	7/11/2022 12:00:00 am	-133 Days -13 Hours -42 Min -39 Sec	312.00
Application Rate	MG18	MG18 - 11	A HDG		90.00	82.00	2/12/2022 4:03:47 am	-9 Days -21 Hours -38 Min -53 Sec	8.0000
Application Rate	MG18	MG18 - 12	A HDG		90.00	2.00	2/12/2022 4:03:47 am	-9 Days -21 Hours -38 Min -54 Sec	88.0000
Application Rate	MG18	MG18 - 15	A HDG		90.00	2.00	2/12/2022 4:03:47 am	-9 Days -21 Hours -38 Min -54 Sec	88.0000

Figure 4-20 Interface for Failed Zone Retreatment

This interface shows the type of failure, where and when it occurred, how much time is left to retreat the failed EDZ, and how much dust is required to retreat the EDZ. The colour of the row is linked to the time left to apply. If the failure time has less than 8 hours remaining, the row will turn orange. If the time has less than 4 hours remaining, the row will turn orange, and once the time runs out, the row will turn dark red.

If it is an Application Rate failure, the dust required is a total kilogram amount that is simply the difference between the actual dust applied to that EDZ and the expected dust application based on the MDAR of the selected PA. If it is a Sample Result failure, the dust required is calculated and displayed as an MDAR per metre rather than a total amount. This MDAR rate adapts depending on how much percentage a sample result is from compliance, meaning an EDZ that only fails by a few percent will not require as much dust applied per metre as an EDZ that fails by a lot.

Clicking on any failed result will automatically open a partially filled Re-dusting Application, which has the same interface as a standard application (Figure 4-13) but with some fields pre-filled and limitations around editing. For a failed MDAR, the Re-dusting Application will primarily require the user to enter the amount of dust applied, and if this is equal to or greater than the dust required, the failure will disappear from the failure list. If it is less than the dust required, the failure will remain on the failure list, and the new dust required will be adjusted. For a failed Sample Result, the Re-dusting Application will require the user to enter the Shift Production in metres so that the MDAR can be applied to ensure the entered amount of dust applied is sufficient before removing the failure from the failed list.

Once a Re-dusting Application is saved, it will show up in the existing Stone Dust Application interface (Figure 4-12) but with the status ‘Re-dusting’ (Figure 4-21).

Area ⇕	Road Type ⇕	Zone ⇕	Dust Method ⇕	Production Area ⇕	Dust Applied ⇕	Shift Production ⇕	Date & Time Applied ↓↑	Status ⇕
MG19	MG - B HDG	MG19 - 10	Trickle	Development Face	200 KG	1.00 Metres	25 Jan 2023 06:35 PM	Re-dusting
MG17	MG - A HDG	MG17 - 6	Silo	Development Face	2000 KG	5.00 Metres	25 Jan 2023 04:18 PM	Pass
MG16	MG - B HDG	MG16- 12	POD	Development Face	5000 KG	10.00 Metres	25 Jan 2023 11:26 AM	Re-dusting
MG18	MG - B HDG	MG18 - 12	Trickle	Development Face	300 KG	1.00 Metres	25 Jan 2023 10:48 AM	Re-dusting
MG17	MG - A HDG	MG17 - 6	Trickle	Development Face	1000 KG	100.00 Metres	25 Jan 2023 10:31 AM	Fail
MG18	MG - B HDG	MG18 - 12	Fling Duster	Development Face	500 KG	5.00 Metres	25 Jan 2023 09:29 AM	Re-dusting
MG18	MG - B HDG	MG18 - 12	Fling Duster	Development Face	1000 KG	100.00 Metres	25 Jan 2023 05:27 AM	Fail

Figure 4-21 Re-dusting Application

The failed list within this component will also be shown below the Live Failure Map in the Live Data Visibility component.

4.7.2 Evaluation Against System Objectives

Comparison with Existing System

This component removes the need for the Stone Dust Coordinator to open the sample results excel emailed from the laboratory and look for failures amongst the results for different Areas. Instead, failed results will immediately show on the interface once the EDRMS receives them via the API once the laboratory enters them into its database. This will save time and ensure complete visibility. Previously, failures would need to be personally communicated to those required, and an ad-hoc process would be conducted to organise the re-dusting required and determine the time remaining. With this new component, there is complete failure data transparency for anyone that needs to access it, including an accurate time remaining. Previously, once the dust was applied to the failed EDZ, it was recorded and verified on the unintegrated Failed Zone Sample Report (Figure 3-13). This new EDRMS component allows personnel of sufficient authority to capture this directly by opening a Re-dusting Application using the new interface. Therefore, this component completely replaces the existing response process to failed EDZ samples. The new simplicity and transparency aid in addressing the system objectives of automating steps (a) and providing an accessible source of data (b).

Additionally, this component has integrated the failure of MDAR from stone dust applications into the process. Previously because these were paper-based and it was challenging to determine failure, there was no process to re-dust EDZs that had insufficient dust applied in a routine application. By the system integrating this into part of the process, there will be better compliance with dust applications, which should lead to fewer failures occurring in the dust samples due to the sufficient dust being applied. This will support a proactive approach to UCM explosion risk management (c).

Furthermore, the culmination of the EDRMS data integration and the distinct process has allowed the dust required for a failed result to be calculated. Previously, as the mine had no insightful measure of how much dust they should apply to failed EDZ, they would just apply arbitrary amounts near the maximum dust needed to be applied to that EDZ in a routine dusting. This amount was often well above what would actually be required for that EDZ to be compliant. With the new EDRMS calculating the specific dust required based on integrated data which adapts depending on how far a result is away from compliance, there will be less over-dusting, making the process more optimal.

Limitations

In comparison to the existing system, this component has no limitations. However, an evident limitation in this current implementation is that the Failed Zone Retreatment component does not consider the recurring frequency of stone dust application that should occur to each EDZ. Although MDAR failures will be displayed when a new stone dust application is made, there is no current check if an entire stone dust application was missed for an EDZ because the exact frequency of routine dusting is not integrated within the system.

Another limitation is the requirement for a user to enter the total Shift Production metres of a failed Sample Result Re-dusting Application to determine the total amount of dust required for that EDZ.

Future Considerations and Standardisation

Based on this limitation, the expected frequencies of stone dust applications should be associated with an EDZ. Based on the previous suggestion of assigning a PA directly to EDZs, the easiest way to implement this would be to associate each PA with a recurring stone dust application frequency. This Failed Zone Retreatment component could then use this to raise an item on the interface if the system has not received a stone dust application for an EDZ within a time period greater than its frequency. This would ensure that the amount of stone dust applied equals the expected amount.

To overcome the second limitation that Shift Production entry is required, the digital twin could be improved so that the physical length of an EDZ can be associated with it. With this, a user would not have to enter the number of metres in the Shift Production of a failed Sample Result Re-Dusting Application to determine the total dust required for compliance.

Usage and Further Discussion

This system component has been developed and is available however, it is not yet implemented because it relies on the entire EDRMS to be introduced to all required personnel involved in failure response. This is being done as part of the Management of Change. If personnel are not using the system for failure response, the failed items raised will time over to negative and not be finalised correctly. Therefore, this component will be implemented following the Management of Change process completion.

Initial feedback has been positive, and the Stone Dust Coordinator has firmly acknowledged the components' advantage over the previous process.

4.8 Live Data Visibility

This component involves the following System Design (SD) requirements:

SD2.10 Using the digital twin of the mine map, create a live map showing all failed EDZ, both sample and MDAR failures. List these with a timer countdown. It should constantly update.

4.8.1 Component Functionality

This component displays the mine map with all currently failed EDZs indicated as different pins, with their colour depending on the time left to re-dust. Selecting a failed pin within the live failure map will display additional information, including the EDZ name, how much time is left to re-treat, and the production area of the fail. This was created as additional visual support for the previously discussed live list of failed EDZs. The live failed list will additionally show on this same interface below the map, so that users can easily see the more detailed information.

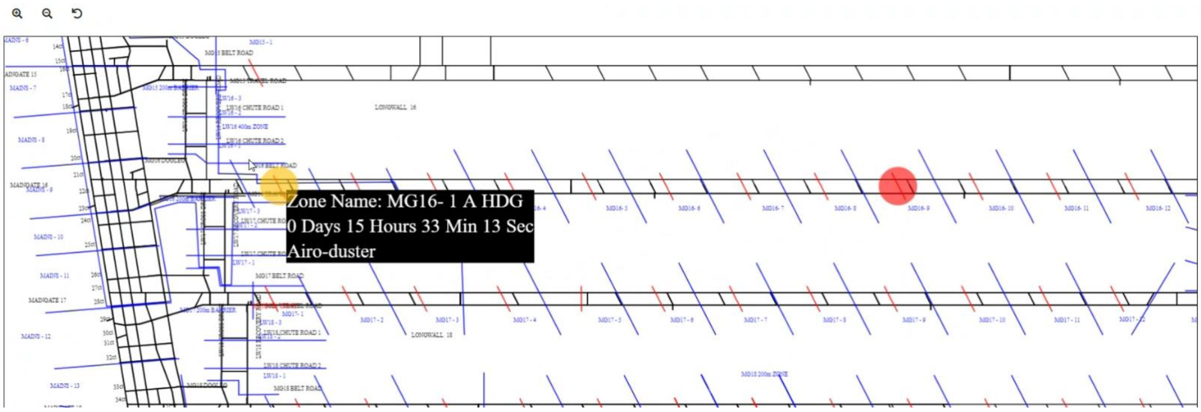


Figure 4-22 Live Failure Map

It is the intent that this screen is displayed on a large screen in a central office, so everyone can see the urgency involved with responding to failed dust applications and samples. As this will be a more publicly available interface, it will be a ‘view’ only. Selecting failed items will not open a Re-dusting Application as it does in the Failed Zone Retreatment component.

4.8.2 Evaluation Against System Objectives

Comparison with Existing System

Previously, there was nothing similar to this functionality. Similar to the historical failure heat map, visually representing the information on the digital twin is easier to digest and more relatable for users. Having urgency linked to colours also makes it even easier for interpretation. By being in a publicly viewable place on a screen, there will be more accountability for all involved to recitify the failures as soon as possible.

Limitations

This component has no direct functionality limitation and serves its purpose as a visual aid. As discussed in the Failed Zone Retreatment, a general temporary usage limitation is that this component has little benefit without complete data and enforced usage because the failed items raised will time over to negative and not be finalised correctly.

Future Considerations and Standardisation

No modifications are required for standardisation at other mines once the digital twin and data integration has been successfully established in the previous components.

As previously discussed, there is scope to integrate other vital risks to display on this map to improve awareness. For instance, if a hazard concept was implemented, any hazard could be raised and graded for severity to display on this live map. As mentioned for the mobile application, it is possible hazards could be raised with photos underground using the mobile app and connected to the live map. This would allow any user in the office to see where hazards are on the live map, and select a pin to see a photo or more information. This would enable more transparency and help with planning and safety.

Usage and Further Discussion

This system component has been developed and is available however, it is not yet implemented for the same reasons as the Failed Zone Retreatment. In anticipation, the research mine has purchased a large screen that will be placed within their planning office, with the intention that the live map will be displayed on it.

4.9 Optimising the Minimum Dust Application Rate

This component involves the following System Design (SD) requirements:

SD2.11 Using all newly integrated data, create functionality that can display the performance and indicate the suitability of MDAR for each Production Area.

SD2.12 Extend the data intelligence surrounding MDARs to determine and suggest an MDAR that will optimise the sample results associated with a Production Area.

This component has not yet completed development for implementation within the new EDRMS. Due to this component's reliance on accurate and complete data to provide useful insight, the rest of the system must be established and operational before this component is valuable. Therefore, it was chosen as the final piece of system implementation. Despite this, its functionality and evaluation can still be explored based on current information and modelling.

4.9.1 Component Functionality

Expected Functionality

For implementation, this component will have a singular interface within the system containing two graphs and a list view table below. These will provide insight into the Production Areas (PAs) and their associated Minimum Dust Application Rates (MDARs). These will be created using the methodology explored in 3.3.

For the date range selected, one graph will be a multi-bar graph that shows three separate bars for each Production Area: the total number of failures, the total number within 5% of failure, and the total number within 10% of failure. These failure totals come from the relationship between dust sample results and PAs. The graph will have drill-down functionality upon clicking any of the PA bars. For the selected date range, if more than one MDAR has been in effect for a PA, the total failures associated with each different MDAR will be shown as separate bars. For example, suppose 24 sample failures for the Longwall Return PA have occurred over the past six months, and in that timeframe, there have been three different MDARs. On the graph, clicking on the bar for Longwall Return would drill down into three separate bars, one for each rate that has been in effect. One rate of 18 kg/m may have 12 fails, the rate of 21 kg/m may have 8 fails, and the rate of 23 kg/m may have 4 fails.

The second graph will be a multi-line graph with a separate trendline for each PA for the date range selected. The data points will be the average proportional percentage deviation from the Minimum Incombustible Dust (MID) target for the related samples of each PA per week, as calculated in 3.3.4.

Below the two graphs, there will be a list view with one row per PA (similar to Figure 4-10). Each PA will contain its current MDAR, the start date of the MDAR, the Rolling Average Deviation (RAD) from the Sample Compliance Target (SCT) since the start date, and the suggested MDAR. As previously detailed, for this real-world implementation, the suggested MDAR will be the current MDAR multiplied by the sum of one and the RAD from CT. The PA rows will be colour coded based on their rolling average deviation as per the Table 4-1.

Table 4-1 Optimisation Rate Colour Coding

Colour	Corresponding Status	Parameters
Red	Increase MDAR	RAD (CT) % > 1%
Green	Satisfactory MDAR	1% >= RAD (CT) % >= -1%

Yellow	Decrease MDAR	RAD (CT) % < -1%

Performance Model

As discussed, the intent is that the MDAR associated with each Production Area would stabilise at a rate that produces sample results around the Compliance Target (10% above the minimum failure rate). This means it would not be aiming for an MDAR that produces 100% dust coverage but a rate that will aim to, on average, produce sample results for that PA at the CT. So, for example, the rates would aim to optimise until sample results are either 77%, 88%, or 93.5%, depending on their MID target.

To help visualise what this would look like, a basic model of how the system may perform has been created. Please note that this is by no means based on real or historical data but shows how the suggested system would behave in a given scenario. For the model, it has been set that the users would implement the new suggested rate every 4 weeks. This means the data indicating how much the rate increases (RAD from CT) would have time to average over every 4 weeks between updating MDARs.

The model assumes the Production Area to be "Mains Return", which would commonly have samples with an 80% MID target and, subsequently, an 88% CT. For this scenario, the initial MDAR has been set to be 15 kg/metre.

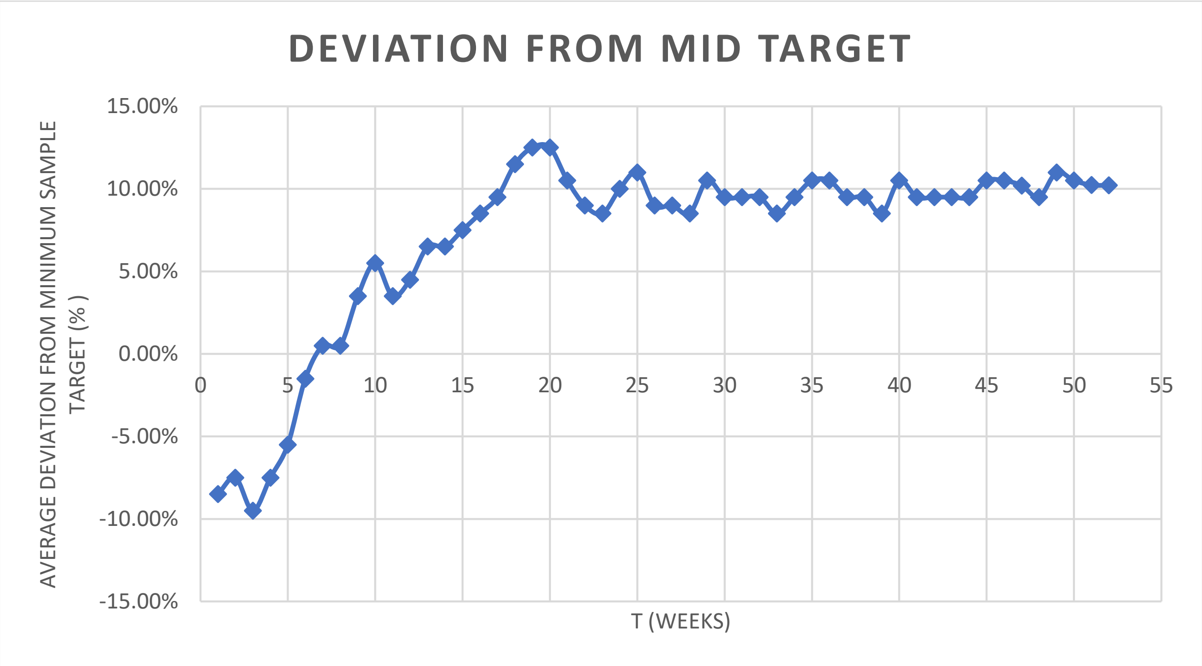


Figure 4-23 Model Deviation from MID Target

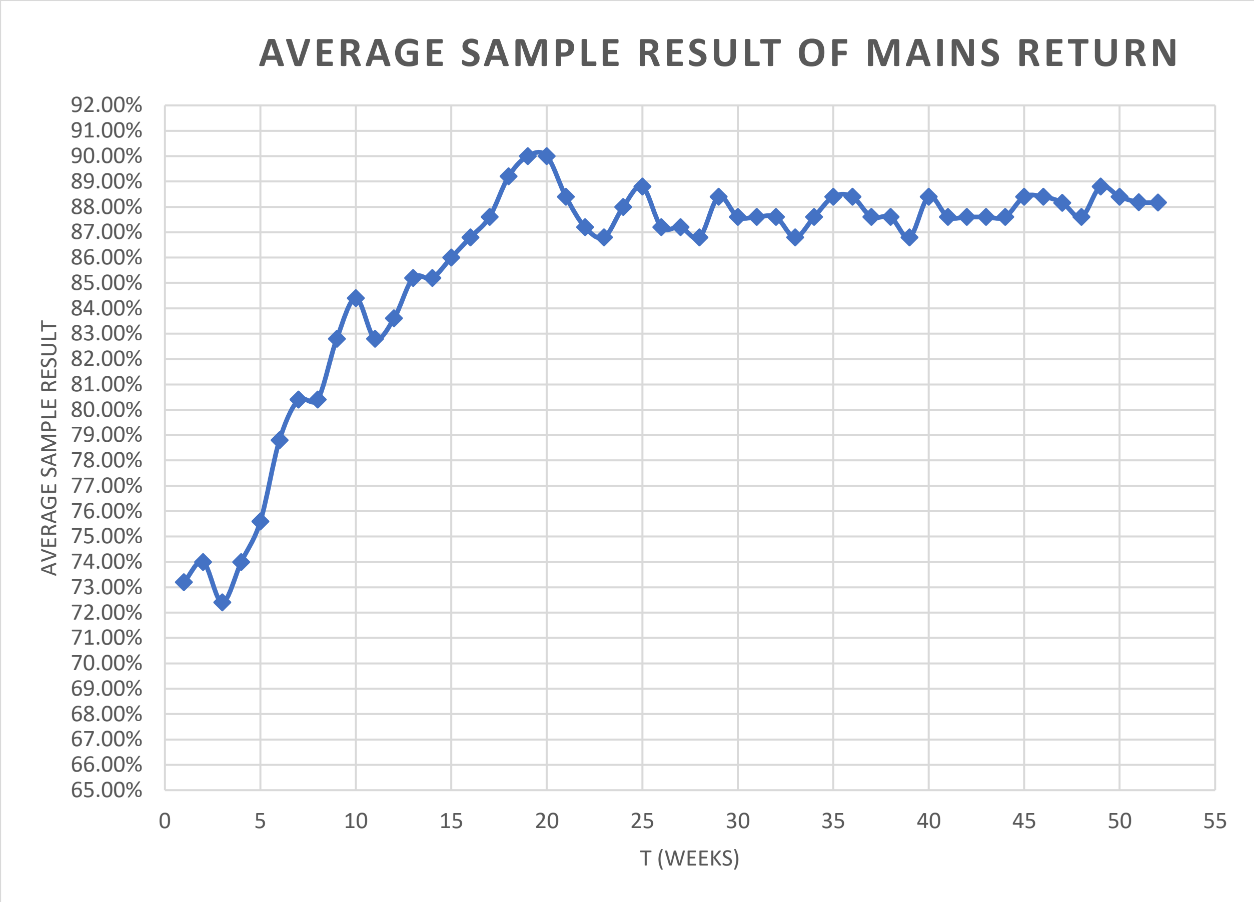


Figure 4-24 Model Average Sample Reult of Mains Return

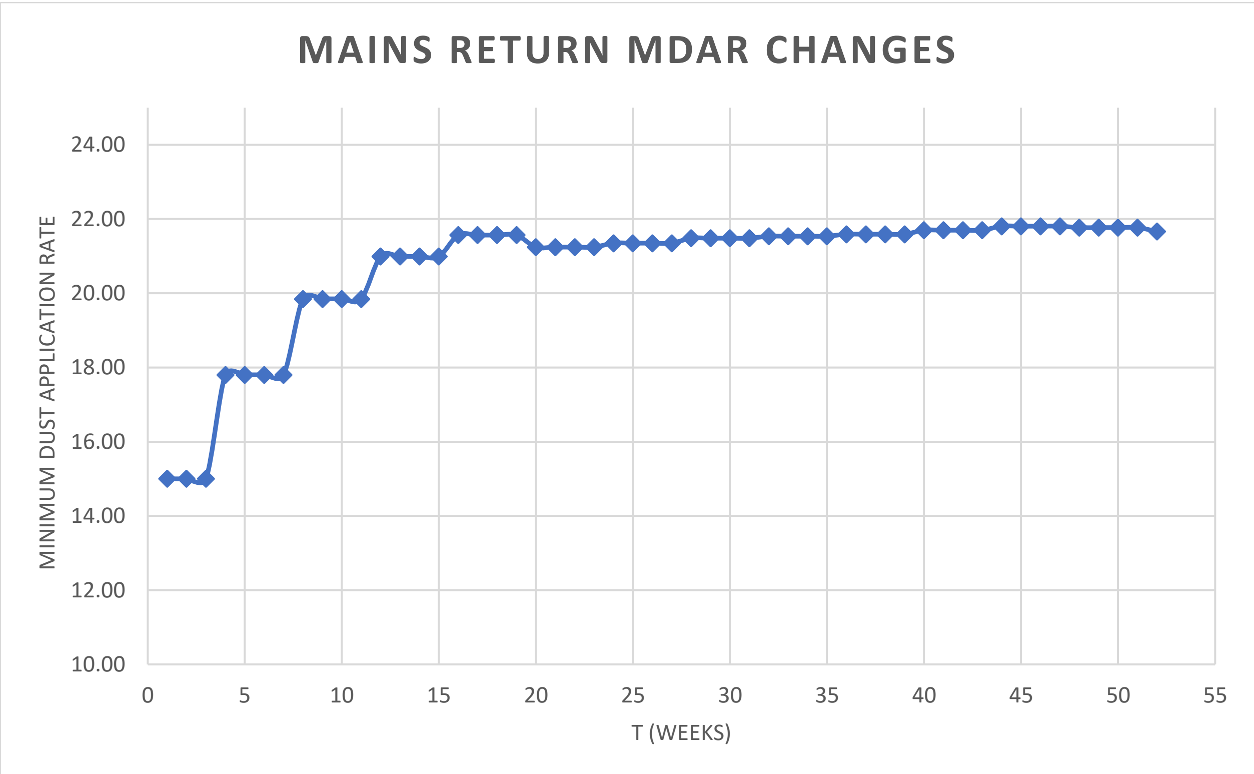


Figure 4-25 Model Mains Return MDAR Changes

The above hypothetical scenario demonstrates that every 4 weeks, the MDAR changes proportional to the percentage deviation away from Compliance Target, which in turn positively impacts the average sample results related to that production area. The system continues to proportionally increase the MDAR until the average results of the samples related to that production area are 10% above the MIC target. Similarly, if the sample results go above the CT of 10% of the MIC target, it suggests a proportionally reduced MDAR for that PA.

4.9.2 Evaluation Against System Objectives

Comparison with Existing System

PAs and their associated MDARs have previously been set by a mixture of "rule of thumb" and experience, which, as identified in the regulatory audit, is common across the UCM industry. Although these rates may change, with their current processes, it is challenging to correlate sample results to a PA. This means that it is currently near impossible to measure the actual suitability of the MDAR rates of a PA. As a result, the research mine and other mines not only expose themselves to the risk of under-dusting PAs but, consequently, out of fear of under-dusting, are commonly significantly over-dusting some PAs. Although it is understandable to ensure safety, research has revealed that PAs with less exposure to coal dust simply do not need as much stone dust applied as those with more significant exposure to coal production and dust. Therefore, over-dusting these low-risk PAs is not an efficient use of resources and leads to unnecessary costs.

Providing a suggested MDAR unique to the UCMs conditions will assist mines in achieving optimal sample results. Therefore, this component supports the system objective of enabling a proactive approach to the planning and management of UCM explosions (c). Additional to just the suggested application rate, displaying a graphical representation of failures in the graphs encourages more discussion for mines to consider the suitability of MDAR, which alone may make them more perceptive and responsive to changes that may be required. It establishes a real-life benchmark of a proactive risk management system for UCM explosions.

Limitations

Production Areas need to be clearly defined for the most accurate component performance and a PA should consistently relate to a MID target (70, 80, or 85). The component does not consider missed stone dust applications during the week, which may be the cause of a sample failure, rather than insufficient MDAR. Currently, due to the risk involved with UCM explosions, the optimal application rate is only suggested and not automatically implemented to be enforced.

Future Considerations and Standardisation

As previously discussed, to form a relationship between sample results and PAs in the current system, a relationship needs to be analytically established. Although this is expected to be sufficient for the purpose of this component, it would be more robust to have a direct relation created between PAs and EDZs in the digital twin, which has been discussed in the standardisation of other EDRMS components.

Several other limitations in the initial implementation were previously considered but are the consequence of the transitional real-world implementation of a new system with no previous real-world comparison. Once the system is more widely adopted at the research mine and sufficient data is gathered, these limitations can be addressed. For instance, once proven in operation, the suggested rate may be automatically enforced if it is outside the bounds of the satisfactory parameters from Table 4-1 Optimisation Rate Colour Coding

Assuming the component behaves as expected, there are minimal adjustments for standardisation at other mines. A significant benefit of the chosen optimisation method is that it is based on ongoing feedback control specific to a PA, regardless of what UCM it is. This means that each MDAR suggested will automatically adapt to the conditions within other mines for the defined PA, even if they differ from the research mine.

Usage and Further Discussion

While not yet implemented, there has been mixed feedback from the research mine surrounding the concept of an 'Optimised' MDAR. In the past, MDARs have been based on experience and generalised research and experimentation, which does not apply to all mines due to the significant variations in coal dust produced and its density, dependent on equipment, wetting methods, and many other uncontrollable factors. This, paired with the previous lack of transparency of overall process and system performance, results in many mines strongly preferring to be over-cautious than under-cautious, which has been prevalent in feedback. At the research mine, some stakeholders have been hesitant about not aiming for 100% stone dust content, even in an EDZ that may only require 70% as a MIC target. The concept that the optimised rate will aim to achieve the Compliance Target at 10% above, so only 77% for a 70% EDZ, is a new and different concept to grasp for some stakeholders. Other stakeholders, such as the Stone Dust Coordinator, have come to an understanding and agreed that the approach would provide an overall benefit to not only the research mines' resources but change the stigma across the UCM industry for how this can be managed. To provide flexibility to the hesitation, the system has been designed so that, if desired, the Compliance Target, which MDARs will aim to stabilise at, can be easily increased above 10%.

4.10 System Utilisation of BI Concepts

Throughout the system design and implementation, there was a focus on utilising BI concepts wherever possible. This benefited the systems' overall usability and standardisation and help bridge the BI system utilisation gap in the mining industry.

4.10.1 Data Warehouse

Likely the most challenging part of the EDRRMS creation and implementation was establishing a sufficient Data Warehouse. Four major steps were detailed in Business Intelligence to get from real-world to well-formed data. These were Data Consolidation, Data Cleaning, Data Transformation, and Data Reduction [25]. With one of the principal causes of ineffective explosive dust management stemming from the lack of data integration and visibility, it was important for the EDRMS to establish a sufficient Data Warehouse. It was also critical that the structure of the DW was as standardised as possible so that other mines may efficiently utilise the EDRMS.

The system uses SQL Server to structure all the back-end data. To consolidate the available data, it had to be collected, selected, and integrated. The new data to collect was primarily around capturing actual stone dust application, which is captured on our desktop and mobile applications. Several existing unconventional data sources required integration, including the AutoCAD Mine Plan and the laboratory dust sample results, which both faced challenges. The AutoCAD file contained many layers of data, making it difficult to decipher and select the essential data to extract. The DWG files had to be thoroughly analysed along with the vector format DXF to determine exactly how the data could be used to create a digital twin and extract the sampling requirements. The previous laboratory dust sample results had no standardised naming conventions and format, which was inconsistent with the EDZ names used in the EDRMS. Thus, they had to undergo Data Cleaning to eliminate inconsistencies and input missing values. First, the historic results had to be thoroughly analysed with assistance from the Stone Dust Coordinator to determine what previous EDZ names would be equivalent to in our system. Then, an equivalent EDZ comparison list was created, which was used to upload the three months' worth of dust sample history required by the system to create accurate labels and integrate with the laboratory.

With all the newly collected, integrated, and cleaned data within the DW, the EDRMS utilised it for other system components such as graphical representation, creating sample plans, and suggesting an optimised MDAR. Throughout these components, the data had to be transformed through aggregation and new attributes and often had to be reduced to exclude unnecessary variables. Establishing and utilising the DW will enable ongoing improvements and evolution of the EDRMS. Purposeful

4.10.2 Business Analytics

The primary BA elements used within the EDRMS components were Descriptive Analytics and Diagnostic Analytics, which provide insight into what happened and why. The EDRMS primarily achieved these through visual analytics with the many insightful data dashboards created. With the DW established, dashboards such as the failure and result graphs could utilise selected information to clearly display "what happened" to the user. Although this was displayed visually, the system used basic multidimensional analysis techniques with simple arithmetic and statistical operations, such as summing up, counting, calculating the mean and deviation, filtering, sorting, and ranking. While straightforward, utilising Descriptive Analytics within the EDRMS is already more insightful than the existing system and process of the research mine.

Although a DW was established to integrate and standardise future data, the historical data available was extremely limited for determining the exact correlation and relationship of different data the system will obtain. Therefore, the current EDRMS only provides a platform for users to detect this relationship and give insight into why something may have happened. With this circumstance, diagnostic analytics heavily relies on the practical design of visual analytics for this insight, which was achieved by enabling drill-down functionality on graphs, applicable graph groupings, and utilising more meaningful views, such as the heat map on the digital twin. Grouping the sample result and stone dust application graphs, each with drill-down ability, enables the user to identify previously unrealised relationships, such as between dust method and sample result failures. Similarly, displaying the data overlaid on the mine map may enable the user to identify relationships unique to particular physical locations.

The other core elements of BA are Predictive Analytics, which suggests what will happen, and Prescriptive Analytics to prescribe actions to make a desired outcome happen. While the EDRMS creates no direct models to suggest what will happen based on the data, the use of feedback control to suggest an MDAR that will achieve the desired sample result outcome does cover Prescriptive Analytics. The system has achieved this without using advanced algorithms such as machine learning or neural network commonly within these components. However, once more comprehensive data is available, these may be considered to improve the optimisation capabilities.

4.10.3 User Interface

As detailed in Business Analytics and evident through the system implementation results, user interfaces are a core component of the EDRMS. Additionally, to the utilisation of visual analytics, the UI component of BI focuses on the primary dashboard features three roles, which include strategic, analytical, and operational.

A strategic dashboard is used primarily by managers to focus on high-level performance measures against long-term strategic goals. The EDRMS implementation utilises this with multiple components of graphical reports, which have been thoroughly described. The strategic level would be achieved by the rolled-up graphs set to a large date range to see overall results. An analytical dashboard offers data-rich comparisons to aid in detecting patterns, which was utilised and explained within the BA component. An operational dashboard presents real-time data in an easily interpretable way that ensures it can attract immediate attention if an operation falls outside an acceptable threshold. The EDRMS design and implementation strongly considered this when creating the Live Failure Map component, which displays failures on the digital twin mine map as soon as they occur.

4.10.4 Business Performance Management

As previously explained, Business Performance Management is more a product of rather than a requirement of BI. BPM offers an overall strategy-driven framework in which a BI system and the process it creates should reflect. This is: strategise, plan, monitor/analyse, act/adjust. The EDRMS and processes involved within it align closely with this. The system supports a UCM to achieve strategic objectives such as no failures through the planning components of EDZ management to produce Sample Plans and Labels. Through the UI performance dashboards, a UCM can monitor and analyse their failure performance. If it is insufficient, it supports the UCM to act by making direct adjustments to the MDAR of PAs to enforce more stone dust applications which should improve and optimise sample results.

4.11 Evaluation Against Regulatory Audit Findings

In addition to improvements for the research mine, this thesis and EDRMS directly address many Queensland regulatory audit findings. These applied to many UCMs audited and can be considered a representative of what may be common across Australia and the world. Please note that these did not all apply to the research mine. The audit findings included [18]:

1. Gross lack of understanding of the intent and requirements of the legislation.
   - The cause and prevention of UCM explosions, legislation and studies on which it is based have been elaboratively explored in this thesis. These were considered in the EDRMS design.
2. Standard Operating Procedure (SOP) lacked a detailed method of zoning and sub-zoning.
   - The EDRMS establishes a digital twin of the UCM that enables users to easily create and manage each Explosive Dust Zone (EDZ).
3. The SOP did not provide for the rate of application of stone dust in development panels, longwall panels and outbye areas.
   - Production Areas were formed as a distinctive, modifiable, and integrated component of the EDRMS, each with an associated Minimum Dust Application Rate (MDAR).
4. Where a stone dust application rate was provided, the rate was based on past experience and sample analysis results, not on a scientific study.
   - Evaluating literature and studies surrounding coal dust generation and rates, it was evident that the impacting parameters vary significantly between UCMs and EDZs due to the fluctuating equipment, ventilation, and physical layout. This implies that a system that is designed based on the research conditions of a specific mine without live and accurate feedback is not robust when used for other mines or changing conditions within the same mine.
   - The thesis and EDRMS system solves this issue by extending the Production Area (PA) concept and utilising feedback control so that the previously set rates adapt and optimise their associated MDAR based on only relevant sample data.

5. No study on coal dust fallout had been carried out to decide the optimum rate of application of stone dust at different sections of mine roadways vis-à-vis source or generation rate of float dust.
    - Addressed by optimising the MDAR of the PA mentioned above.
6. The stone dusting method, dusting frequency, triggers for application of stone dust etc. were not detailed in the SOP.
    - The EDRMS handles all of these components.
7. The SOP did not provide for any sampling scheduling. A general work order for sampling was generated by the survey department. However, there was no spread-sheet or composite record for all the sample points and sampling date.
    - The EDRMS automatically schedules the next sample date of all EDZs based on its last sample date and its current sampling requirements. All records of past sampling and results are integrated and available within the system.
8. Date of collection and analysis of samples were not recorded in the analysis results.
    - All are integrated and available within the EDRMS.
9. There was no record maintained regarding the generation of coal dust at different locations and the required application rate of stone dust.
    - The PA and MDAR component covers this and shows any changes in MDARs.
10. No record of re-dusting locations and results were observed.
    - The EDRMS Failed Zone Re-treatment functionality records re-dusting applications.
11. There was gross inconsistency in the labels of samples, sample results from the laboratory and the work orders for sampling.
    - EDZ naming conventions have been standardised within the EDRMS to avoid this.
12. Sample locations were often not properly recorded on the analysis report.
    - The EDRMS utilises a unique sample ID number when integrating data from the laboratory and relates that to the EDZ and its standardised naming convention.
13. No spread sheet was maintained to keep the records of each sample's analysis result except the hard copy of the report provided by the laboratory.
    - All sampling history data is integrated and available on the EDRMS platform.

5 Conclusion and Future Research

This chapter summarises the work completed throughout this thesis with its original aim and the significance of the contribution made. Furthermore, future improvements and work that can build upon the thesis and EDRMS are discussed.

5.1 Thesis Aims and Objectives

This thesis successfully demonstrates the analysis, design, and creation of a real-world BI system that can provide a more efficient and robust process for managing the required dust sampling, application, and re-dusting practices across the mine to mitigate the risk of a UCM explosion. From assessing the fundamental problems encompassed in managing this risk and the regulatory requirements surrounding them, it was decided that a new integrated, adaptable, and proactive BI risk mitigation system was required. By reviewing existing literature on theoretical systems and the limitations of BI in the mining industry, common weaknesses were found that inhibited their real-world implementation. Combining this knowledge with a comprehensive evaluation of the associated research mines' existing processes and personnel responsibilities enabled the EDRMS to be designed.

Finally, through extensive and continuous requirements analysis and design, almost all the system was iteratively and incrementally developed and then implemented at the research mine to commence real-world use. The components of the new EDRMS were then evaluated against the existing process employed by the research mine, and further considerations and standardisation were discussed. How the EDRMS and this thesis successfully addressed the Queensland regulatory audit findings were briefly detailed. All stages conducted were as per the objectives of this thesis, and therefore, the aim was satisfied.

5.2 Significance and Contribution

This thesis and the EDRMS created within it have made many valuable contributions surrounding explosion risk management within underground coal mines. Overall, the initial implementation of the EDRMS at the research mine has received positive feedback from the Stone Dust Coordinator, including that it has made the process more straightforward, transparent, and robust. The evaluation and new system also highlighted several unforeseen flaws within their existing process and has challenged traditional views around optimal stone dust management. Due to these advancements, the research mine (BHP-Mitsubishi Broadmeadow) desires to nominate the system for an underground coal mine industry safety award.

In addition to improvements just for the research mine, this thesis and EDRMS directly address many Queensland regulatory audit findings detailed in 4.11, which would apply to many UCMs worldwide even if they did not all apply to the research mine. One finding was that no procedure in the UCM industry previously determined the optimum rate of application of stone dust, with the significant gap identified as a lack of studies. This thesis partly challenged this by concluding that a system designed based on the research conditions of a specific mine without live and accurate feedback is not robust when used for other mines or changing conditions within the same mine. The thesis also provides a new methodology using feedback control to provide a foundation that can address this.

With the general utilisation of Business Intelligence throughout the system whilst still considering the complex nature of roles, responsibilities and work culture, the EDRMS becomes another platform that can promote the utilisation of BI in the mining industry.

Existing procedures and legislation worldwide have been stagnant, inconsistent, and inefficient over the past 90 years [20]. Therefore, the successful design, development, and implementation of any real-world system which improves it is covering new ground. With the EDRMS and this thesis offering a standardised process that can improve the risk mitigation of a UCM explosion, it directly contributes to this significant and common real-world problem.

5.3 Improvements and Future Work

Although this thesis and EDRMS have covered much ground for the risk mitigation of a UCM explosion, many improvements and future work are still required to make the system more adaptable and accurate.

5.3.1 Standardisation for Use at Other Underground Coal Mines

As discussed, despite being implemented and suitable for the research mine, limitations still exist in its current implementation that would inhibit it from immediate use at other UCMs. The minor changes required for industry standardisation are detailed in the evaluation of components in Chapter 4. This standardisation limitation was acknowledged in the original design methodology and was knowingly decided upon so that the procedural change could be incremental, which has a better chance of success within the mining industry for BI systems

[36]. It is expected that the EDRMS may be requested for use by another UCM, and if so, the future work required for standardisation will be done during that implementation.

5.3.2 Improved Optimisation Method

When more historical data is readily available for analysis from this EDRMS, and the sensors available improve to measure more environmental conditions, the optimisation of the MDAR can be improved. From the relational performance data of the sample failures associated with a PA, it may be possible to determine a more optimal gain multiplier. With this data and if more live data of different conditions become available, the feedback control could potentially be advanced to Proportional Control, Proportional Integral Control, and Proportional Integral Derivative Control. If an effective stone dust application actuator was created, the dust could be automatically applied at the continuously updated optimal MDAR for the associated PA.

Similarly, with more accurate sensor data available, a real-world applicable multiple linear regression model could be developed to determine the optimal amount of stone dust required given live environmental conditions.

5.3.3 Ability to Integrate Other Hazards and Risks

In the future, there may be scope to integrate other vital risks into the EDRMS to improve their management and visibility. For instance, functionality could be created to raise geological or mechanical hazards, which could be graded depending on their determined risk. These could be raised on desktop or mobile to display on the live map component of the EDRMS and reveal more information and photos to allow better awareness and help with planning and safety. If this was further integrated with a planning and scheduling system, the schedule could be automatically adjusted based on the location and grade of a hazard.

6 References

[1] J. Dubiński, “Sustainable Development of Mining Mineral Resources,” *Journal of Sustainable Mining,* vol. 12, no. 1, pp. 1-6, 2013.

[2] American Geoscience Institute, “What are the main methods of mining?,” AGI, 2022. [Online]. Available: https://www.americangeosciences.org/critical-issues/faq/what-are-main-mining-methods#:~:text=There%20are%20four%20main%20mining,used%20to%20reach%20deeper%20deposits..

[3] N. Aziz, “Longwall Mining,” *Dictionary of Energy (Second Edition),* pp. 335-360, 2015.

[4] T. Ren and J. Zhang, “Investigations of Ventilation Airflow Characteristics on a Longwall Face—A Computational Approach,” *Water-Protection Coal Mining,* 2018.

[5] ACARP, “LONGWALL MINING,” University of Woollongong, 2012. [Online]. Available: http://www.undergroundcoal.com.au/fundamentals/07_overview.aspx.

[6] M. Lalatendu, M. Devi Prasad and K. J. Prasanta, “Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review,” *Journal of Network and Computer Applications,* vol. 106, pp. 48-67, 2018.

[7] M. S., S. K. and A. Esfahanipour, “Human health and safety risks management in underground coal mines using fuzzy TOPSIS,” *Science of The Total Environment,* vol. 489, pp. 85-99, 2014.

[8] G. S. Rice and H. Greenwld, “Coal-dust explosibility factors indicated by experimental mine investigations, 1911--1929.,” United States Department of Commerce, Washington, 1929.

[9] D. P. Mishra and S. Azam, “Experimental investigation on effects of particle size, dust concentration and dust-dispersion-air pressure on minimum ignition temperature and combustion process of coal dust clouds in a G-G furnace,,” *Fuel,* vol. 227, no. 0016-2361, pp. 424-433, 2018.

[10] C. Man and K. Teacoach, “How does limestone rock dust prevent coal dust explosions in coal mines?,” National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA, 2009.

[11] S. Azam and D. P. Mishra, “Effects of particle size, dust concentration and dust-dispersion-airpressure on rock dust inertant requirement for coal dust explosionsuppression in underground coal mines,” *Process Safety and Environmental Protection,* vol. 126, pp. 35-43, 2019.

[12] A. Sikandar and M. Devi Prasad, “Effects of particle size, dust concentration and dust-dispersion-air pressure on rock dust inertant requirement for coal dust explosion suppression in underground coal mines,,” *Process Safety and Environmental Protection Volume 126,* pp. 35-43, 2019.

[13] MSIA, “Mine Accidents Disasters in Australia,” Simtars, March 2022. [Online]. Available: http://www.mineaccidents.com.au/mine-event/279/2022-moranbah-north.

[14] M. J. Brnich and K. Kowalski, “Underground Coal Mine Disasters 1900 - 2010:,” NIOSH, Pittsburgh, 2010.

[15] Mining Technology, “Explosion at Turkish Hard Coal’s underground mine in Turkey kills 41,” Mining Technology , 7 October 2022. [Online]. Available: https://www.mining-technology.com/news/explosion-turkish-hard-coals-41/. [Accessed 2022].

[16] S. Eybers, M. Hattingh and L. Kuoe, “Investigating Factors that Influence the Adoption of BI Systems by End Users in the Mining Industry in Southern Africa,” in *Digital Transformation for a Sustainable Society in the 21st Century,* Springer, 2019, pp. 113-124.

[17] Department of Natural Rescources, Mines and Energy, “Quality of incombustible dust, sampling and analysis of roadway dust in underground coal mines,” *Recognised Standard 05, Coal Mining Safety and Health Act 1999,* 2018.

[18] Queensland Mines Inspectorate Rescources Safety and Health, “Review of Queensland underground coal mines’ stone dust application and sampling and analysis of roadway dust,” Queensland Department of Natural Rescources and Mines, 16 August 2013. [Online]. Available: https://www.rshq.qld.gov.au/safety-notices/mines/review-of-queensland-

underground-coal-mines-stone-dust-application-and-sampling-and-analysis-of-roadway-dust?SQ_DESIGN_NAME=print_preview.

[19] P. R. Amyotte and R. K. Eckhoff, “Dust explosion causation, prevention and mitigation: An overview,” *Journal of Chemical Health & Safety,* vol. 17, no. (1), pp. 15-28, 2010.

[20] M. Harris, K. Cashdollar, C. K. Man and E. Thimons, “Mitigating Coal Dust Explosions in Modern Underground Coal Mines,” National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, 2009.

[21] N. I. F. O. S. a. Health, “Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways,” CDC, May 2010. [Online]. Available: https://www.cdc.gov/niosh/mining/works/coversheet1326.html.

[22] M. L. Harris, M. J. Sapko, F. D. Varley and E. S. Weiss, “Coal Dust Explosibility Meter Evaluation and Recommendations for Application,” NIOSH, Pittsburgh, 2012.

[23] V. V. Khanzode, J. Maiti and P. Ray, “A methodology for evaluation and monitoring of recurring hazards in underground coal mining,” *Safety Science,* vol. 49, no. 8-9, pp. 1172-1179, 2011.

[24] L. M. Pejic, J. G. Torrent, E. Querol and K. Lebecki, “A new simple methodology for evaluation of explosion risk in underground coal mines,” *Journal of Loss Prevention in the Process Industries,* vol. 26, no. 6, pp. 1524-1529, 2013.

[25] R. Sharda, D. Delen and E. Turban, Business Intelligence and Analytics: Systems for Decision Support Tenth Edition, Pearson Education, 2014.

[26] C. E. Morr and H. Ali-Hassan, Analytics in Healthcare: A Practical Introduction, Toronto: Springer, 2019.

[27] C. Cote, “4 TYPES OF DATA ANALYTICS TO IMPROVE DECISION-MAKING,” Harvard Business School, 21 October 2021. [Online]. Available: https://online.hbs.edu/blog/post/types-of-data-analysis.

[28] R. Sharda, D. Delen, E. Turban and D. King, Business Intelligence: A Managerial Perspective on Analytics, Prentice Hall Press, 2013.

[29] C. Cote, “WHAT IS DESCRIPTIVE ANALYTICS?,” Harvard Business School, 9 November 2021. [Online]. Available: https://online.hbs.edu/blog/post/descriptive-analytics.

[30] I. PODOLAK, “MAKING SENSE OF ANALYTICS,” Healthcare Information Management & Communications, June 2018. [Online]. Available: http://www.healthcareimc.com/main/making-sense-of-analytics/.

[31] C. Cote, “WHAT IS DIAGNOSTIC ANALYTICS?,” Harvard Business School, 18 November 2021. [Online]. Available: https://online.hbs.edu/blog/post/diagnostic-analytics .

[32] C. Cote, “WHAT IS PREDICTIVE ANALYTICS?,” Harvard Business School , 26 October 2021. [Online]. Available: https://online.hbs.edu/blog/post/predictive-analytics.

[33] M. Chowdhury, A. Apon and K. Dey, Systems, Data Analytics fro Intelligent Transportation, ELSEVIER, 2017.

[34] C. Cote, “WHAT IS PRESCRIPTIVE ANALYTICS?,” Harvard Business School, November 2021. [Online]. Available: https://online.hbs.edu/blog/post/prescriptive-analytics.

[35] Y. Anastasova, “Possible Applications of Business Intelligence in the Mining Industry,” ResearchGate, 2017.

[36] Z. Hyder, K. Siau and F. Nah, “Artificial Intelligence, Machine Learning, and Autonomous Technologies in Mining Industry,” *Journal of Database Management* , vol. 30, no. 2, 2019.

[37] S. Matloob, Y. Li and K. Khan, “Safety Measurements and Risk Assessment of Coal Mining Industry Using Artificial Intelligence and Machine Learning,” *Open Journal of Business and Management*, vol. 9, no. 3, 2021.

[38] V. Kanade, “Linear Regression vs. Logistic Regression,” Spiceworks, 2020. [Online]. Available: https://www.spiceworks.com/tech/artificial-intelligence/articles/linear-regression-vs-logistic-regression/#:~:text=Linear%20regression%20is%20utilized%20for,regression%20helps%20accomplish%20classification%20tasks.&text=Supervised%20machine%20learning%20i.

[39] R. Bevans, "Multiple Linear Regression," Scribbr, November 2022. [Online]. Available: https://www.scribbr.com/statistics/multiple-linear-regression/.

[40] E. Kim, B. L. T. Roehm and S. Tout, "Control Architectures," in *Chemical Process Dynamics and Controls*, University of Michigan, 2007, pp. 888-903.

[41] B. Schweber, "Proportional Closed-Loop Control: The Foundation of Automated Systems," GlobalSpec, September 2015. [Online]. Available: https://electronics360.globalspec.com/article/5760/proportional-closed-loop-control-the-foundation-of-automated-systems.

[42] TWI, "What is Digital Twin Technology and How Does it Work," TWI, 2022. [Online]. Available: https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin.

[43] J. Brune, B. Goertz, S. McDaniel and T. Rockley, "Development of a Mine Dust Sampling Instrument for use in Underground Coal Mines," Colorado School of Mines, 2015.

[44] X. S. Sun and Y. Li, "Evaluation of Control System Performance Using Multiple Criteria Decision Making Techniques," ResearchGate, Atlanta , 2010.

[45] M. Allahyar, C. Aydin and I. Imil Hamda, "Chapter 3 - Unmanned aerial systems: autonomy, cognition, and control," in *Advances in Nonlinear Dynamics and Chaos (ANDC)*, Academic Press, 2021, pp. 47-80.

[46] P.-C. Ku and R. Mohan, "Graph Theory-Based Approach to Accomplish Complete Coverage Path Planning Tasks for Reconfigurable Robots," IEEE Access, 2019.

[47] I. Manchester, *AMME5520: Advanced Control and Optimisation Course Notes*, 2021.

[48] J. S. Arora, Introduction to Optimum Design, Academic Press, 2017.

[49] The Australian Mining Review, "Fix the Fatigue Cracks," The Australian Mining Review, September 2019. [Online]. Available: https://australianminingreview.com.au/techtalk/fix-the-fatigue-cracks/.

[50] Plantman, "10 TYPES OF HEAVY EQUIPMENT USED IN MINING," Plantman, 14 July 2022. [Online]. Available: https://www.plantman.com.au/10-types-of-heavy-equipment-used-in-mining/#:~:text=Excavators,-

Many%20types%20of&text=They%20are%20so%20commonly%20used,other%20wheeled%20machinery%20can't..

[51] Position Partners , “Drones In Mining To Improve Productivity, Planning and Management,” Position Partners , 2020. [Online]. Available: https://www.positionpartners.com.au/position-partners/drones-for-mining/.

[52] J. F. Peters, “Topology of Digital : Images: Basic,” in *Topology of Digital Images*, Berlin, Springer, 2014, pp. 1 - 79.

[53] H. Horst, “4 - Radiometry of Imaging,” in *Computer Vision and Applications*, Academic Press, 2000, pp. 85-109.

[54] Konica Minolta, “Radiometry,” Konica Minolta, 2019. [Online]. Available: https://www.konicaminolta.com/instruments/knowledge/light/concepts/01.html#:~:text=It%20is%20defined%20as%20the,Steradian%20(Watt%2Fsr)..

[55] R. Girshick, J. Donahue, T. Darrell and J. Malik, “Rich feature hierarchies for accurate object detection and semantic segmentation,” in *Proceedings of the IEEE conference on computer vision and pattern recognition*, IEEE Xplore, 2014, pp. 580-587.

[56] P. Antoniadis, “Mean Average Precision in Object Detection,” Baeldung, November 2022. [Online]. Available: https://www.baeldung.com/cs/ml-map-object-detection.

[57] Y. Jun, W. Wei and L. Guang, “Infrared Thermal Imaging-Based Crack Detection Using Deep Learning,” IEEEAccess , 2019.

[58] NSW Government, “Work Health and Safety Act 2011,” NSW Government, 2023. [Online]. Available: https://legislation.nsw.gov.au/view/whole/html/inforce/current/act-2011-010.

[59] NSW Government, “Work Health and Safety Regulations 2017,” NSW Government, 2023. [Online]. Available: https://legislation.nsw.gov.au/view/html/inforce/current/sl-2017-0404.

[60] Safe Work Australia, “Model WHS laws,” Safe Work Australia, 2023. [Online]. Available: https://www.safeworkaustralia.gov.au/law-and-regulation/model-whs-laws.

[61] The University of Sydney, “Work Health and Safety Policy,” The University of Sydney, 2018. [Online]. Available:

https://www.sydney.edu.au/policies/showdoc.aspx?recnum=PDOC2011/231&RendNum=0 .

[62] The University of Sydney, *Work Health and Safety (WHS) Induction*, 2020.

[63] Waldon Services Pty Ltd, *STD-11 Risk Management Standard*, Waldon Services Pty Ltd, 2023.

[64] Asana, "PERT chart: What it is and how to create one (with examples)," Asana, August 2021. [Online]. Available: https://asana.com/resources/pert-chart.

[65] Lucidchart, "What is a Swimlane Diagram," Lucidchart, January 2022. [Online]. Available: https://www.lucidchart.com/pages/tutorial/swimlane-diagram.

[66] M. Rehkopf, "What is a kanban board?," Atlassian, January 2022. [Online]. Available: https://www.atlassian.com/agile/kanban/boards.

[67] Project Management Institute , "PMI® Authorized On-demand PMP® Exam Prep," Project Management Institute , 2022. [Online]. Available: https://www.pmi.org/shop/p-/elearning/pmi-authorized-on-demand-pmp-exam-prep/el034.

[68] S. M.R., C. Seaman, T. Beck, J. Colinet and S. Mischler, "Characterization of airborne float coal dust emitted during continuous mining, longwall mining and belt transport," *Mining engineering*, vol. 69, no. 9, pp. 61-69, September 2017.

7 Appendix A: Case Study – AMME5520 Advanced Control and Optimisation

7.1 AMME5520 Outline

AMME5520 Advanced Control and Optimisation introduces engineering design via optimisation to find the "best possible" solution to a particular problem. This includes formulating designs that minimise cost and utilising optimisation frameworks emphasising connections to real-world engineering problems. This will be a reflective case study that evaluates how the learning objectives of this unit of study are relevant and relate to this thesis. The Learning Objectives (LOs) of AMME5520 are as follows:

1. Approach research papers in a professional and research-orientated manner, and conduct critical reviews of these papers.
2. Implement simple path generation algorithms, controllers and decision metrics for an autonomous system in order to meet specific mission objectives Use project management tools.
3. Understand a number of different path generation and control algorithms implemented in autonomous systems and how they are linked to optimality criteria, platform stability and vehicle constraints.
4. Understand how "cost functions" are used to define mission objectives in a mathematical form, so that autonomous systems can make decisions about their next action.

LO1. Approach research papers in a professional and research-orientated manner, and conduct critical reviews of these papers

The first learning outcome was directly addressed and demonstrated through Chapter 2 Research and Literature Review, and throughout the general progress of the thesis. Many research papers were read, evaluated, and critically reviewed. This meant not only did relevant background information need to be extracted, but each paper had to be critiqued and parallels drawn related to the problem addressed in this thesis. The research also led to the problem development, starting as a problem initially focused locally (at the research mine), however, through research and literature review, it was realised that the problem was more complex and spanned industry-wide, leading to further development of the addressed problem.

Although not directly classed as research papers, strong familiarity and understanding of the Australian legislative requirements for workplace safety surrounding Underground Coal Mines (UCM) and Explosive Dust Management (EDM) was a key requirement to complete this thesis. Beyond just a familiarity with these legislative requirements, the underlying problem of UCM explosions was thoroughly analysed to understand why and how the legislative requirements had been developed. As part of this, the global context of the regulatory requirements involving EDM was explored, revealing that much of the legislation was fundamentally based on an original study over 90 years old, which, when critically reviewed, revealed it was insufficient for modern mines.

To design the Explosive Dust Risk Mitigation System (EDRMS), a comprehensive understanding of the existing process and requirements was required. Although not research papers, this included evaluating historical sample results, work procedures, scans of paper stone dust applications, and many other disconnected steps involved in the process. These had to be thoroughly analysed to determine the system's fundamental components and what parts were inadequate. This comprehensive understanding was required as it would not be sufficient to just digitally replicate this process, but instead, re-define and improve it to create the EDRMS. The evaluation of research papers surrounding Business Intelligence and its applicability in the mining industry also contributed to this design and development.

LO2. Implement simple path generation algorithms, controllers and decision metrics for an autonomous system in order to meet specific mission objectives

Controllers were directly explored within this thesis for an autonomous system to meet specific mission objectives. The controller utilised was a simple feedback controller, with the mission objective set to optimise the amount of stone dust required to achieve a dust sample result equal to the compliance target, which was 10% above the minimum failure target. Feedback control was initially explored as a feasible option in section 2.5.2, and a proposed framework was comprehensively designed within Methodology section 3.3 for use within the EDRMS created in this thesis. This introduction of a feedback controller within the EDRMS has strongly challenged traditional views around stone dust management by introducing the concept of optimisation to this process by emphasising the waste of over-dusting. The feedback controller was simplified to suit the current infrastructure for real-world implementation. This design and consideration closely align with this subject's general focus of utilising optimisation frameworks emphasising connections to real-world engineering problems.

Despite decision metrics or matrices not explicitly explored and detailed within the thesis, general decision logic was essential to developing the EDRMS. Decision parameters had to be set for the system to behave in specific ways depending on what data it receives. This general behaviour reflects decision metrics and a decision matrix, which has alternative decisions based on the combination of attributes presented to it [44]. An example of this is how the Failed Zone Retreatment component of the EDRMS behaves based on the sample result it receives and its associated attributes. For instance, if a dust sample result of an Explosive Dust Zone (EDZ) returns with 78% incombustible (stone) dust content, before the EDRMS can class the result and determine the time limit to re-dust that EDZ, its attributes need to be considered. If the EDZ is a Face Zone (85% minimum target), it Failed and requires re-dusting within 12 hours; if it is a Conveyor Road (80%), it Failed and requires re-dusting within 7 days; if it is a Gate Road Barrier (80%), it Failed and required re-dusting within 12 hours. This failure class and re-dusting timeframe are then displayed on an interface created within the EDRMS.

Path Generation Algorithms (PGAs) were not explored as part of this thesis however, their capabilities can be related to parts of the problem being addressed. A PGA decides how to navigate a path within a landscape according to available information in the current state and the criteria used, such as the shortest distance or quickest time that is collision-free to a set target [45]. In the context of an Underground Coal Mine Explosion, two examples that could utilise path generation are when a UCM explosion occurs and if automated dust-applying equipment was used. Assuming a detection and direction display system was established throughout the UCM, a PGA could be developed to aid workers in escaping if a UCM explosion occurs. If an explosion was detected, the PGA could identify this as a collision point and then, based on the algorithm, display varying directions on the display screens throughout the mine that inform workers of the quickest way to escape based on their current location and the explosion. If dust-applying equipment was modified to have sufficient sensors and actuators, a PGA could direct it to different EDZ within the mine. The EDZ location target could change for routine dusting, and the PGA could find the quickest route to that location, avoiding obstacles along the way.

LO3. Understand a number of different path generation and control algorithms implemented in autonomous systems and how they are linked to optimality criteria, platform stability and vehicle constraints.

Following on from LO2, path generation algorithms were not explored within this thesis and only a simple feedback control algorithm was implemented. While optimal performance was considered in feedback control, there was no explicit association to platform stability and vehicle constraints within this thesis. As such, path planning algorithms and how autonomous systems link to optimality criteria, platform stability, and vehicle constraints will be explored further to improve coverage of this learning objective.

A foundational concept for path generation is the use of a Graph (G), which Graph Theory defines as a structure that relates a set of vertices, referred to as Nodes (N), through their associated Edges (E). A graph G(N, E) is a non-linear data structure of nodes with either undirected or directed edges connecting them [46]. It can be used to represent important features of a network, such as a path map. A graph can also be weighted by associating additional information to determine the cost of travelling along an edge.

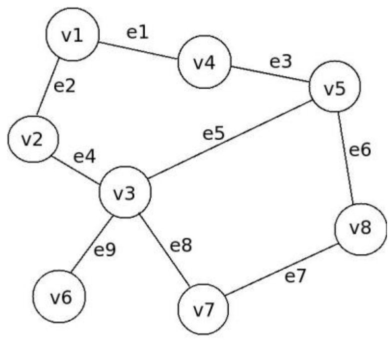


Figure 7-1 Undirected Graph with 8 Nodes and 9 Edges

A path generation algorithm that utilises this weighted graph concept is Dijkstra's algorithm, which can be used to find the shortest path from a chosen start node to all other nodes in the graph. The algorithm retains the shortest distance from each node to the start node and continuously updates these values if it finds a shorter path while analysing the graph. Once the shortest path between the start node and another node is found, that node is identified as "visited" and added to the path. This continues until each node is added to the path, resulting in a path that connects the start node to all other nodes by following the shortest possible path to reach each node [46]. Any non-negative weights can be associated with edges that connect the nodes, representing costs to get from each node to another. By defining these costs to criteria such as distance or money, Dijkstra's algorithm can minimise the defined cost between the initial start node and all other nodes in a graph.

In many implementations, Dijkstra's algorithm has been adapted to perform better or suit specific mission objectives. An example is the A-Star algorithm, an informed version of Dijkstra's algorithm that optimises finding the desired path of a minimised cost between a specified node and a goal node. The algorithm optimises this by incorporating a heuristic that prioritises utilising nodes more likely to be on the shortest path, which results in less explored nodes and, thus, a faster overall computation time compared to Dijkstra's algorithm [47].

Optimality criteria are the conditions a function must satisfy at its minimum point [48]. It is evident this links to path generation algorithms such as Dijkstra's algorithm, which will find the shortest path between nodes considering their weighted edges, which can be associated with many different optimality criteria that are minimised. Similarly, as briefly explored in this thesis, many other advanced control methods can minimise the time it takes to reach a desired set point. The stability of a platform or system is also a staple of feedback control, which stabilises at the set point, which may be a set speed, distance, or any measurable metric, such as the sample result compliance target within this thesis. It is also essential to account for how autonomous systems consider constraints, as some methods may assume that the state and actuation are unconstrained. In reality, there are constraints surrounding all systems, such as actuators having limited power, and states may be limited physically or for safety.

LO4. Understand how "cost functions" are used to define mission objectives in a mathematical form, so that autonomous systems can make decisions about their next action.

A cost function is a mathematical representation of the performance measure a system aims to minimise and is used in autonomous systems to make decisions that will lead to this minimisation [47]. Examples of the cost may include total power consumption, integrated error, or deviation from a reference value of a signal, which in the case of the feedback controller implemented in this thesis, was the compliance target of the sample result. In physical systems, maximising the performance of a system while minimising the effort of the system's actuators is critical. In feedback control, this is done by optimising the overshoot and settling time. As discussed for potential extensions for this thesis, this optimisation of the feedback controller would be essential if more comprehensive sensors and actuators become available.

This optimisation of the feedback controller could be achieved by using the poles of the system however, other methods can also be used, such as a Linear Quadratic Regulator, which would have a different cost function. Each method and cost function has advantages and limitations, so one method will not be sufficient for all mission objectives. Therefore, the method and cost function chosen should align with the mission objectives and consider the constraints surrounding it. This was evidently considered within this thesis with the utilisation of only a simple feedback control system without a gain multiplier, as there were constraints around sensor utilisation, sample reliability, and general data availability.

As explored in LO3, minimising the cost of path generation using relevant algorithms is also essential for many autonomous systems to be capable of making decisions that will achieve their mission objective. Without the cost function of these algorithms clearly defined, these systems would not be able to operate optimally.

Summary

This case study has demonstrated this thesis' relevance to each learning objective and explored additonal content where required to address the LOs sufficiently. The first LO was comprehensively addressed within this thesis's research and literature review and reflected upon. The second LO was partially addressed with the implementation of a feedback controller and decision metrics within this thesis however, the potential relevance of path generation algorithms was also evaluated to cover LO2. There was minimal explicit coverage of the third LO within this thesis, and thus, additional content was researched and presented to demonstrate sufficient understanding. The fourth LO was partially covered within this thesis and also related to content within LO3 and, thus, was only briefly evaluated.

Therefore, this case study, in conjunction with this thesis, has sufficiently addressed the learning objectives of AMME5520 by exploring designs that minimise cost and utilise optimisation frameworks with connections to real-world engineering problems.

8 Appendix B: Case Study – AMME4710 Computer Vision and Image Processing

AMME4710 Computer Vision and Image Processing aims to introduce students to vision sensors, computer vision analysis, and digital image processing. As this subject does not closely relate to this thesis, this will be a theoretical project case study that aims to address the remaining learning attributes of AMME4710 in conjunction with the overall thesis.

8.1 Aim and Objectives

This case study aims to demonstrate an understanding of image foundations and how computer vision and image processing can be applied to real-world scenarios and problems. To achieve this goal, the case study will meet the following objectives:

i. Introduce a real-world project in which Computer Vision and Image Processing can be applied to positively impact how a task is completed.
ii. Provide relevant background on principles of image formation.
iii. Apply the advanced technique of object detection to the project and utilise some basic image processing techniques.
iv. Evaluate the success and feasibility of utilising Computer Vision and Image Processing for the project.

8.2 Project Overview – Detecting Stress Cracks in Mining Equipment

A significant and expensive aspect of maintenance in the mining industry is the repair of fatigue cracking in heavy earth-moving equipment [49]. Heavy earth-moving equipment in mining includes Loaders, Dozers, Dump Trucks, and Excavators, all of which are significantly larger compared to their standard counterparts [50]. As expected, many challenges concern managing and repairing fatigue cracking on such large and complex equipment. These include identifying and reporting the nature and location of cracking, how to assess the severity, monitoring and tracking cracking, understanding the causes, and planning for the weld repair requirements [49].

This case study will investigate how Computer Vision (CV) and Image Processing (IP) may be utilised to aid in the challenges of identifying, monitoring, and tracking cracking, particularly in hard-to-reach locations such as the booms and arms of excavators or trays of dump trucks.

Figure 8-1Mining Excavator Loading Dump Truck

It is understood through previous experience at mining sites that to inspect equipment such as excavators for cracks, the machine must be halted entirely and isolated for safety. Then an exclusive control parameter is established, and equipment such as an elevating work platform is used so that personnel can see critical places such as the joints of connection points of excavator booms, which is the top horizontal arm attached to the body. This procedure takes much time and also exposes people to working at height risks. Therefore, to save time and reduce risk, it would be highly beneficial if these parts of mining equipment could be inspected for cracks without needing such an extensive and interruptive procedure.

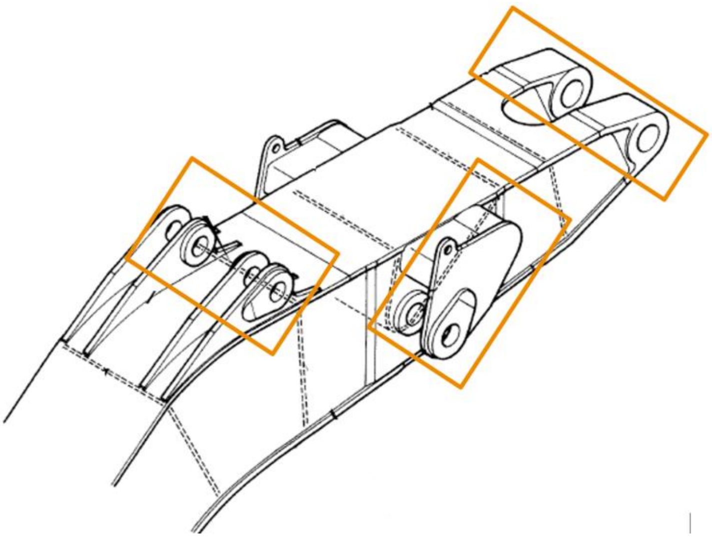


Figure 8-2 High-Risk Crack Locations of Excavators

A potential method to improve this procedure is using drones and CV. Drones have become increasingly popular and common in the mining industry to assist with exploration, surveying and mapping [51]. With this increased use, there are improvements in productivity, planning, and management areas. Therefore, this project proposes that Drones could be seamlessly used in inspections of mining equipment to capture high-quality images of hard-to-reach places. This could be done without isolating the machine and using assistive equipment to raise personnel, resulting in less downtime, risk, and personnel needed. A CV and IP approach could then be utilised on these captured images for Equipment Crack Detection (ECD), which will be the primary focus of this case study.

8.3 Background of Image Formation

A digital image is a discrete representation of the observable world at any given moment. This discrete representation is through physical points in a raster image, known as pixels. Each pixel within a digital image can be represented by the Intensity (I) of light colour at spatial coordinates within it (x,y), with colour images extending each (x,y) coordinate into a 1 x 3 array containing intensity elements of red, green, and blue [52]. Three standard types of images are a binary image, which contains pixels that are only black or white, a greyscale image which contains pixels visible as different tones of black, white, and grey, and a colour image, which is a multidimensional image with pixels of one or more colours.

Figure 8-3 Binary, Grayscale, and Colour Image

Each pixel within an image and its spatial layout and intensity variations result from information from an optical sensor. This is the response of an optical sensor to a particle of light (photon) reflected off parts of objects within its field of view. For digital images, the information is usually a point sample of a single number in a greyscale image or a set of three numbers in a colour image. Each time a sensor captures an image, its sensitivity to the magnitude of the electromagnetic energy determines the radiometric resolution, which is the ability of the system to detect minor differences in reflected or emitted energy. Radiometry is the measurement of radiometric quantity, such as radiance, irradiance, or intensity. [53]. Radiance is the radiant flux emitted, reflected, or transmitted by a surface, which can give insight into an object's brightness. Irradiance is the radiant flux received by a surface or the flux that is incident on the surface, which can give insight into the distance. The intensity is the radiant power emitted from the source through a certain angle [54].

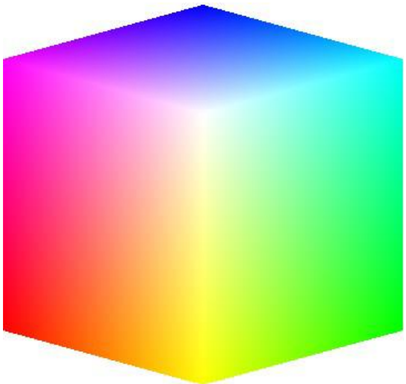


Figure 8-4 Red Green Blue Colour Cube [52]

These foundations of image principles are used in IP and CV techniques to obtain information about the underlying physical processes and object properties. There are constant trade-offs between spatial, spectral, and radiometric resolution, which must be considered when utilising different optical sensors for varying purposes [53]. Although these principles can impact the initial information within a captured image, this information can be transformed using image processing techniques.

8.4 Equipment Crack Detector (ECD) Methodology

The ECD will utilise the advanced computer vision method of object detection to detect cracks in metal images. In the addressed scenario of this project, the images would be captured by a drone doing a routine inspection of a piece of mining equipment. To replicate this scenario, this case study will create an original dataset of 60 images sourced from Google, which can be used to train the object detection system. The ECD will utilise Microsoft Azure’s Custom Vision service, a platform that enables trained object detection based on appropriate datasets. Custom Vision utilises a Fast region-based convolutional neural network (R-CNN), which is a deep learning approach applied to object detection. As the R-CNN name suggests, regions are defined from an input image. Then, a convolutional neural network is used to perform forward propagation on each region proposal to extract its features. The features of each region proposal can then be used for predicting the ‘class’ of that region. For Fast R-CNNs, an Edge Boxes algorithm generates region proposals and aggregates the features corresponding to each region proposal to make the process more efficient. [55].

The ECD will utilise the Custom Vision platform using two datasets and training approaches. Approach 1 will use the original dataset of unprocessed images to train the ECD. Approach 2 will apply basic image processing techniques to the original dataset, such as filtering to exaggerate image properties before training the ECD.

8.4.1 Approach 1 – Unprocessed Dataset Model (UDM)

The original unprocessed dataset comprises 60 images, each containing some form of crack in metal. The preference for images was some form of mining equipment, such as excavators and trucks, which contained a visible crack. Only 39 images of this preference could be found using Google images. Therefore, the 21 remaining images used to complete the dataset were of cracks in general metal structures, such as pipes and beams.

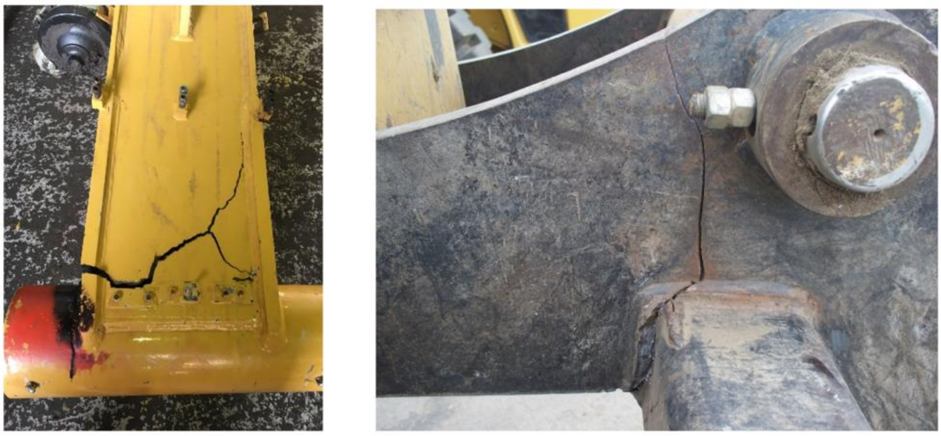


Figure 8-5 Cracks within Mining Equipment

Next, this dataset was input into Custom Vision, and as it utilises R-CNN, boxes of the crack regions need to be defined and tagged as a specific class. This needs to be done manually for each image before the entire ECD can be trained.

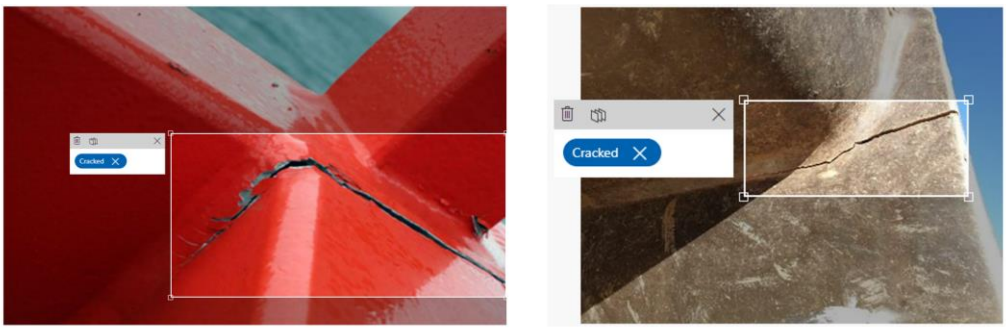


Figure 8-6 Labelling Crack Regions in Custom Vision

Once the regions of cracks are defined for the entire dataset, the model can be trained using Custom Vision, which splits the dataset into two subsets, a Training Set of 38 images and a Validation Set of 12 images. These are later used to determine the precision, recall, and mean average precision of the UDM.

8.4.2 Approach 2 – Processed Dataset Model (PDM)

This approach uses the same dataset of 60 images as the first approach, however, it introduces the additonal step of applying Image Processing techniques. Before inputting the dataset through the ECD in Custom Vision, each image is processed to highlight the cracks within it.

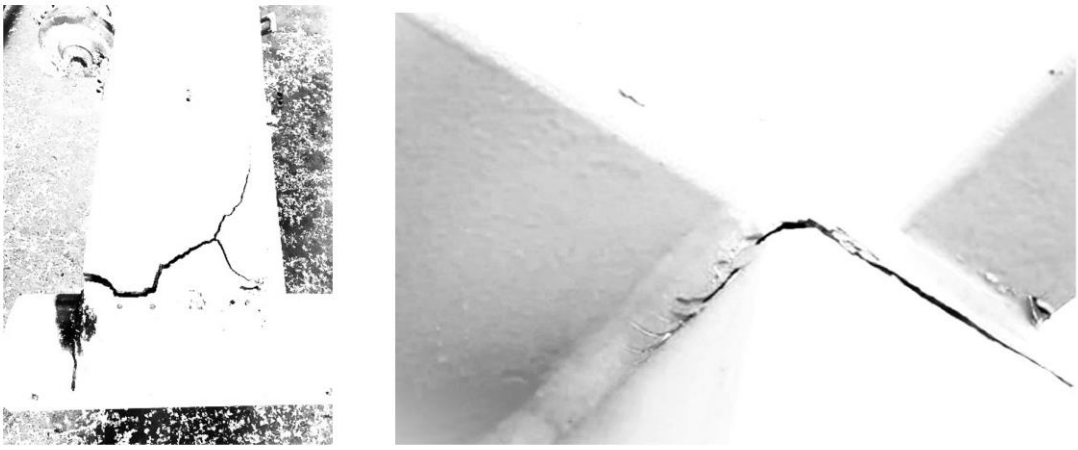


Figure 8-7 Image Processing of Crack Images

Figure 8-6 Image Processing of Crack Images shows that the cracks within the metal are defined from the rest of the image by applying basic filtering techniques using standard image viewing software. The main adjustments to achieve this are removing the colour from the images, increasing the contrast and exposure of the images, and decreasing shadows within the image, all of which can be completed with most standard image-viewing software. These image-processing techniques exaggerate the features of the crack regions within the image and, therefore, are expected to work better than UDM with the R-CNN of Custom Vision.

Once all images are processed, the dataset is uploaded into Custom Vision and has the crack regions defined and tagged as “IPCrack” for each. The ECD will be trained using the IP dataset separated into 48 training images and 12 validation images.

8.5 Results and Evaluation

8.5.1 Evaluation Parameters

To evaluate the separate approaches, the three metrics of precision, recall, and mean average precision is used. These are determined based on two defined performance criteria, the probability threshold and the overlap threshold. The probability threshold is the minimum probability score needed for an ECD prediction to be considered valid, which will be set at 50%, as it is typical for object detection models [56]. The overlap threshold is the minimum percentage overlap required between predicted bounding boxes created by the model and the user-defined ground truth boxes. This criterion typically varies depending on the scenario. It has been set to just 35% as some user-defined ground truth boxes contain substantial areas that may not contain a crack due to its path. Also, even a portion of a crack suffice to alert the user.

Table 8-1 EDM Dataset Parameters

	Dataset Parameters
Probability Threshold	50 %
Overlap Threshold	35 %
Training Set Images	48
Validation Set Images	12
Test Set	15

All three metrics are then determined using these two thresholds within the Validation Set of images. Precision is the percentage of true positive crack detections out of the total of true and false positive detections. Recall is the percentage of correctly identified true positive cracks out of the total instances of cracks within the Validation Set. The mean average precision is the mean of average precisions for each class tagged. Each of these metrics are calculated automatically within Custom Vision based on the defined performance criteria. Each of the two ECD models can be further tested with an upload of test images into Custom Vision. This will be done using a Test Set of 15 images for each model, which will be different from the Validation Set.

Table 8-2 ECD Performance Across Both Approaches

	Approach 1 (UDM)	Approach 2 (PDM)
Precision	100.00 %	100.00 %
Recall	66.67 %	83.33 %
Mean Average Precision	100.00 %	100.00 %

8.5.2 Precision and Confidence Comparison

As demonstrated in the results, both datasets produced a model with 100% precision, meaning that if a positive crack was detected (i.e., the confidence of being a crack is above the probability threshold of 50%), it was a true positive crack. This means no false positives were detected within either of the Validation Sets. Although both the UDM and PDM resulted in the same precision, the degree of confidence of the detected cracks notably varied between the unprocessed image and processed image sets. Figure 8-8 shows that the IPCrack was detected with a confidence of 83.7%, which is over 17% higher than the UDM Crack. In this case, neither model captured the top portion of the crack however, this was not of concern as it would still be capable of alerting inspectors.

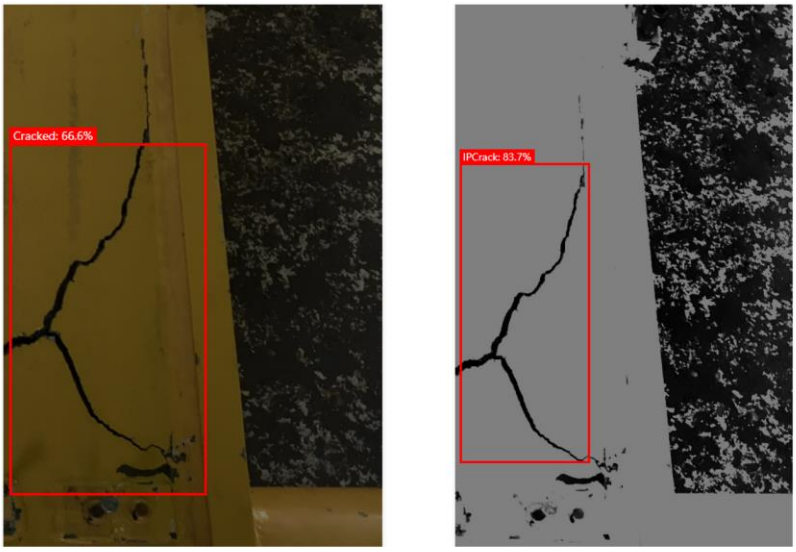


Figure 8-8 ECD Confidence Comparison 1

Similarly, Figure 8-9 demonstrates that the IPCrack is again detected with higher confidence, more than 30% above the UDM. However, in this test, the IPCrack detected far less of the actual crack than the original.

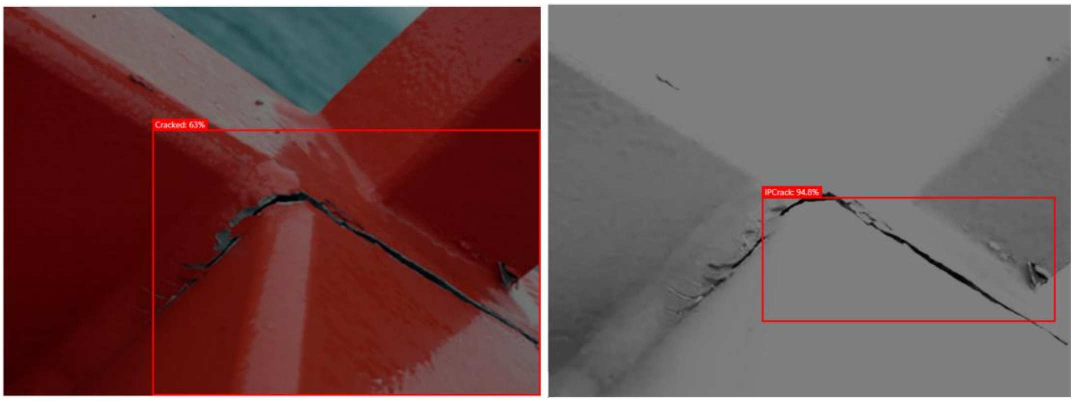


Figure 8-9 ECD Confidence Comparison 2

Whilst the IPCrack detection of the PDM frequently had higher confidence than the UDM Crack detection, there were some circumstances where it was below, such as in Figure 8-10, where it is 4.9% lower.

Figure 8-10 ECD Confidence Comparison 3

Of the 15 test images used with each ECD model, there were 12 cracks detected with higher confidence using the PDM. The PDM model had 10 of 15 cracks detected with confidence above 71% and overall average confidence of 80.4% across the test set. The UDM had 10 of 15 cracks detected with confidence above 56% and overall average confidence of 63.6% across the test set.

8.5.3 Recall Comparison

It is evident from Table 8-2 that the PDM had a better recall than the UDM, which means it had fewer failures at detecting cracks within the Validation Set. Out of the Validation Set of 12 images, the PDM failed to detect 2 cracks, resulting in a recall of 83.33%. In comparison, the UDM failed to detect 4 cracks from the 12 images, resulting in a recall of 66.67%. Figure

8-11 shows failed detection from each model's Validation Set. While there was indeed a crack detection, the confidence is below the probability threshold of 50%. This means that despite having an overlap threshold above 35% of the ground truth boxes (outlined in white), this crack detection was not considered in evaluating the recall.

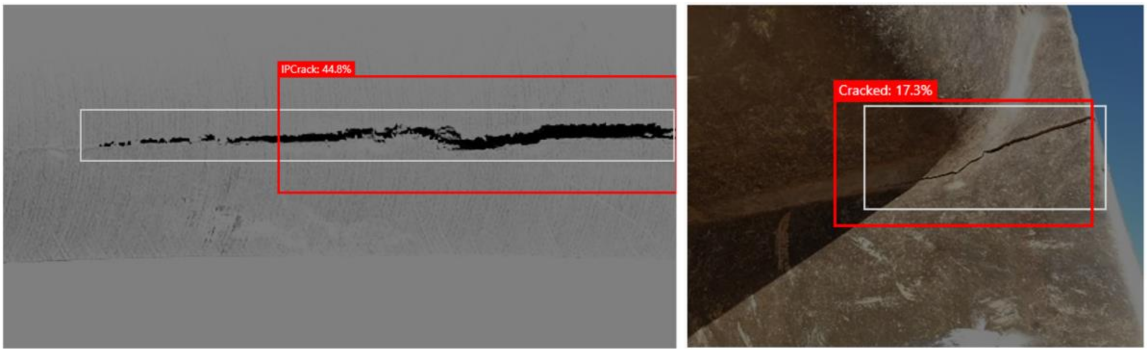


Figure 8-11 Insufficiently Confident Crack Detections in Validation Set

Additionally, when each model was tested using the 15 test images, both similarly had some failed detections. The failed detection from the UDM seen in Figure 8-11 was one of the test images selected for the PDM to test performance. Interestingly, as seen in Figure 8-12, the PDM also failed to detect the crack above the probability threshold in this image. It is believed that the low confidence of detecting this crack in both the unprocessed and processed sets is due to the other conflicting shadow features within the image, and there were not enough images within the training set that contained these heavily conflicting features to make the model more confident.

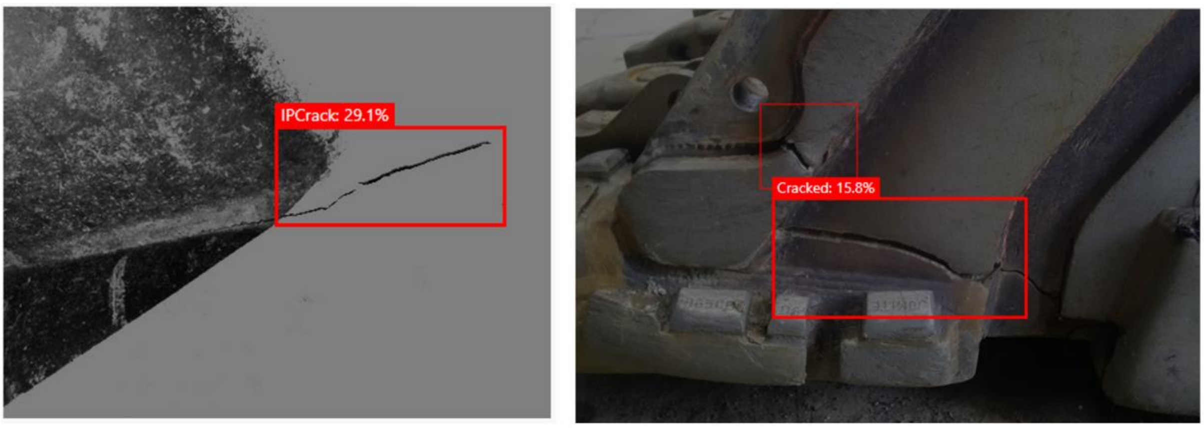


Figure 8-12 Insufficiently Confident Crack Detections in the Test Set

The other test image in Figure 8-12 from the UDM test set failed to detect either crack within the same image with sufficient confidence. The low confidence of both these crack detections (15.8% and 21.3%) was likely due to the other complex, conflicting features in this particular image and a lack of these types used in the training image set. From the 15 Test Set images for the UDM model, there were 4 where a crack was not detected, resulting in a recall of 73.3%, which was better than the Validation Set of 66.67%. The PDM model failed to detect a crack in 3 of the 15 images, resulting in a recall of 80.00%, which was below the Validation recall of 83.33%. These notable variations between the recall of the validation and test sets are likely a consequence of the small dataset that results in a more significant impact on percentage performance when discrepancies occur.

8.6 Limitations and Future Work

Although there was an overall positive performance considering the project's confinements, future work is required to address the evident limitations. Firstly, the most impactful limitation was the unattainability of sufficient images of cracks in mining equipment, resulting in a considerably small dataset. Therefore, future work would need to consider visiting a mine site to attain more images of new cracks, preferably using a drone to capture the images without isolating the equipment, as suggested by this case study. Using these images and gaining access to a company database of existing crack images would enable a more comprehensive dataset to be used in training, giving a better indication of the models' performance with images of varying features.

This case study demonstrated that the performance of utilising images that had been processed to exaggerate the features of cracks was better than the raw images. Therefore, a wider range of image processing techniques using more advanced software such as MATLAB should be considered in future work.

Another limitation was that the model has not been tested in a practical sense where it would also be processing images with no cracks within it and other landscapes. Thus, future work would need to include a more extensive Test Set of images that includes images of these different scenarios to ensure the model is robust for practical use. Another consideration for practical use is the scenario of identifying non-visible cracks under the surface. Currently, these are detected using a vision-based approach of infrared thermal images taken by inspectors. There are studies pertaining to the use of R-CNN on thermal images to detect cracks [57] which could be considered along with the ability of drones to capture thermal images in future work.

8.7 Conclusion

This case study introduced the real-world project of developing an Equipment Crack Detetctor that can utilise Computer Vision and Image Processing to positively impact how the task can be completed. Relevant background on image formation and other aspects of CV and IP was provided throughout to aid in understanding. The advanced CV technique of object detection was applied through Custom Vision and utilising Fast R-CNNs in conjunction with IP techniques to develop two ECD models successfully. By evaluating the success of these models, it was learnt that the image dataset that had been through IP had a better overall performance in detecting cracks on mining equipment. This evaluation then helped highlight the limitations within the current implementation, which can lead to future work that will make the model more feasible for practical use.

Through this development and evaluation of the Equipment Crack Detector, it is concluded that the project achieved its objectives, and this case study has addressed learning attributes of AMME4710 in conjunction with the overall thesis.

9 Appendix C: Work Health and Safety Report

9.1 Introduction

My industry placement was taken over six months with Waldon Services. The company does not have a physical office, so all its employees, including myself, work remotely online. This meant that I was located at home most of the time during my placement. Occasionally, some employees are required to travel to a physical client mine site in either remote QLD or NSW. I travelled three times throughout my industry placement, twice near Moranbah in QLD to visit the project mine site and conduct research for this thesis, and once to a mine site in Muswellbrook NSW to gain more insight on other projects handled by Waldon Services.

Despite working from home, Work Health and Safety (WHS) laws still apply, meaning I, within Waldon Services, am still obliged to comply with the Work Health and Safety Act 2011 [58] and the Work Health and Safety Regulation 2017 [59]. The essence of these is that an employer must eliminate or minimise workers' health and safety risks, so far as is reasonably practicable, and that employees have an obligation to take care of their own and others' health and safety [60].

The University of Sydney also has its own WHS Procedures (2016) [61] and provides a WHS Induction Module [62], which outlines standard processes that support the implementation of a safety management system to support an appropriate level of risk. The University utilises the risk matrix below to asses a hazards associated level of risk, depending on its consequences and likelihood.

			Potential Consequences				
			L6	L5	L4	L3	L2
			Minor injuries or discomfort. No medical treatment or measureable physical effects.	Injuries or illness requiring medical treatment. Temporary impairment.	Injuries or illness requiring hospital admission.	Injury or illness resulting in permanent impairment.	Fatality
			Not Significant	Minor	Moderate	Major	Severe
Likelihood	Expected to occur regularly under normal circumstances	Almost Certain	Medium	High	Very High	Very High	Very High
	Expected to occur at some time	Likely	Medium	High	High	Very High	Very High
	May occur at some time	Possible	Low	Medium	High	High	Very High
	Not likely to occur in normal circumstances	Unlikely	Low	Low	Medium	Medium	High
	Could happen, but probably never will	Rare	Low	Low	Low	Low	Medium

Figure 9-1 Risk Matrix Utilised by The University of Sydney [62]

9.2 Waldon Services Practice

Waldon Services implements its own Risk Policy (POL-04) and Risk Management Standard (STD-11) to maintain an acceptable level of risk concerning all business operations. The process for assessing, treating, monitoring and reviewing risk within the business is outlined in Figure 9-2.

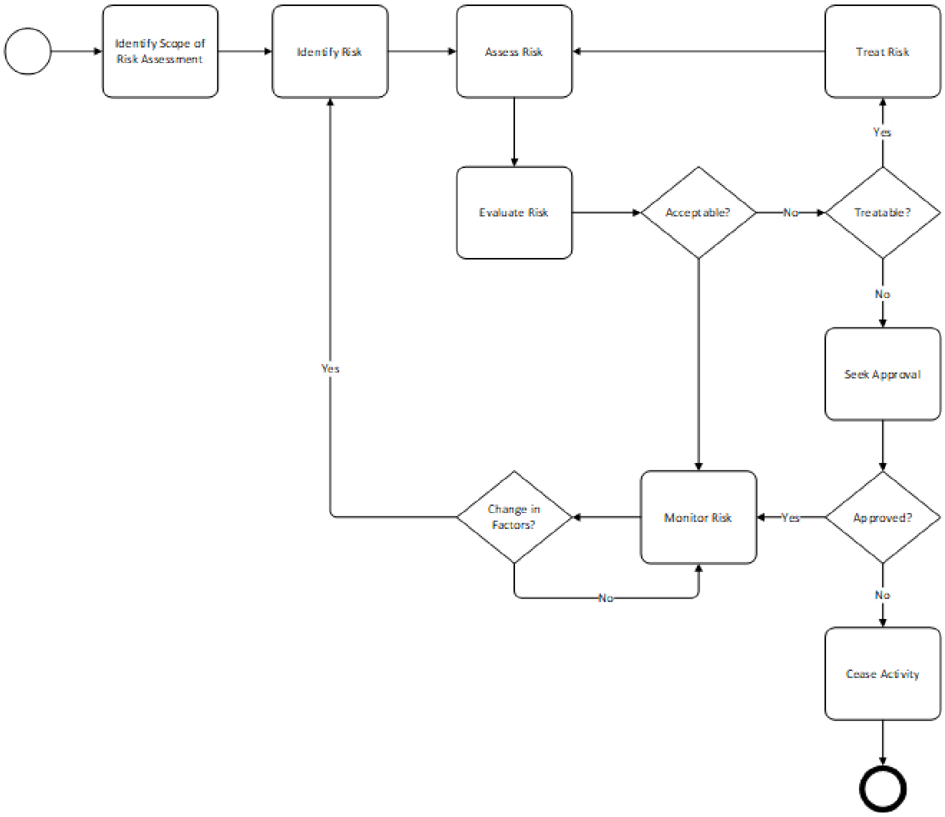


Figure 9-2 Risk Assessing, Treating, Monitoring [63]

Although most work is computer-based from home, there are also hazards with associated health risks. Some of these include:

- Repetitive data entry tasks
- Sedentary work, such as prolonged sitting
- Peak periods of high workload
- Inadequate face to face support
- Limited opportunities to debrief after difficult conversations

- Lack of training and mentoring
- Workers feeling disconnected from their managers, colleagues and support networks
- Workers being distracted and not managing workloads

Waldon Services have processes to try to mitigate these risks where they can. This includes, upon initial employment, sufficient home office equipment such as monitors and better chairs are offered which can improve ergonomics. Poor ergonomics increases the risk of postural problems and may even lead to back, arm, neck, wrist and hand pain. Even with sufficient equipment, it is still the employee's responsibility to maintain regular physical movement and stretch while working will also help prevent injury and keep the body limber.

Another essential process implemented by Waldon Services is routine daily “stand-up” meetings and enforcing a “wellness share” before any meeting. These routine daily stand-up meetings are vital as they provide an opportunity to connect with managers and colleagues while focusing on ensuring everyone is on task and managing their workload. A wellness share is done at the start of every meeting, including stand-ups. It is an opportunity that requests anyone to provide wellness, gratitude, or experience share with everyone else. This routine builds a further, non-work related connection with everyone and creates a comfortable and safe working environment as people can share anything, good or bad. This simple process is crucial for maintaining good mental health while working from home. Another beneficial routine implemented by Waldon Services is a Weekly Virtual Afternoon Tea. This is an hour-long session after Thursday lunch where everyone in the team gets together and participates in some form of activity. This is an important practice to understand colleagues better and improve general mental health.

With Waldon Services, an employee is exposed to the most significant risk when visiting one of the client's mine sites. There are far more safety measures in place to combat this increase in risk due to the presence and significance of more hazards. The most notable is the Personal Protective Equipment (PPE) required when moving most places around and in the mine site. This includes:

- Long-sleeved Fluro shirts are provided to protect workers from sun and light scratches and increase the worker's visibility. Similarly, long pants must be worn.
- Steel cap boots are provided to protect the feet in case anything heavy or sharp objects fall.

- Safety gloves are provided to protect a worker's hands and limit the chances of lacerations.
- Hard hats are provided to protect workers' heads from potential falling objects.
- Safety glasses are provided to limit any dust or objects entering a worker's eyes.
- Dust masks must be worn if in dangerous atmospheric conditions

Figure 9-3 Mine Site Personal Protective Equipment

In addition to the PPE, extensive safety measures and restrictions are in place to ensure that only people qualified and capable of completing specific tasks on the mine site can complete them. One safety measure is randomly drug and alcohol testing all workers to limit the chance that somebody incapacitated is completing a high-risk job such as driving a large truck, which could injure or kill themselves and others.

When visiting a mine site, you must comply with all their work health and safety rules, regulations, and procedures. In the case when I visited the research mine, BMA Broadmeadow in QLD, I had to complete extensive safety training before I was allowed to go underground. This included learning to use safety equipment such as the Compressed Air Breathing Apparatus (CABA). These are required in the event of an emergency underground that may make the air unbreathable. In this event, these CABA units are situated at emergency points throughout the mine with sufficient re-fill stations for use. Other emergency techniques were also learnt, such as how to signal for help using hard-wired stations throughout the underground coal mine.

9.3 Summary

Throughout the placement, I felt adequately supported in learning all the hazards I was being exposed to and their associated level of risk. Common WHS issues were initially learnt through the university WHS module, and then further consultation was done during my onboarding at Waldon Services. I was adequately trained for the various tasks I had to complete, whether at home or at a client mine site. I learnt how to assess different hazards for risks and respond accordingly to tasks I needed to carry out. Even with the support, it is crucial that nobody gets complacent and is always observing for hazards to ensure a safe and healthy work environment.

10 Appendix D: Practical Experience Logbook

10.1 Logbook Weekly Table

Week 1 (04/07/2022 — 10/07/2022)	• Ensuring I am familiar with the team and processes and what my new work schedule will be like. • Start thinking about how my project of underground coal mine explosions can be formulated into a thesis • Talking with research mine regarding the new development of an underground risk mitigation system
Week 2 (11/07/2022 — 17/07/2022)	• Organise with Academic Supervisor Guodong to have a meeting and discuss scope • Ensure understanding of the managing explosive dust zones is sufficient in an UCM so that requiremnts are in line • Continue familiarity within the role
Week 3 (18/07/2022 — 24/07/2022)	• Guodong unfortunately sick for a meeting, organise meeting for the following week • Initial digital twin component of system requirements defined and approved by research mine • Ensuring comprehesnive understanding of regulatory requirements surrounding stone dusting .
Week 4 (25/07/2022 — 31/07/2022)	• Meeting with Guodong, great to think about the scope for the thesis component and how it does not have to be limited by what I am practically implmented within work • Sample Labels and Plans compoennt of system defined and approved by research mine
Week 5 (01/08/2022 — 07/08/2022)	• Begin creating a draft stucture and project plan for thesis, leant toward Intelligent Risk Mitigation for Underground Coal Mines • Working with software developer to develop the digital twin component of system

	• Continuing to refine the entire components of the system to be ready
Week 6 (08/08/2022 — 14/08/2022)	• Working with other software developer to start integrate sample results, naming conventions seem to inconsistent • Workflow plan for most of the approved system delivery planned • Started Project Maagement course for training to imporve my project delivery skills. Very interesting and useful, will allocate time each week to do
Week 7 (15/08/2022 — 21/08/2022)	• Software Developer is Facing difficulties integrating with the AutoCAD file, we spend a lot of time analysing everything together in detail • My turn to run the activity for Virtual Afternoon Tea this week, I decided to do ice breaker bingo
Week 8 (22/08/2022 — 28/08/2022)	• First version of digital twin was finalised however, after I tested its functionality I noticed many flaws that would not be feasible. Working with software developer to rectify them. • Adding relevant detail to my thesis writing where I can
Week 9 (29/08/2022 — 04/09/2022)	• Brad provided some feedback to my general user interface layout of the developed system so far, had some variations from what are standard with our platform • Getting more familiar with User Interface Standard for the companies software. Ensure thesis system design accounts for it
Week 10 (05/09/2022 — 11/09/2022)	• Production Area concept start development along with stone dust application • Mobile application begin development • Meeting regularly with research mine to discuss the system as it is developed

Week 11 (12/09/2022 — 18/09/2022)	• Adding additional detail to progress report and doing additional research on other systems out there • Preparing to travel to the research mine to gain a better understanding of the processes involved
Week 12 (19/09/2022 — 25/09/2022)	• Travelled to the research mine BRM broadmeadow in QLD • Went with Industry supervisor Brad Waldon, stayed in Moranbah together. • Went underground in the coal mine to get a better sense of real life limitations, awesome 146xperience • Helped scope out some other potential work for the platform involving other risk management
Week 13 (26/09/2022 — 02/10/2022)	• Lots of research into risk mitigation and literature • Finalising progress report • Progress Report submitted
Week 14 (03/10/2022 — 09/10/2022)	• Second visit to QLD • Attended another underground coal mine company safety day to talk to a different set of users about explosions and how their system manages it
Week 15 (10/10/2022 — 16/10/2022)	• Tired from travels • Preparing for thesis school seminar submission for video, needs to be submitted to canvas • Finalising video
Week 16 (17/10/2022 — 23/10/2022)	• The system is over a 1/3 developed • Planning to release the first lot of components over the next few weeks for use in production. Digital twin, sample labels, stone dust application • Present my progress and Project thesis seminar day, I think I did well
Week 17 (24/10/2022 — 30/10/2022)	• Release digital twin component to production environment for the research mine

	• Lots of work involved trying to assit them to initially set up the polygons required. Once done it does not have to be done again to such detail
Week 18 (31/10/2022 — 06/11/2022)	• Release the stone dust capturing ability on desktop • Mobile app created, developer having difficulties with offline functionality so we spent a lot of time trouble shooting. • Manually creating comparative sample zone sheet to match their past excel zone names
Week 19 (07/11/2022 — 13/11/2022)	• Developed historical data viewing interface for sample results • Failure capability of stone dust applications not working as expected, spent a lot of time de-bugging but has been fixed • Difficult to try compare with their previous dust zone names as it is so inconsisitent
Week 20 (14/11/2022 — 20/11/2022)	• Great productive meeting with Guodong, got some good feedback on how to better structure my thesis. • Starting to have some really good content for my thesis and it is taking good shape. Narrowing my scope slightly with less focus on risks outside of explosions because there is so much involved
Week 21 (21/11/2022 — 27/11/2022)	• We are doing a large system upgrade of the platform, from .NET 3 to .NET 6. This is taking up a lot of time and rescources • EDRMS system probably nearly ¾ developed. Finding lots of gaps in their existing process
Week 22 (28/11/2022 — 04/12/2022)	• Travel to Brisbane for a Waldon Services Christmas gathering which is really nice to see everyone in person. • Really buffing out my thesis writing. Getting very busy trying to balance work with the thesis writing as implementing the system and debugging is very time consuming

Week 23 (05/12/2022 — 11/12/2022)	• Released more interfaces for viewing historical information including the heat map. • Failed zone functionality being developed • Have 2 week extension on due date of thesis due to the break (so to 15th of January). • Having a fair few issues still with the sample result integration due to their existing terrible naming conventions. Spending lots of time to try rectiy
Week 24 (12/12/2022 — 18/12/2022)	• Trying to get as much done as possible before the Christmas break and we can not develop anything • Focusing on the optimisation component of my thesis
Week 25 (19/12/2022 — 25/12/2022)	• Trying to get as much writing done while the new system compoennts are not being released. Focused on methodology section of optimisation. • Christmas!
Week 26 (26/12/2022 — 01/01/2023)	• Introduction and literature chapters refined • Cleaning up my system implementation and results section • Work is off so can not get some information
Week 27 (02/01/2023 — 08/01/2023)	• Not at work this week still but focusing on finishing my system implementation thesis section as much as possible • Doing my project management case study. • Will not be able to finish by end of next week but have requested extension.
Week 28 (09/01/2023 — 15/01/2023)	• Finished system implementation and results sections • The majority of the system has been developed now, only component that hasn't been developed yet is the optimisation component. I have thoroughly designed and it has started development but it will not be done by this thesis • I was granted an extension, next week I will be on the Indigenous Australian Engineering School camp at

	university all week as a mentor/leader. New due dat 29th January • Finished Project management case study. Primarily need to do computer vision case study
Week 29 (16/01/2023 — 22/01/2023)	• On Indigenous Australian Engineering School camp at the university of sydney all week helping as a house parent for students trying to come to university. • No time to do anything else, we are staying at the same accommodation as the students and responsible, so up early and bed late
Week 30 (23/01/2023 — 29/01/2023)	• Focused on finalising my Computer Vision case study and refining remaining thesis content to be ready for submission • My project management case study that I have already written was rejected as it is not an advanced MTRX subject, it is MECH (annoying). Granted a week extension so I can do another case study. I have selected AMME5520. • Finished Computer Vision case study and started AMME5520
Week 31 (30/01/2023 — 1/02/2023)	• Finished AMME5520 case study. • Finalise thesis structure • Refine the WHS report • Submit Thesis