Application of critical controls for fatality prevention in mining operations

Case study in an AngloGold Ashanti gold mine

by

S.P.M. Franzen

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday November 29, 2017 at 15:45 PM.

Student number:	4016378	
Project duration:	March 15, 2017 – November 29, 2017	
Thesis committee:	Prof. dr. ir. M. W. N. Buxton	TU Delft, supervisor
	Ir. M. Keersemaker	TU Delft
	Prof. dr. ir. B. Lottermoser	RWTH Aachen
	Prof. dr. ir. M. Rinne	Aalto University
	G. H. Coetzee	AngloGold Ashanti Ltd.

This thesis is confidential and cannot be made public until November 30, 2022.

Abstract

Up until now, global mining companies have failed to create a fatality free environment for their employees, whether it be through increasingly difficult conditions or inadequate safety management approaches. Desiring to maintain the social license to operate, these companies are now looking into alternate ways of safety management with the aim of mitigating fatalities in the workplace. In this study, a new risk management approach was applied to mitigate fatal incidents through the utilization of critical controls. The aim of this study was to create a scalable, minimally invasive proof-of-concept for AngloGold Ashanti that can successfully be implemented at any of the company's mining operations.

The foundation for this implementation was laid through a literature study blending contemporary safety and risk management approaches with Business Intelligence systems thinking and a perspective on industry best-practices. Subsequently, a framework of organizational requirements was set up based on 26 interviews with stakeholders in various departments within the company. Both design and implementation were conducted on-site at an AngloGold Ashanti operation in Western Australia.

The system was designed by adhering to organizational requirements, and ensuring that it is suitable to any mining environment. The designed Critical Control Management System was subsequently implemented at Sunrise Dam, one of AngloGold Ashanti's Australian mining operations. To ensure that critical controls were also assessed at the operational level, a workplace inspection process was modified to generate control data. All sources of data subsequently were fed into a Business Intelligence environment enabling insight into critical control performance to all company stakeholders. Doing so informs decision-making on safety priorities company-wide, based on real-time data generated on the operational level.

Two case studies were performed to assess two of the most significant hazards at Sunrise Dam. The studies showed that the effectiveness of reactive controls changes irrespective of their compliance and performance. Furthermore, the influence of human factors within risk management remains difficult to quantify. Finally, it demonstrates the potential for integration of incident data into the Critical Control Management System, thus creating both leading and lagging indicators for safety performance.

The conclusion of this study is that an effective and scalable Critical Control Management System can be successfully implemented in a mining operation if the right conditions are generated. The approach of integration in existing processes demonstrates that companies can achieve greater control over fatality prevention without the need for an additional safety management system. On this basis, it is recommended that other operations are supported in creating an environment suitable for adaptation before Critical Control Management is implemented.

Contents

List of Figures

List of Tables

List of Abbreviations

AFFF	Aqueous fim forming foam
AGA	AngloGold Ashanti
ALARP	As low as reasonably practicable
BI	Business Intelligence
CCM	Critical Control Management
CCMS	Critical Control Management System
DCP	Dry Chemical Powder
EMS	Event Management System
ERP	Enterprise Resource Planning
ERT	Emergency Response Team
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
ICMM	International Council of Minerals and Mines
IT	Information Technology *or* Integrated tool carrier
JHA	Job Hazard Analysis (- process)
KISS	Keep it Simple, Stupid
LV	Light vehicle

MHS	Major Hazard Standard
MUE	Material Unwanted Event
OEM	Original equipment manufacturer
OHS	Occupational Health & Safety
OLAP	Online Analytical Processing
PS	Performance Standard
PPE	Personal Protection Equipment
PRV	Pressure Release Vessel
RBD	Reliability Block Diagram
RDW	Regional Data Warehouse
SDGM	Sunrise Dam Gold Mine
SFAIRP	So far as is reasonably practicable
SLAM	Stop & think, Look, Act and Manage (- process)
SWIC	Start Work in Control (- process)
WPI	Workplace Inspection
UG	Underground
UML	Unified Modelling Language

Nomenclature

Bow-tie model	A model that combines causes and consequences of incidents into a single diagram. By applying a comprehensive barriers or so-called controls on pathways from cause to incident to consequence, defense in depth can be applied to mitigate severe incidents and their consequences.
Business Intelligence	Process utilized to leverage business information generated to enhance corporate performance for competitive advantage and increased profitability. Can be applied to all sorts of information generated within a business, such a finance, safety or workflow data.
Critical Control	A control that is crucial in preventing or mitigating the consequences of a significant incident with possible fatalities or severely injuried employees. Such an event is also called a Material Unwanted Event.
Event Management System	Software suite that allows reporting, storing and management of incidents, actions, injuries and other related occupational health & safety data. It is used as a platform for increasing compliance and driving OHS insight throughout the business.
Major Hazard Standard	Major hazards present categorized with their corresponding critical controls to ensure their prevention and mitigation of their consequences. An example of a Major Hazard Standard is that of Underground Ground control, the major hazard faced within underground mining leading, amongst other events, instances of falls of ground.

Performance Standard	Management-approved expression of performance thresholds, requirements, expectations, dependencies and validations that need to be met to ensure a corporate standard level of performance. These are used in this research to ensure management of critical controls is adequate.
Top Event	Critical event in which loss of control is sustained within a bow-tie model. A brief example might be losing power of the steering wheel: control is lost, yet no injuries or damage is yet sustained. Causes can be analyzed, and further harm might still be prevented.

1

Introduction

Eliminating fatalities remains one of the biggest challenges in the mining industry today. Partly driven by regulatory requirements, professional culture and significant incidents, obtaining a sufficient occupational health and safety standard has changed the operational priorities of mining companies. Changes in societal norms mean it is simply no longer acceptable to have fatalities during work (Galvin, 2016). Carrying the reputation of a dangerous, polluting industry, mining companies often struggle to gain positive public perception. In order to change this view, "Zero Harm" has been one of the core goals for major mining companies seeking to gain and maintain the social license to operate (AngloGold Ashanti, 2015, Glencore, 2016). Even with the objective of 'Zero Harm' in mind, mining companies have fallen short of the mark.

This is corroborated by benchmarking studies across the industry by the International Council Minerals and Mines (ICMM), fatality rates per 1,000,000 hours worked have only gone down marginally from 0.033 in 2012 to 0.032 in 2016 (ICMM, 2015, 2016). As ore grades decline and deposits run out, mining companies must dig deeper to reach viable deposits, only compounding the high-potential safety issues already encountered (Lane et al., 2015, Prior et al., 2012).

1.1. Changing Safety Management in Mining

Traditional safety approaches focus on a multitude of systems, hazard management plans and safety procedures. This comprehensive framework can hinder employees in emergency situations due to the presence of too many prevention systems, causing uncertainty as to what is the optimal reaction strategy (Makin and Winder, 2008). Additionally, studies show that fatal accidents are both foreseeable and preventable but keep occuring in the same ways (Pillay and Tuck, 2017). This suggests that contemporary safety management approaches have not been successful (Pillay et al., 2010). The apparent lack of progress has caused a paradigm shift toward alternative methods among mining companies looking to reduce risks in the work space. One of the ways in which solutions are sought is through the establishment of common interest platforms like the International Council of Minerals and Mines (ICMM, 2015a).

Within the domain of fatality prevention, the ICMM is currently committing significant effort into Critical Control Management (CCM). This method focuses on low-likelihood, high-impact events that most often cause fatalities and serious injuries in the work place. It concentrates on a relatively small amount of identified controls that are simultaneously monitored, reported and improved. What makes these controls "critical" is typified by being the first or last line of defence, preventing multiple possible incidents or by working independently to mitigate events endangering the lives of employees (AngloGold Ashanti, 2015).

Within the industry, AngloGold Ashanti is one of the companies in the mining industry currently driving the approach of critical control management to prevent fatal accidents, also called Material Unwanted Events (MUE's). The company has been doing so since 2014, identifying those hazards in the workplace causing fatalities and establishing controls in place to mitigate MUE's (AngloGold Ashanti, 2014). While software had been purchased for identifying critical controls, no single system had yet been implemented to assess control performance. When built, such a system could support employees company-wide in identifying hazardous areas, prioritizing maintenance and informing safety management decisions. To understand why AngloGold Ashanti is interested in such a system, one only needs to look at the nature of its business.

1.2. Challenges at AngloGold Ashanti

AngloGold Ashanti operates mines which, by nature, are highly dynamic working environments. Some of the company's assets in South Africa operate at depths exceeding four kilometres depth from the surface. In such conditions the pressure of native rock on mine openings leaves very little room for error, both literally and figuratively. Compounding the issue is the fact that employees across the three continents in which AGA operates widely differ in terms of culture, levels of education, and economic development (Australian Bureau of Statistics, 2007, Hajkowicz et al., 2011, Kitula, 2006).

Due to the semi-autonomous status of the different business units within AngloGold Ashanti, a multitude of measures and systems have been implemented to mitigate fatal incidents within the mines. While existing systems correspond with local challenges and culture, in some cases these have failed to adequately respond to emergent risks. Investigations into fatal incidents often identify a common factor, which is that the controls needed to prevent incidents were known and available, but not in place or properly maintained (ICMM, 2015a). Furthermore, a myriad of systems can lead to a false sense of security as it conceals operational issues (Bakolas and Saleh, 2011).

1.3. Motivation

The pattern of complicated safety approaches as discussed in the previous paragraph led to identification of the need for a simple, robust system that focuses on those critical controls that prevent fatalities. By directly influencing these controls, a more transparent safety management approach can be applied, to the benefit of the public, the regulators and naturally the employees themselves.

With this goal in mind, senior management officials at AngloGold Ashanti authorized this study. Using a scientific approach, contemporary knowledge on relevant fields of study was to be combined to deliver a state-of-the-art system. As the entire development of such a product was estimated to exceed the limits of a thesis study, a scalable proof-of-concept was set as main deliverable for the company. Other deliverables included a literature study on contemporary best-practices, identification of potential additions to the proof-of-concept and a roadmap indicating further development for a short to medium time horizon. The proof-of-concept was implemented at AngloGold Ashanti's gold mining operation Sunrise Dam in Western Australia during a field work study conducted from April 2017 to August 2017.

1.4. Proposed Method

Critical Control Management has been identified as a potential method for mitigating MUE's at AngloGold Operations. By developing a simple, robust system that monitors the performance of these controls, safety decision-making of stakeholders can be supported. This enables AngloGold Ashanti to have greater control of safety within its operations.

In order to develop a system that adequately responds to company requirements and operational constraints, contemporary safety and risk management thinking was combined with Business Intelligence. This was used as the foundation for further design and implementation of the proof-of-concept Critical Control Management System. The focus here was on proof-of-control, as the influence of stakeholders on design and implementation could not be asserted during the scoping stage of the study.

1.5. Research Questions and Objectives

In this section, the research questions and objectives of this study will be discussed. First, the purpose of the study is given. Subsequently, the research questions are presented. Finally, Several objectives are elaborated upon to indicate what elements are required to answer the research questions.

Purpose:
Support employee decision-making on fatality prevention through management of critical controls with the creation of a simple, robust and scalable system that can be used by stakeholders in the company.

Research question:
How can an effective Critical Control Management System be implemented in AngloGold Ashanti operations to mitigate fatal incidents?

The research question can be divided into several sub-questions that guide the research to its intended purpose. The sub-questions are:

1. *What are the key elements for successful implementation in an AngloGold Ashanti operation?*
2. *How can design of the system incorporate scalability to other AngloGold Ashanti operations?*
3. *In what ways can critical control monitoring be introduced into a mining operation?*
4. *How can indicators for the performance of critical controls be introduced and measured?*

Based on the sub-questions, several objectives were set out for development of the Critical Control Management System. Objective 1 relates to sub-question 1, objective 2 to sub-questions 2 & 3 and objective 3 to sub-question 4.

Objective 1: Assessment of Organizational Requirements and Operational Contraints

The proposed system functions in a multi-faceted environment with a plurality of stakeholders. Defining the framework in which the Critical Control Management System should operate requires determination of two components:

1.1 Develop a comprehensive understanding of contemporary literature with regards to operational safety, risk management and best-practices.

1.2 Create a framework of current practices, practicable applications and organizational requirements which supports the implementation of a Critical Control Management System.

Objective 2: Design and Implementation of a Critical Control Management System

After the required framework is established, a design is created that adheres to set requirements while allowing for possible expansion to other operations. This includes accounting for the working environment as well as incorporation of company standards into the proposed methods of data acquisition. Subsequently a strategy for implementation of the proposed system is developed. Using that methodology, an existing business process is targeted for critical control integration. The data generated can then be fed into the Business Intelligence part of the greater systems design to allow application of data analytics. Measures generated in this part can then be delivered to stakeholders based on the data that is applicable to them. This objective is specified using the following components:

2.1 Consideration of all relevant features, applications and the required flow necessary for design of the Critical Control Management System.

2.2 Assessment of the critical control process set forth in the company standards for alignment to data acquisition processes.

2.3 Development of a Critical Control Management System's architecture adhering to all identified requirements, contraints and priorities.

2.4 Creation of a strategy that allows rapid implementation of critical control monitoring in an operational environment.

2.5 Selection of a business process applicable for critical control integration and data aqcuisition. The selected process is conducted by operators on a pre-defined frequency and integration accomplishes several things: awareness of critical controls by operators and implementation of a technical assessment of critical controls on the work floor.

2.6 Integration of critical controls into the selected business process, allowing for performance data to be generated.

2.7 Develop a feed from critical control performance data into a reporting suite, which allows stakeholders to make decisions relevant to them on operational safety.

Objective 3: Validation of Critical Control and Systems Performance

Two case studies are executed to demonstrate potential effectiveness of the Critical Control Management System. Secondly, the relevance of incident data to critical control monitoring is shown. Finally, the nature of the data is examined to assess underlying issues that could be present in an operational environment. The following components are applicable to this objective:

3.1 Assess the potential effectiveness of the Critical Control Management System based on historical incident data.

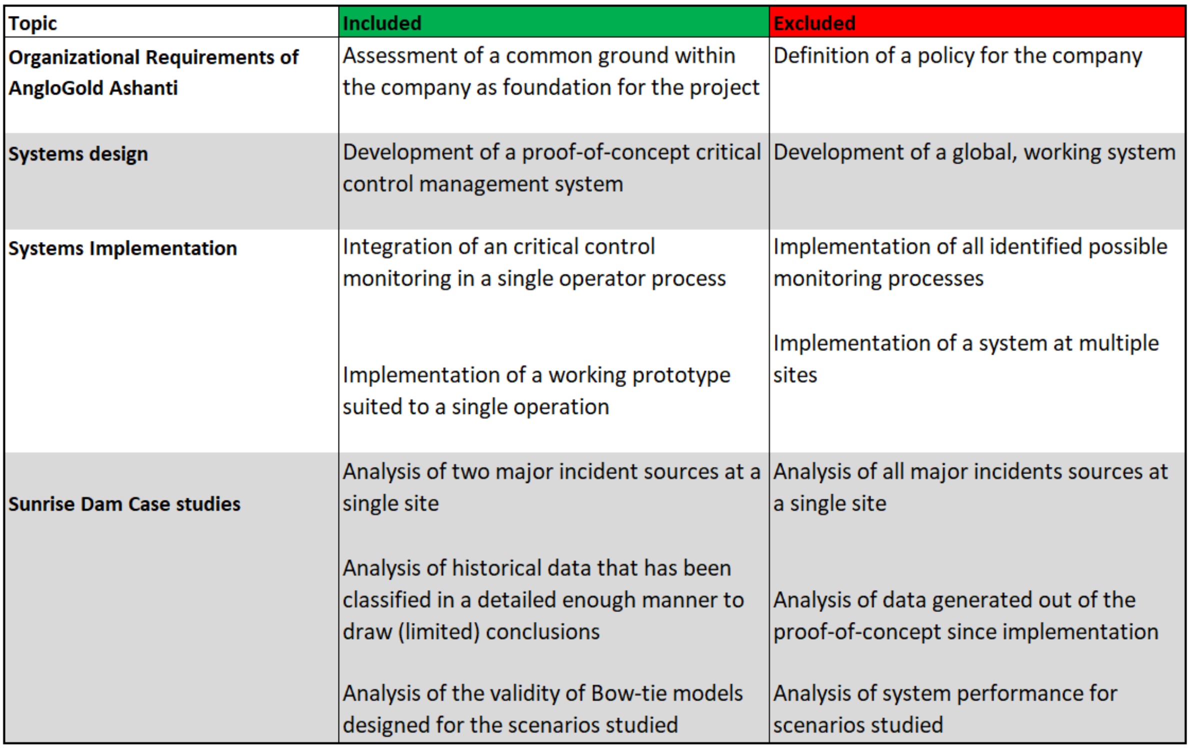
3.1 Demonstrate the viability of the inclusion of incident data into the greater Critical Control Management System. This in turn provides a lagging indicator for operational safety.

3.2 Review incident data to assess the possibility of systemic, significant safety issues in an operational environment.

1.6. Project Scope

The scope of work described in Section 1.5, Research Questions and Objectives, is substantial both in size and ambition. To mitigate potential negative consequences of scope creep, a framework was set up to define what is included and what is excluded in scope for the study.

A successful outcome of this project could be used as the foundation for critical control management at AngloGold Ashanti in the years to come. This means that besides from scientific merit, practicality for AngloGold Ashanti is a key element to assure a positive outcome. After conducting an extensive literature study, the knowledge gained is applied with and within the systems available at AngloGold Ashanti. This means that any outcome is optimized for the company and its current systems. To give a clear indication of what is included and exluded in the scope of the study, Table 1.1 has been drawn up do indicate all items in-scope and those classified as out of scope.



Topic	**Included**	**Excluded**
Organizational Requirements of AngloGold Ashanti	Assessment of a common ground within the company as foundation for the project	Definition of a policy for the company
Systems design	Development of a proof-of-concept critical control management system	Development of a global, working system
Systems Implementation	Integration of an critical control monitoring in a single operator process	Implementation of all identified possible monitoring processes
	Implementation of a working prototype suited to a single operation	Implementation of a system at multiple sites
Sunrise Dam Case studies	Analysis of two major incident sources at a single site	Analysis of all major incidents sources at a single site
	Analysis of historical data that has been classified in a detailed enough manner to draw (limited) conclusions	Analysis of data generated out of the proof-of-concept since implementation
	Analysis of the validity of Bow-tie models designed for the scenarios studied	Analysis of system performance for scenarios studied

Table 1.1: Table in which the scope for relevant sections of the project is given

1.7. Project Approach - Agile

To enable flexible (re-)scoping during the project should requirements change, a research setup based on Agile software design was utilized. This methodology is suitable for situations in which quick adaptation to changing requirements is required (Hoda et al., 2017). Instead of high-frequency, two week intervals, common for an Agile project approach, four to six week periods were used to deliver intermittent results to (company) stakeholders based on their availability and on the nature of the deliverables. Different stages identified in the Agile approach can be viewed in Figure 1.1.

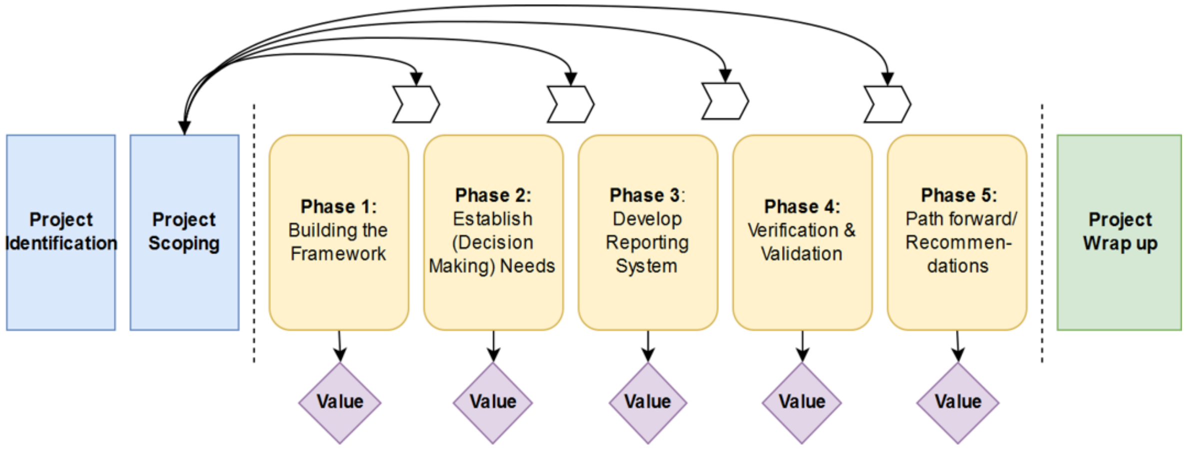


Figure 1.1: The Agile-based process used to allow fast re-scoping of research as required

All steps identified in yellow were conducted as operational phases for AngloGold Ashanti, with phases two to four being conducted at corporate headquarters in Johannesburg in South Africa, regional headquarters in Perth, Australia and Sunrise Dam Gold Mine, Australia. The phases correspond to the following chapters:

- Phase 1: Chapter 1 and 2
- Phase 2: Chapter 3 and 4
- Phase 3: Chapter 5 and 6
- Phase 4: Chapter 7
- Phase 5: Chapter 8 through 10

Benefits of returning to project scoping will be discussed in Section 8.7, to demonstrate the potential of this approach. The value generated after each step was presented as a deliverable to company officials.

1.8. Thesis Outline

2. Literature Review	Builds a comprehensive framework for further research that discusses safety science, risk management, risk quantification and current industry best practices. Safety science is examined to build understanding of contemporary ways approaches of managening operational safety. Risk management discusses the incorporation of uncertainty within the scope of operational safety. To determine what acceptable risk is, possible quantification methods are discussed. Finally, some of the industry's leading mining companies and a collaboration platform are examined to look into state-of-the-art approaches.
3. Methodology	firstly, proposes interview structures to be used in gathering qualitative data on organizational requirements. Secondly, it demonstrates Business Intelligence as a domain that has the potential to support the building of a system to manage operational safety risk.

4. The organizational environment	Assesses the needs within AngloGold Ashanti that serve as the framework for further design and implementation. First, it goes into detail as to what the current company safety management practices are. Secondly, potentially fatal hazards relevant to the operations are examined. It builds on this knowledge by discussing critical controls, the systems in place to mitigate fatal incidents. Furthermore, company standards and site selection for implementation of the system are discussed. Finally, the organizational requirements are set out in five broad tenets.
5. Systems Design	Outlines the systems design applied to manage critical controls business-wide. General considerations for the design are discussed first. Next, company standards that govern the verification of critical controls are examined. Consequently the required working environment is elaborated upon after which all design implications are summarized. Finally, the architecture of the system is demonstrated along with remarks on potential expansion and room for improvement.
6. Implementation	Exhibits the process of implementing the aforementioned design in the selected operational environment. First, the overall strategy for implementation is discussed, followed by adoption of necessary company standards. Subsequently operational processes are assessed for critical control integration, after which integration is carried out. Next, the roll-out of the greater system is showcased. Finally, notes on differences in implementation at other sites are discussed.
7. Case Studies	Demonstrates a quantification of the risk profiles of two of the most significant hazards faced in any underground mining environment. First, incidents related to underground fire are examined in order to assess the validity of reactive mitigation measures implemented. The focus within this case study is on the effectiveness of Aqueous Film Forming Foam, an engineering critical control. Next, underground fall of ground incidents are discussed in order to validate the effectiveness of preventative critical controls in place. Finally, results of the case study are discussed in order to give recommendations for further improvement of the system implemented.
8. Discussion	Puts the outcomes of this study in a broader perspective and relates its implications to avenues for continued research. First, the aspects relevant to systems design are discussed. Subsequently, ways to expand current progress are examined. As the main deliverable was to implement an effective proof-of-concept, methods for achieving more mature systems and reporting are proposed. Next, potential implementation issues at other sites are discussed. Finally, an indication is given on what would be required to work towards predictive risk in a mining environment.
9. Conclusions	Summarizes the results set forth in this research. It places the outcomes in a larger context and relates back to the goal and objectives set forth in the introduction to assess if all deliverables have been achieved.

2

Literature Review

The current safety management practices at AngloGold Ashanti have been shaped by little less than a century of development. Since the 1930's, safety management has gone through major development stages, each shifting the focus of the problem to a different area (Borys et al., 2009, Hale and Hovden, 1998, Pillay et al., 2010). The evolution of these approaches forms the basis for this chapter, in which the development of operational safety practices and industrial risk management will be discussed. Subsequently, that knowledge will be built upon to shape the next generation of tools with which to manage operational safety in mining.

First, a brief overview of safety management through the 20th and 21st century will be given. Next, the evolution of barrier-based modelling within the broader context of risk management will be discussed. Finally, industry best practices will be examined. This will set the stage for the design strategy of such a process for fatality prevention in chapter 5.

2.1. Brief history of Safety Science

The basis for modern-day safety thinking was developed in the 1930's, when the first era of safety thinking came into its own. This era brought forth the well-known work by Herbert Heinrich in 1931, in which he proposed his Domino theory. A brief overview of safety eras in the last century can be seen in Figure 2.1.

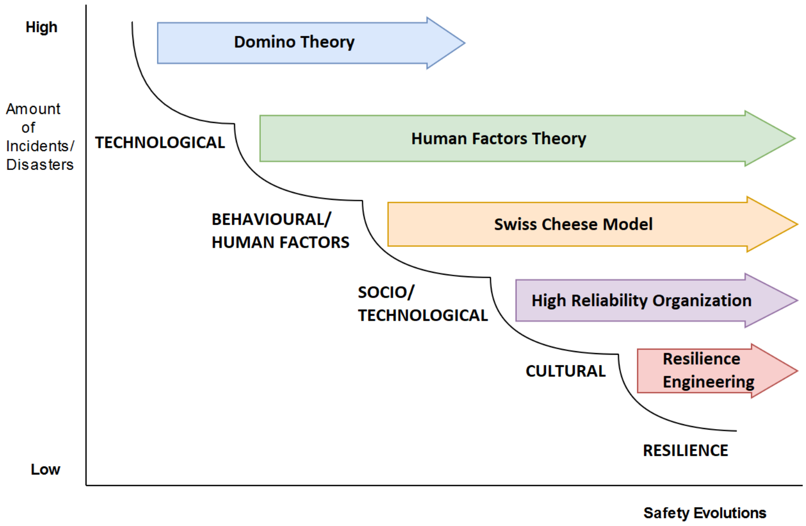


Figure 2.1: The five era's of safety as adapted from (Pillay et al., 2010)

Heinrich's work moved the onus of incidents away from technological failures to the idea that these issues were caused by a series of events, triggering one another and subsequently leading to an incident. The first domino stone in that sequence was then always attributed to a technological failures such as mechanical faults (Heinrich and Petersen, 1980). Subsequent domino's falling would then relate to operator error, substandard working conditions, incident causation and finally damage to people or property (Pillay et al., 2010).

Each metaphorical domino stone triggering failure of the next. By withdrawing one stone from the sequence, incidents could be prevented.

This era of safety thinking lasted to well in the 1950's. After and during the Second World War, the development of both military and other equipment was accelerated immensely. Examples of this development are the invention of the atom bomb, jet engines, rocket science and the broad-scale application of radar through microwave technology. The interface of humans with these new applications in high-pressure environments subsequently led to causation of incidents as technology was changing faster than the people applying it could handle (Swuste et al., 2014). This led to the development of the Human Factors theory, which represents systems with human interaction as information flow models. When a person within the system is not able to understand or transfer information in a timely manner, the flow within the model would be disrupted. After such a disruption, errors would be made and (significant) incidents could occur.

When Reason presented his now well-known Swiss Cheese Model to try and explain incidents it resulted in the next paradigm shift within operational safety thinking (Reason, 2000). This theory moved away from technological failures triggering human mistakes as stated by Heinrich's Domino Theory. Instead, it imagined certain vulnerabilities within the organization to line up in the wrong place and the wrong time. These vulnerabilities could be imagined as temporary and/or permanent holes in layers of the eponymous cheese, all lining up to allow an incident to occur. Something that the Swiss Cheese Model was able to explain well was that humans were rarely the sole cause of an incident. This gave rise to a new era of safety thinking, in which organizational aspects were also slowly adapted as a factor in incident causation. Moving away from the individual, reflection centred more significantly on ways the organization could have prevented the incident. Aspects such as (hazard) training, appropriate working times and procedures came to the forefront as necessary aspects of a sound safety approach (Pillay et al., 2010). To successfully mitigate incidents, safety management systems were developed that incorporated all these aspects into a single framework.

2.1.1. Understanding the Safety of a System

Simultaneous to development of the human factors theory, safety analysis techniques were developed. Based on the Domino system, these understood an incident to be a sequence of events leading to eventual failure. Among these techniques is Failure Mode, Effects and Criticality Analysis (FMECA), which is still widely in use to develop maintenance strategy for complex industrial systems. Other methods of analysis to come from the domino system were Hazard and Operability study (HAZOP) and Fault Tree Analysis (FTA) (Swuste et al., 2014).

FTA was developed in 1961 at Bell laboratories to visualize a system and its failure mechanisms in a diagram (Ericson, 1999). The moment the system suffers a loss of control event, which is also called a top event, is characterized by a tree of failure paths using Boolean logic (de Ruijter and Guldenmund, 2016). Through Boolean logic, the probability of single events within the tree can be determined with which the probability of the top event can be calculated. An example of a fault tree can be viewed in Figure 2.2, demonstrating its Boolean logic leading to a loss of control, a so called top event.

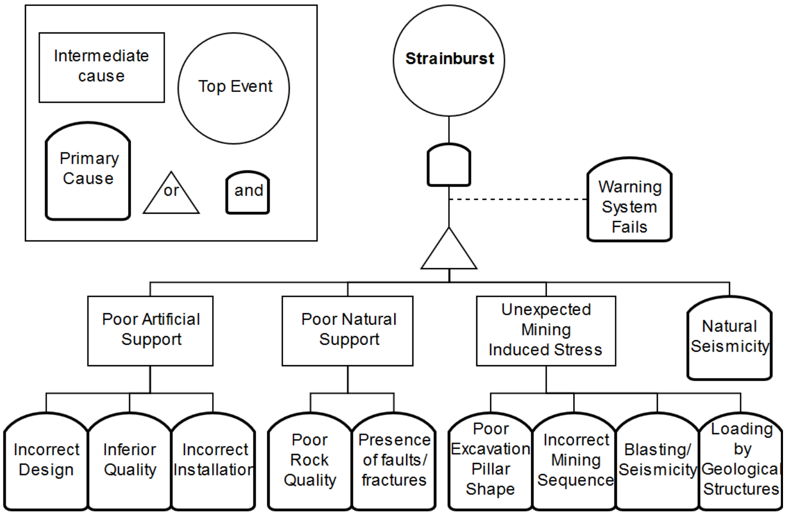


Figure 2.2: Simplified Fault Tree Analysis diagram showing intermediate and underlying causes as adapted from (Mishra et al., 2017)

While Fault Tree Analysis focuses on the path towards a loss of control event, Event Tree Analysis (ETA) explores the range of possible outcomes through event paths leading away from the top event to their eventual outcomes. Using similar Boolean logic, a tree is drawn up from the top event towards possible consequences. By understanding how an event can eventually lead to an incident, intermediary steps can be taken to avoid such an outcome. A simple diagram for an event tree analysis can be viewed in Figure 2.3.

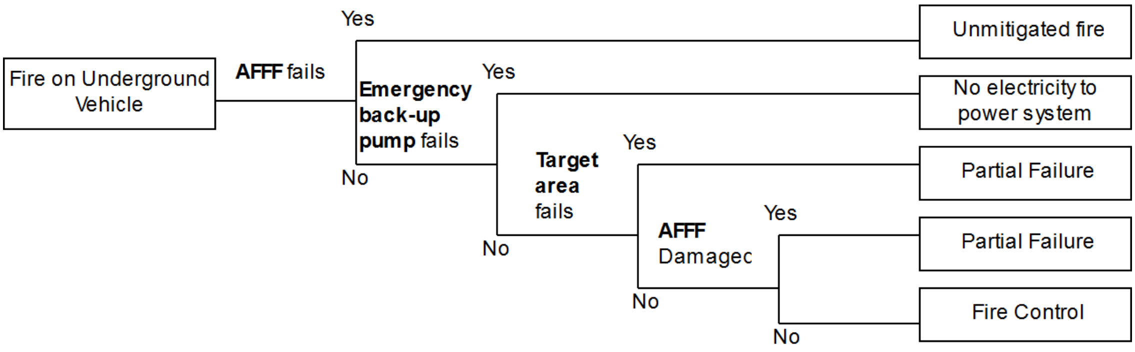


Figure 2.3: An Event Tree Analysis displaying several subsystems of the fire protection system Aqueous Film Forming Foam (AFFF).

The example of an Event Tree Analysis shown in Figure 2.3 was developed during the course of this study and displays one of the main fire suppression systems used in underground mines (Hansen, 2017). Aqueous Film Forming Foam (AFFF) smothers fires that are caused by inflammable solids and liquids. When a fire is detected, the AFFF is released to mitigate further damage to a vehicle. If the AFFF is not set off, or if it fails to activate, it will lead to an unmitigated fire if no other firefighting methods are applied. For simplicities sake, these are out of scope for this example. In reality, fires will often be put out using a combination of AFFF and other handheld fire extinguishers (Hansen, 2017).

One of the first actions taken by the operator is shutting down the engine to disrupt additional fuel being added to the fire. For the AFFF to operate, the emergency back-up pump should run in order to supply electricity to the system. If none is produced, the system will not operate. While the AFFF might work as intended, the design of target areas will often not include every part of the vehicle. If fire originates elsewhere than the AFFF is applied, the system will fail at least partially by design. Should the AFFF be damaged before or during fire fighting, its effectiveness will be limited. Only if all subsystems work and the fire is in the right place will the AFFF actually work. By modelling these discrepancies, the limits of prevention and mitigation methods can be assessed. This analysis can be done for both FTA and ETA, thus giving a comprehensive view of causes and consequences and their effects. The first model to include both FTA and ETA was developed by Nielsen in 1971 (Swuste et al., 2016).

2.1.2. Introduction of Barrier Thinking

In 1963, Haddon proposed his Hazard-Barrier-Target model (Haddon, 1963). This model emphasized potential sources of risk (hazards) and the barriers in place to prevent those hazards from harming vulnerable objects. By ranking the hazards on a four-point scale from 0 (no hazard) to 4 (serious), parts of a plant could be rated in terms of potential hazard. This model was later expanded by Haddon to include mitigation techniques. Depending on the rating, ten prevention techniques could be applied to mitigate harm on the work floor (Haddon, 1968).

This barrier thinking was adopted by Reason (2000) when adopting his theory of the Swiss Cheese Model. This model moved away from a series of sequential failures or mistakes. Instead, a set of particular issues pertaining to the individuals involved, the work floor and the broader organization allowed a failure to continue. This concept is akin to layers of cheese with all the holes lining up, until eventual consequence is brought to bear. Not only did this model shift the focus away from human interface with systems, it also brought barrier thinking to the forefront of safety thinking (de Ruijter and Guldenmund, 2016). If any one of the holes in the cheese is prevented from lining up, incidents can be mitigated.

2.2. The High Reliability Organization

The shift away from human interface also led to the recognition of organizational and cultural factors as indicators for safety performance. One of the organizational concepts developed was that of High Reliability Organizations (HRO's). These organizations and their systems, such as the operation of nuclear installations, require extraordinary measures to maintain acceptable risk levels (Saunders, 2015). The basis for an HRO is centred on five main concepts (Weick and Sutcliffe, 2007):

- Problem Anticipation
- Containment of Unexpected Events
- Just Culture
- Learning Orientation
- Mindful Leadership

In the next five paragraphs, each of the trademarks High Reliability Organizations will be discussed, as well as the implications that these have for the mining operation in which the project was set up.

2.2.1. Problem Anticipation

Problem anticipation within the organization relates to preoccupation with failure, reluctance to simplify and sensitivity to operations. Preoccupation with failure can best be described as a chronic unease about potential failures. As such, near misses and incidents are used as an indicator for the overall performance or health of the system (Lekka and Sugden, 2011). This principle is also applied at AngloGold Ashanti's operation Sunrise Dam, where all incidents are to be reported, whether they are near misses or actual incidents. Reluctance to simplify refers to the capacity of organizations to systematically collect, analyse and prioritize warnings from its systems. Although information is systemically collected, the potential for translating that data to real-time and using it often remains neglected. In order to truly transform to a high reliability organization, it is necessary to make the information about incidents and related safety data available and digestible for relevant stakeholders. The sensitivity to operations then refers to the capacity of operations and managers to continually communicate with "front line" staff to ascertain the bigger picture (Weick and Sutcliffe, 2007). That sensibility can only be achieved if personnel that are not directly on the work floor, understand what is going on at the work floor.

2.2.2. Containment of Unexpected Events

When an unexpected event occurs, HRO's have the capacity to contain unexpected events through an inherent resilience within the organization (Schulz et al., 2017). This containment is achieved through multiple processes. In an emergency, the traditional hierarchical structure is dissolved, instead deferring to individual's expertise for the problem at hand (Porte and Consolini, 1998). One of the concepts that is applied in HRO's with regards to operational safety is the application of defence in depth. If one back-up fails, another might still prevent an incident from further escalation (Roberts, 1990).

Understanding of the systems in place thus becomes critical in ensuring the defence in depth is maintained at all times. A mine is a dynamic environment where production areas are opened and closed, air flow and water inflow changes with new development and ground conditions can vary per meter of drift. These factors make that the risk profile of the mine can change significantly over time. Only continual re-assessment of this profile can provide any assurance that the defenses in place will function as required when needed.

2.2.3. Just Culture

Furthermore, the culture at an HRO is geared towards separating unacceptable actions that require disciplinary measures, and actions taken without malice or attributable cause that result in a hazardous situation. An example of this is the inadvertent use of inadequate equipment (Reason, 2000). Instead of dealing out punishments, the goal of incident recording is to improve working conditions of all personnel. This assures that even when someone makes a mistake, they feel inclined to share it with the organization. This subsequently leads to an open culture of reporting incidents and near misses. This can then help the organization understand what the problems are it is facing, whether they are endemic to the operation or for instance caused by a lack of training, which builds on having a good problem anticipation.

2.2.4. Learning Orientation

Subsequently, the findings from incidents are continually used to facilitate learning within the organization, in combination with extensive training and re-training of personnel. Defining what gaps there are with regards to operator capacities within specific departments can further the effectiveness of (re-)training programs immensely. Within any industrial scenario, major hazards can differ significantly in shape or size. Examples of this are hazards related to working at heights and confined space entry. Both have a significant likelihood of resulting in severe injuries, one or even potentially multiple fatalities if risks are not managed properly. Having the data available to ascertain what part of the organization needs what kind of training related to these hazards not only makes the program more effective, it simultaneously reduces cost and the amount of risk faced on a daily basis.

2.2.5. Mindful Leadership

Finally, management in HRO's pro-actively look at fixing weaknesses within the system (Hopkins, 2009). It becomes central for senior management functioning that "bad news" is encouraged to be transmitted from the shop floor, allowing early warning and pro-active response. Additionally, senior management should commit to safe operation, allocate resources to improve safety and truly believe that it is as important as any other business objective (Costella et al., 2009). In order to help personnel in a leadership position make the decisions necessary for assuring a safe working environment, information is needed to inform that decision.

Because every decision-maker works within his own sphere of influence, the information needed might differ significantly from person to person. An example of this is a comparison of the decisions a maintenance manager makes versus those of the underground manager, both working at the same underground mine. While the overall working environment is the same and both function on the same level in the organizational hierarchy, their decisions are based on generally unrelated data. In order to help both with their decision-making, the information needs to be tailored to their needs. As a result, the application of mindful leadership is enabled as higher level personnel is aware of the problems on the operational level and can therefore react swiftly and adequately.

2.3. Bow-tie modelling

In order to better understand the safety systems in place within an organization, bow-tie modelling has been in use as a tool to map hazardous processes for some time. One of the earliest uses was the version developed for Shell after the Piper Alpha disaster in 1990 (de Ruijter and Guldenmund, 2016, Pasman and Rogers, 2013). By employing concepts of defence in depth, early warning and complex systems, bow-tie modelling evolved out of FTA and ETA merging a Cause-Consequence model into one diagram. Due to its excellent visualization properties and ease of use it however quickly spread into other fields such as the chemical process industry, health care, and mining (de Ruijter and Guldenmund, 2016, Galvin, 2017). It allows rapid identification of causes and consequences of unwanted events and incidents. Consequently barriers or so-called controls can be introduced on the pathways to mitigate both likelihood and consequences of risks. It accounts for barriers along possible failure pathways, leading to a top event or loss of control and subsequently consequences. An example of a generic bow-tie Model can be seen in Figure 2.4.

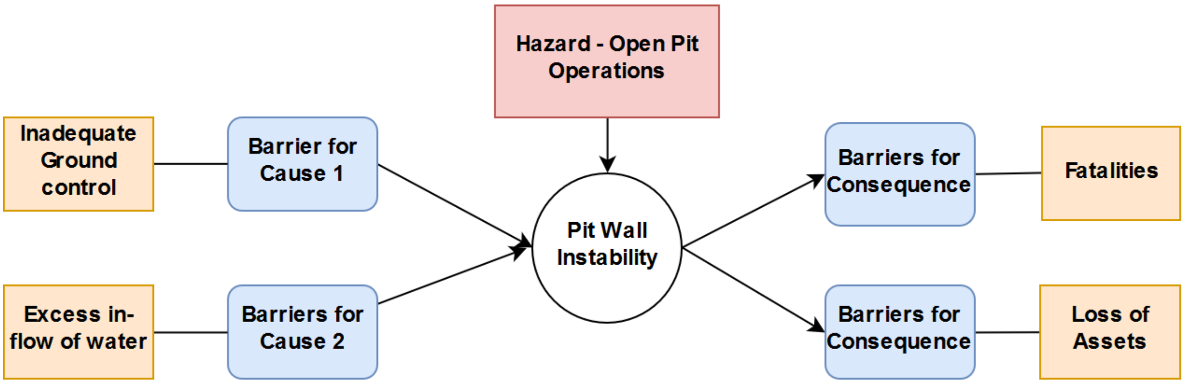


Figure 2.4: Simple Bow-tie model displaying two causes and consequences for an open pit operations scenario with regards to pit wall failure

Central to the model is a top event signalling loss of control over a hazardous situation. In the example in Figure 2.4, the top event is called "Pit Wall Instability". What makes a good top event is uncertain. Authors de Ruijter and Guldenmund (2016) point out that some top events resonate more with certain audiences, based on the nature of their description. This suggests they should be tailored the stakeholders involved in the risk assessment process in order to be successful. One example of the need for tailoring is the level of granularity applied to the top event, that will differ when discussing issues with operators or board members of a company. Like the example given in Figure 2.4, all top events signify a moment where the potential for consequence has gone up significantly, although prompt reaction might still mitigate worse outcomes.

As well as a top event, any bow-tie model has causes or threats and consequences. Both ends of the spectrum contain more than one cause and consequence, thus leading to the bow-tie shape as can sbe viewed in Figure 2.4. Through addition of more causes and/or consequences, all possible scenarios to a hazard can be included in a model, at the price of added complexity. This concept aligns with problem anticipation, with which an HRO can be established. In the bow-tie model in Figure 2.4, the two causes for pit wall instability are specified as inadequate ground control, and excess in-flow of water. The potential consequences of pit wall instability are given as fatalities and loss of assets.

Another concept that reflects HRO strategy is the use of defence in depth. In the bow-tie model, this is achieved through the addition of barriers to failure pathways. By adding more barriers to vulnerable or dominant pathways, risk relating to a specific incident cause or consequence can be reduced. A barrier to mitigate the consequence "Loss of Assets", the second one listed in Figure 2.4, could very well be an extensive emergency evacuation plan. Withdrawing all machinery from the pit operation in time would not prevent the wall from collapsing, however machinery integrity would be maintained. Note that collapse of the pit wall could itself be seen as a loss of assets, as significant effort would have to be undertaken to restore the pit operation to working order. The model also allows a barrier to be utilized for multiple pathways. Take the aforementioned emergency evacuation plan. Successful execution of this plan would mean that the outcome of possible fatalities could possibly be mitigated as well.

2.3.1. Hierarchy of Controls

With the emergency evacuation plan in the previous Section, an indication was already given that some barriers might be more effective or critical than others. With regards to the emergency evacuation plan, this was due to its functioning as a reactive barrier, also called control, on multiple pathways to listed consequences. This multi-purpose functioning is only one of ways in which a control can be defined as more critical than other systems in place.

Another method, is applying the so-called "hierarchy of controls". This concepts ranks controls based on the way risks and hazards are mitigated. The way in which the hierarchy of controls is defined depends on the organization and its according needs. The hierarchy of controls used by AngloGold Ashanti can be viewed in Figure 2.5

As is shown in Figure 2.5, the most effective form of controls is elimination of the hazard itself. An example of such a control simply stopping with certain aspects of an operation when the risks are deemed unacceptable. Being the most potent of controls, these often also result in secondary effects such as severe financial consequences if and when a site stops operations. As one moves down the hierarchy of controls, the potential effectiveness of each category is reduced. As such, wearing PPE is deemed the least effective protection to mitigate both minor and severe incidents.

Lower order controls

That PPE is categorized so low is due to the environment in which an operator works. When working with industrial smelting operations for example, a hard hat will do nothing to prevent contact with molten metal. Administrative and PPE controls are often referred to as lower order controls, and their effectiveness to stop severe incidents is often very limited (Floyd and Floyd, 2017). Being the least effective, they are also most easily implemented. Part of this is also due to the adaptation of control hierarchy after operations or plants have already been built. Redesigning processes, replacing certain materials or isolating hazards effectively will often have significant financial impact on an organization. Implementing re-training programmes in such a situation can be just as effective as redesigning a process, at a considerable lower cost. While the effect might be the same, applying an administrative control like retraining does not give business owners a guarantee that the process will be carried out safely.

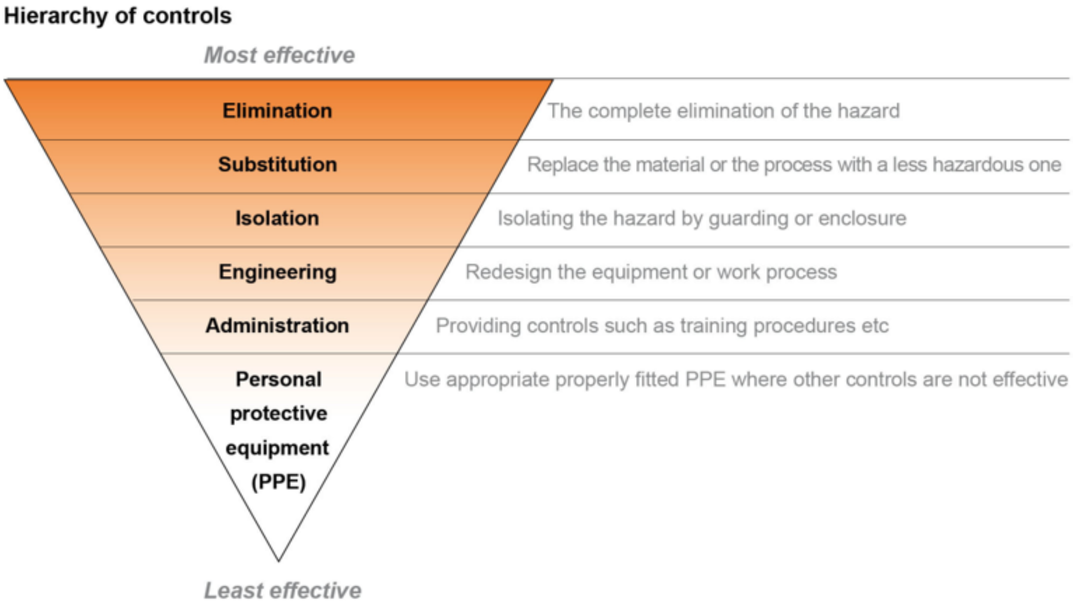


Figure 2.5: Hierarchy of Controls as applied in AngloGold Ashanti operations to determine potential criticality to controls.

2.4. Risk Management

Identification of uncertain scenarios is one of the main reasons companies employ bow-tie modelling (Galvin, 2017). That uncertainty, left unchecked, could have a significant, unforeseen, negative impact on the organization or company. To demonstrate this effect, the re-training programme example in the previous paragraph can be utilized. The control could very well eliminate incidents related to a certain hazard for any period of time. An operator involved with the hazardous task at hand might still be fatigued, preoccupied with other things and forget to apply what he or she learned in the re-training program. In that moment, the control fails. This uncertainty is part of what makes some controls more effective than others. A redesign in the work process cannot forget its training, it simply is. That redesign might not be financially feasible however. Substituting the redesign with a re-training program might be more cost-effective, reduce possible impact as well as the chance that an incident occurs. It is more effective than doing nothing, yet less effective than a redesign. Is that change then an adequate solution to make sure that operators work safely and are protected from harm? That is uncertain. That uncertainty, a product of probability and consequences, is called risk.

2.4.1. Definition of Risk

Risk is one of the central concepts within this research. Although a familiar term, risk is presented in many shapes or forms depending on its use or field of practice. Aven (2012) suggests there is no single agreed definition of the concept of risk. In addition, the most widely used standard to adress risk management, the ISO standard 31000, refers to risk as the “effect of uncertainty on objectives” (International Organization for Standardization, 2009). The use of such an ambiguous term reflects the ISO standard’s intention of referring to positive risk as well as negative risk. An example of positive risk is discovery and recovery of higher than expected ore grades as based on the geological modelling for a section of a mining operation. Negative risk is what is generally used in the context of occupational health and safety. Here, uncertainty propagates events that have a negative effect on employees.

When referring to risk in the context of this thesis, it will concern negative risk unless otherwise specified. Furthermore, it deals with the potential for severe injury or fatalities. This means that some Lost Time Injuries (LTI’s), which are a significant incident by themselves, might not even qualify based on the premise that an injured employee can resume work the next day.

2.4.2. Quantification of Risk

When quantifying risk, oftentimes a probability function is utilized to calculate an expected value for uncertainty (Aven, 2009). In that sense, it is the combination of the probability of an event or series of events and the estimated consequence of those events. The way that risk is defined as a metric depends on the situation.

Some examples of risk metrics are (Aven, 2016):

- Combination of probability and severity of consequences
- Expected consequences (loss or damage), as calculated through for instance:
  - Expected damage to assets
  - Expected fatalities
  - Expected loss of production
- A probability distribution for damage to assets or people

Which metric is the most suitable for risk assessment all depends on the situation in which the assessment is applied. Furthermore, one should consider that risk by itself is only the measure of uncertainty for a single scenario. An accurate risk assessment helps a decision maker answer the question: How can I do business profitably and sustainably, given the current configuration of business assets and employees? What the weight of these elements is in making a business decision depend on the maker of that decision. If we look back at the company's referred to in the introduction with their goal of 'Zero Harm', it would seem their inclination would be to business sustainably first, profitably second.

2.4.3. Assessing Uncertainty in Risk

In the previous paragraph, several possible metrics for assessing risks were demonstrated. These revolve around a probability figure, be it a distribution or an expected value. Among these, probability analysis is the foremost method for risk quantification. When conducting risk studies, two types of parameter uncertainty are applied (Abdo et al., 2017):

- Stochastic or aleatory uncertainty
- Epistemic uncertainty

Stochastic or aleatory uncertainty describes the variation in possible outcomes which is due to randomness in the process or some sort of natural variability. An example of a random process with aleatory uncertainty is that of flipping a coin. Sometimes it is heads while other times the outcome is tails. Natural variability can be observed in discharge of a river. At t = 0 it may be 10 m^3/s, while at t = t + dt it may be 12 m^3/s. To assess aleatory risk, limit frequency assessments are used to define a probability distribution given infinite outcomes. This method can only be reliably applied if the underlying process generating aleatory risk is stochastic in nature.

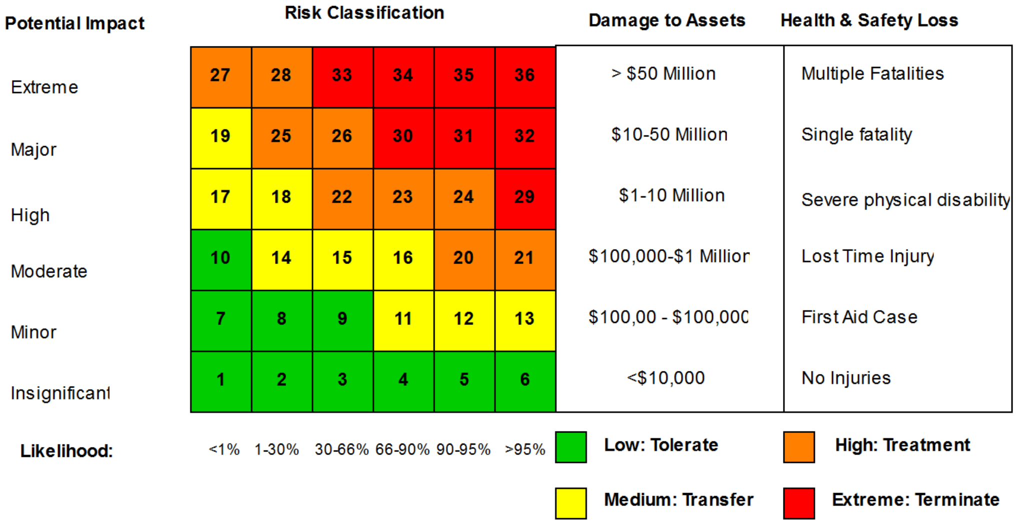
Epistemic risk refers to a lack of knowledge, imprecision or measurement error. This could for instance be due to a lack of understanding with respect to the issue at hand (Abdo et al., 2017). One way to deal with epistemic risk is to gather a second opinion by experts in a certain field. However, there might still be a lack of knowledge unbeknownst to the experts consulted, which is also a measure of epistemic uncertainty.

Oftentimes companies classify both types of uncertainty using a risk matrix. In such as diagram, several categories of probability are categorized on one axis, while a similar amount of categories of consequence is assessed on another axis. This approach therefore assumes that both forms of uncertainty can be quantified in the same way. An example of a risk matrix can be viewed in Figure 2.6

Instead of using an exact probability, a confidence interval is taken to classify uncertainty. Similarly, a linear or exponential set of outcomes as is the case in Figure 2.6 can be assigned. When this is applied to all hazards or uncertainties, a measure of their criticality for the company can be specified. Whatever make up of the risk matrix is used depends on the risk appetite and priorities of the respective organization. How this is established will discussed in detail in Section 2.5. Depending on what category hazards can be assigned to, several methods of risk mitigation might be applied:

- Tolerate: accepting the likelihood and consequences of a risk
- Transfer: using insurance or third parties to take risk on behalf of the company
- Treatment: controlling the amount of risk through actions reducing likelihood or minimizing impact
- Terminate: altering processes or simply removing the necessity for carrying out business a certain way

Whatever method is applicable has to be determined through comprehensive risk assessments of the business. In some cases, it might not be feasible or practicable to mitigate both axes to an acceptable level. In such cases, further determination by the company is needed to assess whether business can be continued.



Potential Impact	Risk Classification						Damage to Assets	Health & Safety Loss
Extreme	27	28	33	34	35	36	> $50 Million	Multiple Fatalities
Major	19	25	26	30	31	32	$10-50 Million	Single fatality
High	17	18	22	23	24	29	$1-10 Million	Severe physical disability
Moderate	10	14	15	16	20	21	$100,000-$1 Millio	Lost Time Injury
Minor	7	8	9	11	12	13	$100,00 - $100,00	First Aid Case
Insignificant	1	2	3	4	5	6	<$10,000	No Injuries
Likelihood:	<1%	1-30%	30-66%	66-90%	90-95%	>95%		

🟩 **Low: Tolerate**
🟧 **High: Treatment**
🟨 **Medium: Transfer**
🟥 **Extreme: Terminate**

Figure 2.6: Example risk matrix used by companies to assess criticality of hazards

2.4.4. Layer of Protection Analysis

Combining the ideas of barrier-based risk management and probability-based risk analysis is Layer of Protection Analysis (LOPA) (Pasman and Rogers, 2013). This method seeks to quantify the probability of consequences after unwanted events through attributing probabilities to both causes and controls in the model. An example of a LOPA quantified model developed during this study is shown in Figure 2.7, which is a modified version of the Event Tree Analysis diagram presented in Figure 2.3.

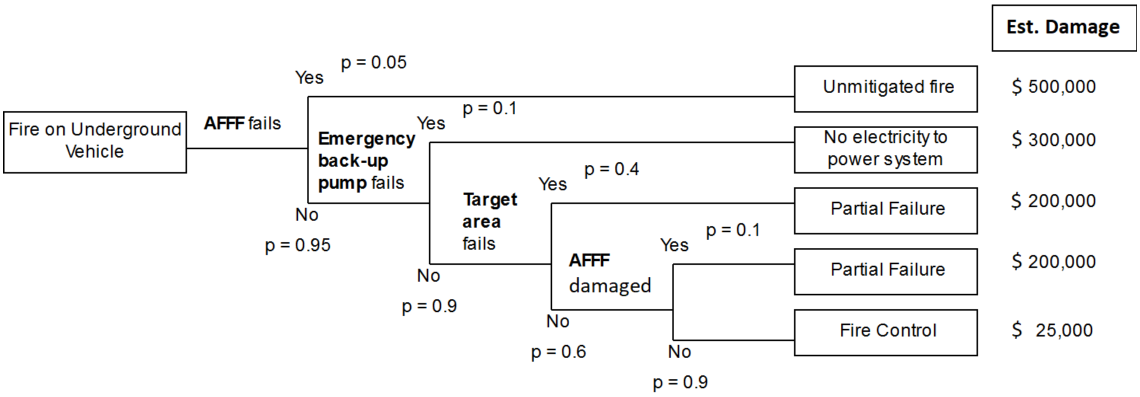


Figure 2.7: LOPA Analysis diagram categorizing risk and potential damage suffered

The probabilities that are attributed to causes of incidents are probability figures indicating their estimated frequency of occurrence. These can be based on historical data or through probability analysis of controls.

Within LOPA, controls are attributed a probability of failure on demand (PFD). This measure specifies how often a control fails when depended on. The PFD combines availability, interval between demands, failure detection and adequacy for a scenario. A simple example of PFD can be seen in Figure 2.7, where the PFD for the AFFF system failing is set as p = 0.05. By combining all PFD's with their damage category, a measure for the estimated cost of an incident can be made. The benefit of a LOPA model is that dominant pathways to more prone consequences are easily identified. Additionally, an estimation can be given for the total risk profile given a specific hazard.

While LOPA is seemingly powerful, it is limited by the amount of scenario's a LOPA analysis effectively can cover (Pasman and Rogers, 2013). What will become clear in Chapter 7 is that when presented with multiple scenario's with different levels of complexity, getting accurate figures for PFD is practical nor attainable, even within the scope of a thesis study.

2.5. What is acceptable risk?

After all possible outcomes and probabilities are estimated, what is ultimately an acceptable level of risk to face in an operation? Setting a level for risk tolerance is often found difficult, much more so when decisions potentially have a long term impact (Berner and Flage, 2017). Factors that apply in determining what is acceptable are for instance:

- The type of organization
- The (local) social and cultural norms applied
- The hazards faced by an organization and the understanding thereof
- Background knowledge
- Models, data or expert statements

Depending on the nature of an organization, the tolerance for risks can be much higher. Compare an administrative job in an ordinary office to being an operator in an underground mine. In the second instance, solely being underground means one is exposed to a multitude of hazards that could be potentially fatal to the individual. Some of these hazards are for instance vehicle-vehicle or train-person collisions, inundation of the underground workings or inhalation of toxic fumes. Even so, some of these hazards might not even exist in another mine, simply due to the fact no trains are utilized in that specific mine or toxic gasses do not permeate from within a certain deposit.

Differences in social norms across continents are very visible in mining as injury rates differ not only from mine to mine, what is acceptable also very much depends on the local culture. Because mining companies tend to work globally, what is applied in the company as acceptable often shapes safety performance across the board.

Defining what level of risk tolerance is acceptable often relies on incomplete understanding of hazards or dated background knowledge. To make up for these gaps, models are made, data is gathered and experts consulted. When dealing with low-frequency, high-consequence events such additional knowledge might not fully represent the "true" risk (Aven, 2014).

2.5.1. "As Low As Reasonably Practical" or ALARP

One way to account for all of the aforementioned discrepancies is applying the principle of "As Low As Reasonably Practical", otherwise known as ALARP. This process is hazard-based and looks to diminish risks faced in an organization (Robinson and Francis, 2014). ALARP works through applying a simple process to map out hazards and risks, after which countermeasures can be applied if deemed necessary. In Figure 2.8, a flow chart is shown that shows the steps taken to reduce risk to an ALARP level.

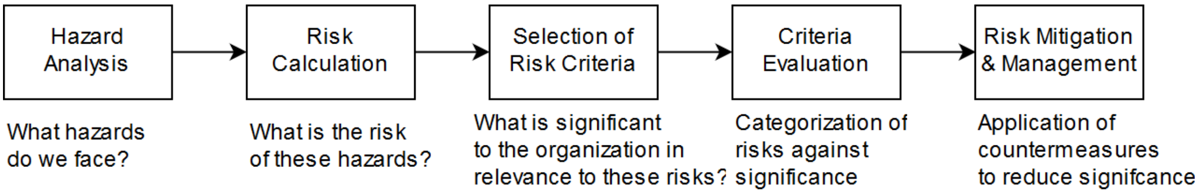


Figure 2.8: The process applied to mitigate risks based on the ALARP principle. Underneath the steps the main questions or actions per process item are outlined, as adapted from Robinson and Francis (2014).

Within the environment of a generic underground mine, a hazard can be assessed using the ALARP process. In this example, the case for fall of ground incidents will be examined. More hazards ought to be determined in the first step of the ALARP process, but for the example a single hazard will suffice. The second step of the process is determining what the level of risk for a fall of ground incident is. Depending on the prevailing conditions at the start of underground operations, an assessment can be made as to what the implied strength or integrity of the surrounding rock is. For this, methods such as RQD or Q-classification can be applied.

Based on such an assessment, dimensions for drifts and stopes may be calculated in which a safety factor is used in accordance with conventional mining theory. This safety factor is partially based on the amount of support that is implemented in the underground workings, be it through rock bolts, shotcrete, or meshing.

Even so, there is some measure of likelihood that ground control incidents will occur. Like the example FTA in Figure 2.2, several categories of failures may occur through primary causes. For each of these, a probability density function may be quantified to estimate the potential of all foreseeable consequences. Then the risk of all of these outcomes is compared to risk criteria, functioning as a would-be target for the organization. Possible criteria in the case of fall of ground might be figures for:

- amount of fatalities per year
- amount of production loss
- reputational impact
- damage to assets

Even if no one is harmed, damage is sustained or production losses occur, a fall of ground might still lead to damage in the form of reputational repercussions. Comparing fall of ground incidents to the risk criteria, a target probability for a fall of ground incidents can be specified. If the frequency of such events instances is higher than is specified as acceptable, countermeasures ought to be applied until the target frequency is achieved. A generic outcome for the example is then: the probability that a fall of ground incident occurs is estimated to be once every twenty years *after countermeasures are implemented.* If a mine has an estimated lifetime of five years, such an outcome could be viewed as an acceptable level of risk.

2.5.2. "So Far As Is Reasonably Practical" or SFAIRP

Recent developments however have pointed out that an approach like ALARP leaves a company vulnerable in an aspect outside of its operations: a court room (Dixon, 2011, Robinson and Francis, 2014). The very nature of legal institutions within a country can define whether an ALARP based approach suffices as substantial due-diligence when faced with a lawsuit after a (significant) incident.

2.5.2.1 Common Law

It is not uncommon for Western countries in which mining has a significant presence to have a common law system. Examples of such countries are the United States, Canada and Australia. Furthermore, countries such as South Africa have a mixed system that is partially based on common law. The systems for code of law in these countries was inherited through English colonization and the concept itself dates back to 12$^{\text{th}}$ century England. In that period of time, judges would hear cases on the king's behalf and base their judgement on instinct, sometimes Roman law, customs or traditions. The notions for their verdict would be recorded and in time, other judges felt the need to adjust their verdicts to those decreed by their predecessors, forming the concept of precedent law. (Robinson and Francis, 2014).

By itself, that is not a bad thing. It does however have a very big implication. In deciding over a case, judges will base their verdict on the precedents set by their forebears. In their 2014 paper, Robinson & Francis set out several conditions that apply in adversarial courts, i.e. those in which lawsuits about safety are decided. These are:

- the courts are always right, even if they are wrong
- courts are not about dispensing justice, they are about winning actions
- courts deal in opinions, not facts

When a judge therefore decides a verdict in an adversarial court, the laws of man take precedent over the laws of nature. Furthermore judges preside over the instances in which something went wrong, not how often it went right. In all of these cases, the outcome is already certain. In a judge's eyes, that means any calculations done beforehand to assess risks must have been flawed. By itself, that provides reasonable proof that insufficient due diligence was carried out, thus proving negligence. Mitigating a risk to having a once every hundred years probability might seem like a perfectly acceptable standard for a ten year operation. Even if the calculation is completely accurate, the process can thus be assessed as flawed. If a judge deems it unsatisfactory based on precedents set, one can still be held liable for damages. How that can affect a court case is reflected well in the following exchange, as reported in an Australian court as the result of a significant railroad incident (Robinson and Francis, 2014):

> Judge: "What do you mean you did not think it could happen? There are seven dead."

Using a hazard based approach such as ALARP is thus intrinsically flawed. It assumes some probability to be acceptable, when if an incident occurs, no due diligence can be attributed to the risk assessment process. That by itself proves negligence and thus liability beyond reasonable doubt. In order to avoid this issue, the way in which a judge makes up his or her verdict has to be examined closely. Instead of working precautionary, hindsight dictates the decision-making of a judge. After all, every outcome is already known. Thus a precautionary approach is needed that deals with this potential liability.

2.5.2.2 The precautionary approach

Instead of looking at what hazards can and should be mitigated, another methodology focusses on preventing critical hazards from leading to significant outcomes. The central questions applied within this approach are:

1. What could possibly happen?
2. What could reasonably be expected by the courts to assure due diligence?

Answering these two questions is central to SFAIRP ("So Far As Is Reasonably Practicable"). Although the abbreviation does not necessary roll off the tongue, it does have an interesting proposition. Instead of dictating an artificial acceptable risk level, it assesses all possible countermeasures and implements those as are presumed reasonable by a court of law. It is therefore inherently an outcome based approach. In Figure 2.9, a flowchart can be seen with which to apply the SFAIRP process.

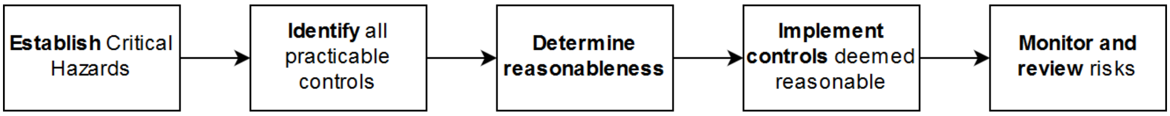


Figure 2.9: Flowchart demonstrating the SFAIRP precautionary process for mitigation of significant outcomes which could potentially confer liablity in a court of law, as adapted from Robinson and Francis (2014).

The third step in Figure 2.9 deals specifically with the question: "What does a court of law need to prove beyond reasonable doubt that due diligence has been carried out correctly?". The sentiment of courts in a common law system seems to be that where it is possible to guard against risk, albeit with a low probability, can be done with little effort or expense, the failure to adopt controls is determined negligent (Robinson and Francis, 2014). This implies a certain cost-effectiveness that is inherent to the controls implemented. If little costs are involved for little effectiveness, a control should always be implemented. By assessing all controls available to mitigate a critical hazard, that assessment can always made conscientiously beforehand. In order for a mining company to successfully execute this methodology, it needs to understand what hazards and controls are critical, and monitor their performance.

2.6. Current Industry Best Practices

AngloGold Ashanti and all other global mining companies face the issues outlined in the introduction. Focusing on critical risks and prevention of Material Unwanted Events has become a staple safety approach for the world's leading mining companies. This section gives a brief, limited overview of some of these organizations and the way in which managing critical risk has become central to their approach, based on material made publicly available. However, this section is in no way meant to represent the opinions or standpoints of the organizations in question and is merely a perspective on material made public by these organizations.

2.6.1. Rio Tinto

A global mining company with a diverse range of commodities, Rio Tinto is one of the world leaders in the advances of safety management in mining. The ten ways in which it manages safety all correspond with the goals set out in this project (Rio Tinto, 2017). Of these commandments, the following are of special interest:

- **Report and investigate** all incidents, ensuring the **learnings are shared and implemented** across the organisation
- Implement safety performance standards and expectations for **managing critical risks** associated with aviation, confined spaces, cranes and lifting, electrical works, isolation, vehicles and driving, and working at heights

- Maintain an appropriate safety assurance framework through a **range of audits, reviews and verifications** against our standards
- Develop, implement and embed a **focus on process safety and fatality prevention programmes**
- **Establish, implement and monitor critical control plans to manage our key safety risks.**

These are but five of ten ways in which Rio Tinto aims to improve their standard of safety. All of these align exactly with the goals set out in the introduction, while their other initiatives at least provide synergy to the set-up for this project. The programme that Rio Tinto applies is called "Critical Risk Management (Rio Tinto, 2017) and focuses directly on the implementation and auditing of critical controls. It integrates across the chain of command, providing everyone with different tasks yet endeavouring to achieve the same goal.

On their website, Rio Tinto claims to have performed 1.3 million critical control verifications in 2016, with 6.500 company leaders completing tasks and states that it has been implemented across all 60+ sites. Although the current scope of the project only relates to one site, eventually critical control management should be incorporated at all AngloGold Ashanti sites. Not only does the Rio Tinto case show it is possible, they also show that it is worth significant effort to get this right Rio Tinto (2017).

2.6.2. BHP Billiton

Perth-based BHP Billiton is the largest mining company in the world industry with operations on four continents. Similarly to Rio Tinto, BHP have set out extensive documentation regarding the management of critical risks and associated controls. Many of the hazards set out by BHP mirror those found at AngloGold Ashanti, stemming from the similar nature of operations conducted BHP (2016). Furthermore, like AngloGold Ashanti, BHP Billiton is one of the founding members of the International Council of Minerals and Mines (ICMM).

2.6.3. ICMM

Founded by a collective of global mining companies, the ICMM was initiated as a collaboration platform to achieve a safe, fair, and sustainable mining industry. With members like AngloGold Ashanti, BHP, Rio Tinto, Anglo-American, Freeport-McMoran, Barrick, Gold Corp, Teck, Glencore and others, over 30% of global mining production is represented on the platform (ICMM, 2015b).

The ICMM has worked continuously since 2012 to reduce fatal incidents. Central to the approach are operators facing (high-potential) hazards in the operations themselves. Through combined assessments it was found that reducing Lost Time Injuries does not decrease the frequency of fatalities. Instead, the focus was shifted towards High Potential Incidents (HPI's) and their causes. During investigation of HPI's, the weaknesses of controls and their adequacy became apparent. In 2015, a good practice guide on critical controls was published by the ICMMM, followed shortly by an implementation guide. (ICMM, 2015a).

It is clear that within the domain of operational safety, critical control management is considered to be an essential part of doing business sustainably within the mining industry. On the path to complete integration of critical control management lies measuring their performance. This the second to last step and it was the aim of this study to support AngloGold Ashanti in making those leaps, implementing the next generation of safety and risk management approaches.

3

Methodology

The aim of this research was to develop a scalable, non-invasive Critical Control Management System for AngloGold Ashanti. In order to fulfil this goal, a wide range of methods was applied to ensure that the system functions as intended. In this chapter these methods and their implications are discussed. First, the interview strategy with which to gather organizational requirements is examined. Next, the bow-tie modelling software used throughout the project is presented. Thirdly, the domain and application of business intelligence is discussed, after which its use for risk management is demonstrated. Finally, a summary is given of all methods and applications used to complete this research.

3.1. Interviewing technique

The use of interviews is one of the main research methods within this project. By interviewing key personnel on their opinions and wishes around a Critical Control Management System, a framework of organizational requirements could be developed. The method applied in these interviews was that of semi-structured, open-ended conversations centred on multiple open questions. This form of interviews is considered the most-used format for qualitative research (DiCicco-Bloom and Crabtree, 2006). Through usage of a standardized interviewing format, comparing and combining requirements into satisfactory categories was a straightforward process.

3.1.1. Selection of stakeholders to be interviewed

The goal of interviewing key employees of AngloGold Ashanti was to get a broad, yet deep understanding of the way safety and risk management is applied throughout the organization. Based off that knowledge, further conversation could then explore the possibilities for critical control management. Gaining this understanding was only deemed possible through interviewing employees on every level of the organizational hierarchy.

Selection of personnel to interview was an iterative process focusing on current or potential future stakeholders. An example of this phenomenon is that of the heads of other sustainability disciplines. While critical control management is currently only being piloted for operational safety, other sustainability disciplines will also follow suit, pending successful trial. Taking their wishes and opinions into account allowed for establishing a better foundation of the system.

A second, non-explicit goal during the interviews was re-familiarizing the employees with critical control management. This lack of familiarity was not without risk for the project itself. If any of the senior managers would have found that the project was at odds with their own goals, long term support could have been lost. The nature of these interviews was therefore very non-committal, without official statements and anonymous.

In total twenty-six interviews were conducted with personnel based at group headquarters in Johannesburg, regional headquarters in Perth and at Sunrise Dam Gold Mine. An overview of the roles fulfilled and their base of operations is provided in Appendix D.

3.1.2. Set-up

All interviews were planned beforehand as a 30 minute session on developing understanding of requirements for a Critical Control Management System. Because some of the personnel to be interviewed only had a very limited timeframe, no preparation was asked from the employees to be interviewed. Instead, it was explicitly stated that a broad introduction to the topic would be given before getting into the questions section of the interview.

The general set-up of the interviews consisted of three distinct parts. First, an introduction to the project, interviewer and purpose of the interview was given. Secondly, the history of critical control management at AngloGold Ashanti was explained as the building blocks for a next-generation safety management system. Lastly, the official interviewed was asked to contribute his or her opinion on what such a system would need to become successful. This success was measured both with regards to the wider organization and the person in question.

In order to frame the conversation and standardise the type of answers received, several open ended questions were asked at the last phase of the interview. These questions were:

- What uncertainties do you face with regards to risk management?
- What would you like to see come out of this project?
- What is the level of granularity you look at when dealing with safety or risk?
- How could output from this project support your decision-making?

The first question was designed to get the employee interviewed to think about his or her work. It revolves around identifying current gaps in knowledge hindering decision making. The second question builds on that thought process by implying these unknown do not need to stay that way. This opens up an entire perspective on fixing those things that now have to be decided on gut feel or without confidence. The third question sets the interviewee up as a potential stakeholder. When the data behind uncertainties is clear it needs to be presented to the right person, at the right level. Finally, the fourth question helps the interviewee think about his or her decision-making, whether that would be stopping or increasing production, changing out a fleet or implementing new controls.

After these four general questions, two specific ones were asked related to the work or initiatives of the interviewee. These specifically looked into integration of critical controls in their work. An example of these questions was around the issue of integrating another sustainability discipline into Critical Control Management. As the officials within this domain had already made their bow-tie models, a successful trial of the project could lead to accelerated inclusion of this specific discipline into the wider system. This led to the adjustment of design scoping to be able to include the other sustainability disciplines in due time.

3.1.3. Execution

Because all interviews were conducted one-on-one, special attention was paid to interviewer conduct during the interview. Main goals for behaviour were being clear, patient, and knowledgeable while interpreting and remembering the items discussed during the conversation. Of the objectives stated, interpreting answers correctly was paramount to the successful completion of an interview. Although gentle steering was applied, during some interviews conversations strayed into very abstract territory. This had no negative consequences, but it was difficult to scope such an approach in a six month study. The use of remembering became more apparent in later interviews, as the amalgamated views of the officials previously interviewed could be presented as a middle ground if need be.

After the interview was finished, a short review of the conversation was held to confirm agreement on the official's views. If requested or precipitated in the conversation, updates of project progress were subsequently shared with the official interviewed.

3.1.4. Analysis of outcomes

During interviews, notes were taken on comments as the speed of conversation allowed. These were entered into a combined file within a day to preserve recollection of the interview. This document was then reread before a new appointment to take the outcomes of other interviews into account. After no new themes emerged from the data, a high-level overview was presented to the project owner, of which the results will be discussed in Section 4.6.

3.2. Bow-tie Modelling

The application of bow-tie modelling has already been discussed in Section 2.3. The software package that AngloGold Ashanti uses to develop their bow-tie models is called BowTie XP and is developed by CGE Risk Management Solutions. This package allows in-depth building and modification of models to suit a given operational environment. Currently being trialled is a web-application version of this software package called Bow Tie Server. This online platform allows sharing of bow-tie models through a company and has added the preliminary functionality of sending audits to personnel for review. By storing all data in one place, Bow Tie Server functions as a hub for all bow-tie related data that AngloGold Ashanti has developed over the years.

3.3. Business Intelligence

The data that is generated within a company often remains unused other than as a document for future reference. An example of this phenomenon is the registration of incidents on-site at a mine. This process is carried out as part of the due diligence process required of an HSE department. What and where it happened, what personnel and machinery were involved are all entered into records. Unless the details of an incident are required by some future event or need, the data will merely be archived. However, the aggregate of that data might provide some interesting thoughts about the business.

This is the domain of business intelligence (BI), where meta-data generated by a company is examined in order to predict trends in performance, detect underlying issues and solve business process inadequacies (Al-Aqrabi et al., 2015). The reason that BI is central to this thesis is that it has significant potential for risk management and operational safety purposes. Previously unrelated incidents can now be correlated to controls implemented to prevent them. This could result in identifying areas within a mine with significantly higher risks, thus justifying a re-evaluation of processes carried out in those areas. Through monitoring the health and performance of controls, one of the essential steps is taken in applying a precautionary approach to risk management.

By providing analysis of this data to decision makers in real time stakeholders can make informed decisions, replacing gut feel with facts. Note however, that the aggregation of data is subject to the knowledge and skills of a business intelligence developer. This can apply a degree of subjectivity to the data, so relying solely on business intelligence analytics should be avoided if possible. Furthermore, a BI system does not simply take meta-data and transforms it into analytics. It consists of seven different layers (Al-Aqrabi et al., 2015):

1. IT infrastructure
2. Data acquisition
3. Data integration
4. Data storage
5. Data organizing
6. Data analytics
7. Data presentation

For the purpose of this thesis, the IT infrastructure is beyond scope. All other layers have been applied in some shape or form. The methodology of this these revolves around moving through each of the steps listed above to develop the system and included BI environment. In the next few paragraphs, the steps taken through each of the BI layers are explained in a general sense. Of these steps, data acquisition required the most significant effort by a large margin, and will be discussed extensively in Chapters 5 and 6.

3.3.1. Data Acquisition

Traditionally, BI has been one of the most data intensive business processes (Al-Aqrabi et al., 2015). It draws the data from databases across the organization and stores it in relational data warehouses. These are updated as frequently as business demands to enable use of data in (near-)real-time. The data of interest in this study revolves around performance of critical controls, safety incidents and holistic bow-tie models.

Because critical control data is being gathered through multiple processes and transferred to Bow Tie Server (BTS), it served as a convenient intermediate source of all bow-tie related data. Through adapting BTS into the BI environment, all related critical control data can be used for analytics. The other major source of data used is the Event Management System utilized on site to record incidents and actions related to operational safety. AngloGold Ashanti Australia uses a platform called InControl by INX to store all their incidents and related meta-data. Together, these form the foundation of data sources for a management system that monitors both leading and lagging indicators with regards to critical control performance.

3.3.2. Data Integration and Storage

After data is moved from its source to a warehouse it is merely stored though rows and columns, forming an array. Even from a single source, multiple arrays might be needed to encompass all data. This is especially true when dealing with the import of models into the BI environment. An example of this can be seen in figure 3.1. For each of the distinct entities an array is drawn up, such as hazards, threats or controls. Each of these have their own properties, are applied within certain models and can be used more than once. When storing data from multiple sources, another layer of complexity is added. Arrays linking a single application have to be related to other applications. Both integration of single and multiple sources is done through a process called Online Analytical Processing (OLAP). Through applying queries, it allows multi-dimensional analysis of data warehouses. These combine the arrays into so-called data cubes. After cubes are built, OLAP allows manipulation of the underlying data. A representation of a data cube with interface is shown in figure 3.2.

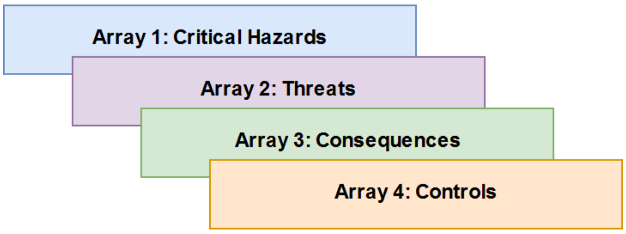


Figure 3.1: Several arrays created when importing a Bow-tie environment into a Data Warehouse

Figure 3.2: Generic dashboard interface that allows manipulation of the underlying arrays, forming a data cube

The system that was used to gather and store primary data was a SQL-based Server based in Perth. This infrastructure was already present and useable when project execution moved to Australia. A benefit of this type of server is that it allows easy integration with a PowerBI environment, which will be discussed in the next paragraph.

3.3.3. Data Organization, Analysis and Presentation

OLAP enables presentation of data in the form of dashboard interfaces to business intelligence developers or other end-users. As such, OLAP combines data organizing, analytics, and presentation. An application that provides this OLAP capability is PowerBI. Developed by Microsoft, it allows small users and businesses alike to perform data analysis on a wide variety of sources. Key in the use of PowerBI or OLAP applications is relating the stored arrays. As an example, one can relate different arrays formed through import of the Bow-tie models.

It is important to understand that the BI environment does not automatically relate the different arrays back into a bow-tie model. In order to assess performance of the model holistically, queries need to be applied. The arrays that are formed often have relational columns in which the relation to other entities is specified. If one looks back to the Bow-tie model in figure 2.4, a threat can be related to a so-called parent bow-tie hazard. Because this is something that can be made for each threat, a column can be made that specifies what the parent hazard is for that threat. In that way, loose arrays are joined again forming data cubes, enabling analytics. This means that multiple sources can be integrated in a straightforward manner, as long as the relationships between these sources are applied correctly.

3.3.4. Potential for Risk Management

Using data analytics to assess company performance is one of the key elements of successful HRO functioning. It supports multiple core tenets of the HRO such as assisting in problem anticipation, learning orientation and mindful leadership. It allows stakeholders to be knowledgeable of what goes on at the shopfloor, even if not present at the location in question. Secondly, system performance provides a clear indication if problems are more likely to occur. By providing the means to identify negative trends, problem anticipation within the company is enhanced. Thirdly, it has the ability to provide this information at a moment's notice, depending on the frequency with which the data is refreshed within digital warehouses storing the data. Furthermore, by relating multiple incidents over a longer time span, one can start to identify underlying patterns in risk exposure for an operation or company.

Incidents and assessments might be far and few in between at a well-run operation, thus reducing the inherent potential. Therefore, trialling this project at an operation with a good safety record was a double-edged sword. Stakeholders were assumed to be more inclined to adaptation, as aspects of the HRO such as Just Culture and the Learning Orientation had already been (partially) adopted. The return on investment for the system might not have been as high as an operation with a worse safety record. However, one thing that the system would provide when implemented was the definition of "what good looks like". This will make duplication of the system much easier after successful implementation. It will make the identification of gaps in operational safety at other operations much more straightforward, as a good example is already present. That is why the goal of this study was getting the system to click. If other operations can see the small benefit is it generating in a safe environment, the potential of critical control monitoring becomes visible to the other operations as well.

3.4. Summary of Methods and Applications

In this thesis, both qualitative and quantitative research methods are applied. Before designing and building, a thorough review of literature was performed. After the state-of-the-art was assessed, it could be applied to the problem at hand. As AngloGold Ashanti has a decentralized structure, an in-depth analysis of the organizations global requirements had to be conducted. These were elicited through semi-structured, open ended interviews. Systems design was done using the standard sub-systems of BI to extract data from multiple business processes into one environment for analysis and presentation. During systems building the following applications are used:

- Bow Tie Server
- INX
- SQL Server
- PowerBI

The first two listed applications function as data sources for controls and incidents, respectively. The other two make up the infrastructure of the BI environment. Together, these form the foundation of the Critical Control Management System designed in Chapter 5 and implemented in Chapter 6.

4

Organizational environment

In this chapter, the current practices at AngloGold Ashanti will be introduced that relate to operational safety and risk management. The theory discussed in Chapter 2 will be brought to the fore and applied to the processes found. Next, the organizational requirements will be discussed that have been ascertained during twenty-six interviews with employees ranging from the COO's of international and South African operations to the coordinator of processing operations at Sunrise Dam Gold Mine. These requirements have been amalgamated into several main categories in Section 4.6 to keep discussion clear when moving forward towards designing a system for continuous risk management.

4.1. Current safety systems in place

Moving from theory into practice, this section will discuss the ways in which AngloGold Ashanti already manages its safety issues. The goal of this paragraph is not to discuss all elements in detail. Rather, an impression of the company's safety approach is developed through the major systems it applies within its operations. At a company like AngloGold Ashanti, compliance is a key element of demonstrating that operational safety issues are adequately addressed. In order to meet this required compliance, different international standards are used depending on where a specific operation is located. One of the main standards applied is the OHSAS 18001 standard, which was developed by an international collaborative group and distributed by the British Standards Institute (2017) to form a single approach to managing safety. It lies at the basis of ISO 45001 standard currently in development, which aims to be the most comprehensive OHS standard to date.

4.1.1. Safety Management System

In order to comply with the OHSAS 18001 standard, AngloGold Ashanti has developed an extensive safety management system. Not only does it function as a repository for procedures, AGA standards, training manuals and more, it also puts all of the requirements for OHSAS 18001 in one place. Some of the key elements that need to be managed within the system are:

- Occupational Health and Safety policy, planning and objectives
- Competence, training and awareness
- Documentation System
- Operational Control
- Emergency Preparedness
- Internal Auditing
- Incident Investigation
- Non-conformity, corrective & preventative action
- Company Risk Assessment & Hazard Identification

The Safety Management System deals with several of these requirements by itself through making all relevant documents available in one place. Here, the company's procedures, commitments and goals are specified. Any auditor can come in and discuss all related issues through assessing the different sub-elements of the system. This reflects a high degree of document control.

4.1.2. Training, Competence and Awareness

One of the main pillars of OHSAS 18001 is making sure operators are adequately equipped to deal with hazardous situations when working in any environment. At AngloGold Ashanti that means employees are trained through extensive programmes aligned to risk assessments of their working environments. Only after they are verified and validated as being competent can they fully enter the working environment independently. Should an operator change jobs within the same mine, re-training and verification of competency is carried out. After certain periods of time, operators might be required to re-assess their skill level.

Two other ways in which operators are trained in making decisions every day are Job Hazard Analysis (JHA) and Stop & Think, Look, Act and Manage (SLAM). These personal programmes are tools an operator uses to assess if a job could potentially be hazardous, or if a hazardous situation is currently ongoing. A JHA is carried out before each task marked as potentially hazardous and requires sign-off from a supervisor. It recognizes risks and helps operators to take the necessary steps to carry out a task safety. SLAM is a procedural tool that operators can use on the job when they feel a something is or seems to be unnecessarily hazardous. This four step programme helps an operator to identify the steps needed to mitigate a hazard successfully.

4.1.3. Emergency Preparedness

Every operation has its own emergency response team (ERT). These are often drawn up from employees at the mine itself, performing this duty to assure the safety of their co-workers. Being an ERT member does not just mean one is exposed to hazardous situations. Being a member grants access to extensive training programmes on first response, working at heights and firefighting, amongst others. Secondly, operations specific perks may be given such as free use of sporting facilities and use of ERT vehicles.

4.1.4. Internal Auditing

To become OHSAS 18001 verified, a company has to conduct internal audits into safety performance. Essential to this auditing is a systematized approach that verifies if:

- company OHS goals are met
- controls for health & safety are effective
- data is recorded and mitigating actions are carried out
- monitoring systems are calibrated according to standard

Apart from actions being completed, no specific auditing frequencies are given. A company should set these for itself depending on the findings in risk assessments and safety performance. AngloGold Ashanti has its own audits set up by the sustainability disciplines and its internal auditing team. It uses a cross-departmental approach that assures both individual processes and overarching systems are running as desired. Apart from that, commitment is shown by the board through frequent updates on company safety performance and high level involvement in improvement discussions.

4.1.5. Incident Investigation

After an event has occurred in which occupational health or safety was (possibly) impaired, a detailed investigation has to be conducted. The outcome of this process then results in recommendations for changes to procedures, processes or systems in order to mitigate similar incidents in the future. Every mining site at AngloGold Ashanti manages their own incident reports and needs to report on those incidents that could have potentially had a high impact. This data is entered into an Event Management System (EMS) which allows returning to cases if need be.

4.1.6. Operational Risk Assessment

Only after the risks in a specific situation are understood, proper controls can be introduced to mitigate Material Unwanted Events. AngloGold Ashanti has conducted risk assessments of all operations, indicating the most problematic issues faced throughout the company. By doing this, they have established a detailed overview of what operators might encounter on a day-to-day basis.

There is one problem with these assessments however, which is not addressed in OHSAS 18001 either. An analysis of the risks on site provides merely a snapshot of operations, hazards and controls in place. This might give an operation full marks at the time of auditing, while deteriorating assets are not identified until they fail. This creates potential for holes in the cheese of Reason's model as discussed in Section 2.1.

4.1.7. Above and beyond the standard

While being OHSAS 18001 compliant is an objective of AGA safety strategy, the goal is to provide a safe working environment for its employees. Exceptional conditions require exceptional measures, both of which are essential for profitable and sustainable operation. So while the standard is used as a framing document, managing safety at AngloGold Ashanti means being a step ahead of the rest. This is clearly identified when comparing the goals of this research to OHSAS requirements:

- Hazard Identification - 1. Indicate performance on hazards and the performance of controls
- Operational Control - 2. Grant operations real-time information on safety performance and actions
- Internal Auditing - 3. Provide information to relevant stakeholders in real-time
- Incident Investigation - 4. Assess trends in incidents to identify systemic issues

What this research aims to do is move safety management from a static to a dynamic situation. This gives all relevant stakeholders the power to change safety performance on a day-to-day basis. Instead of spending time on reporting, employees can spend their time on achieving process excellence. To get to the desired dynamic state, one needs to understand how hazards are identified at AGA.

4.2. Hazard Identification at AngloGold Ashanti

Barrier-based risk management has been one of the main pillars of safety thinking at AGA since 2014 (AngloGold Ashanti, 2014). Since that time, the company has identified 19 Major Hazard Standards (MHS) which are the cause of the majority of fatal or high-potential incidents in its operations. These MHS are part of normal operations and demonstrate the processes involved in the aforementioned incidents.

One example of a MHS is the use of hazardous materials. Through the carbon in-leach process, crushed gold ore is mixed as a slurry with a solution of cyanide in a staged circuit of tanks. As the slurry moves through the tanks, the gold continually leaches into the cyanide solution. Carbon particles are simultaneously suspended in the tanks to adsorb the gold ions from the cyanide solution. Carbon with the highest gold value is then sent to the elution process for further extraction (Wadnerkar et al., 2015). Other examples of chemicals and hazardous materials used include hydrochloric acid, caustic soda and hydrogen peroxide. This does not include the use and handling of explosives, which have a dedicated MHS. The entire list of Major Hazard Standards is listed below (AngloGold Ashanti, 2015).

- Aviation
- Confined Space Entry
- Electrical Installations
- Energy Isolation
- Equipment Safeguarding
- Explosives
- Fire
- Hazardous Materials
- Heavy Mobile Equipment
- Inundation, Inrush and Submergence
- Lifting Operations
- Light Vehicles
- Pressurized Equipment
- Surface Excavations
- Underground Ground Control
- Underground Rail bound Transport
- Underground Ventilation
- Underground Vertical Transport
- Working at Heights

These MHS cover the entire company, therefore not all MHS are suited to each operation. Exactly which hazards are applicable to a certain site are determined by a site-based approach. Each site has its own bowtie models in order to map the hazards and controls relevant to them. Because regulations differ from country to country and perhaps even more so from continent to continent, safety thinking requires tailoring to local norms and regulations. On top of that, Critical Control Management can potentially provide a one-size-fits-all solution for fatality prevention. Not through application of specific controls, but by providing a single platform for management of these controls.

4.3. Critical Controls and their Application

All operations of AngloGold have made Bowtie models based on the hazards faced on site. To mitigate these hazards successfully, controls applicable to both the reduction of cause and consequence escalations were identified. If all possible and practical controls are then implemented correctly, the theory states that material risk to the operation should be prevented. Applying this way of thinking when modelling can lead to expansive models that demonstrate all possible pathways and all critical controls. This loses the visual effect of quickly identifying vulnerable pathways and possible controls. Oftentimes, implementing such an extensive approach with numerous systems proves too difficult (Bakolas and Saleh, 2011). After identification of all possible controls, focus shifts to assessing their criticality.

The central question to control assessment in this stage is: which controls are critical to mitigating Material Unwanted Events (MUE's)? (Sklet, 2006). To answer that question, the International Council of Minerals and Mines has adopted a critical control identification flowchart as seen in Figure 4.1 (ICMM, 2015a).

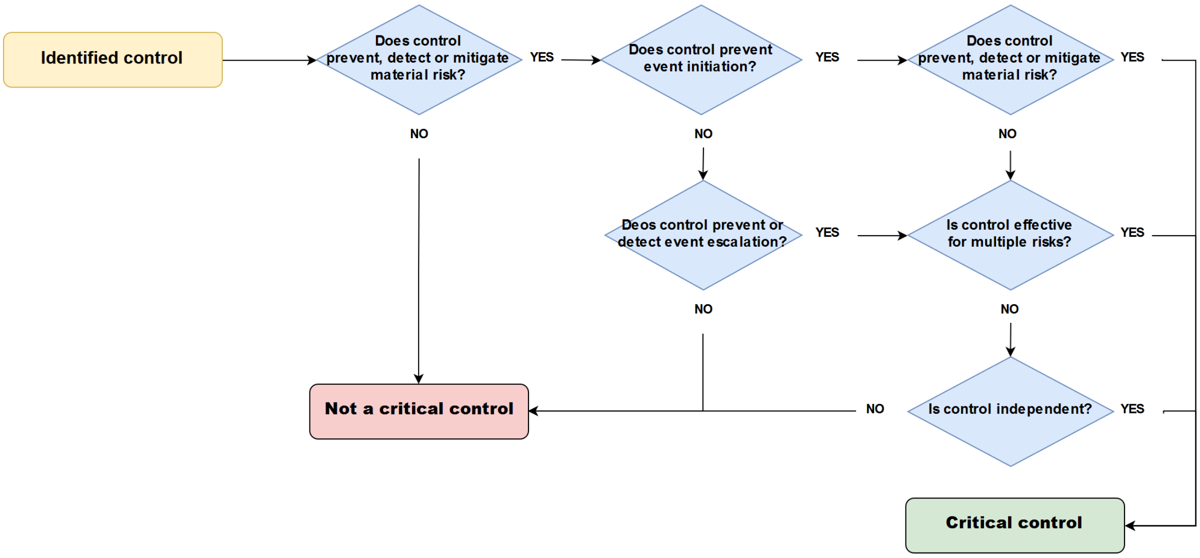


Figure 4.1: Decision tree for the identification of critical controls as specified by the ICMM (2015a).

Assessments of controls applied globally at AngloGold Ashanti identified multiple thousand controls already in place. After applying the flow-chart in Figure 4.1, AngloGold Ashanti identified 134 critical controls essential to risk management in occupational safety. When spread over the relevant hazards each MHS has 5-9 critical controls that are considered essential in mitigating the relevant MUE's, possibly resulting in fatalities.

Although the possible pathways, MUE's and critical controls were identified on a corporate level, the actual degree of implementation of critical controls company-wide was not known. Due to AngloGold Ashanti's international nature, operating in 3 continents with 4 operating languages, communication and standardization is made difficult. Making matters worse is that each mine can be completely different in nature, varying from surface operations to shallow and ultra-deep underground operations. Depending on the concerns of running day-to-day business, each operation is at a different stage in the implementation process of critical controls.

4.4. Performance Standards

In order to draw the different operations level in terms of critical control monitoring, AGA developed so-called Performance Standards (PS). These specify the nature of each critical control and the way in which verification and validation should be applied. As such they help operations understand the nature and operation of critical controls. By adhering to the PS set for the relevant critical controls on-site, an operation automatically achieves required company standard.

Although the Performance Standards themselves are merely a page in length, achieving the set company standard takes significant effort. The PS know six aspects that are relevant to the operations:

1. Functionality - Aim of the control
2. Availability - Competency required to use the control
3. Survivability - expected integrity of control after incident
4. Dependency - Requirements of other systems in order for control to function properly
5. Compatibility - Relationships to other systems when functioning
6. Validation - Steps with which to ensure performance of control

Because the corporate Performance Standards will apply to all operations in equal measure, integrating these standards into the design will ensure the long-term viability of Critical Control Management at AngloGold Ashanti. It should be noted that the Performance Standards are a broad, yet not exhaustive list of controls. This means they will not cover all of the critical controls on each site. It is therefore each site's accountability to add site-specific critical controls to manage the risk for MUE's relevant to their operation.

The corporate Performance Standards were rolled out during the course of the project. Its adaptation was therefore identified as a common goal for both the project and the AGA global safety team. By adopting Performance Standards on-site, avenues of approach could be created for integration of critical controls into normal business processes. One such Performance Standard can be viewed in Appendix A. Here, the entire Performance Standard document for a critical control on hazardous materials is detailed to give an impression of a Performance Standard and their level of detail.

4.5. Site selection

Successful trial of Critical Control Management depended both on the system being developed and the site in which it was trialled. Site selection was therefore based primarily on capability for adopting critical controls. AngloGold Ashanti's Western Australian gold mine Sunrise Dam had already been introducing critical controls in some shape or form over the last 5 years. This meant the knowledge and support for critical controls was already present on-site. The willingness of SDGM's safety department to implement critical controls was the deciding factor in picking this site as the platform for further stages of Critical Control Management implementation. Although there might be more pressing concerns regarding safety for AngloGold Ashanti worldwide, it was deemed more important to create a system that works. Once it is up and running, other operations can utilize the ready-made version to their advantage.

4.5.1. Sunrise Dam Gold Mine

Located about 50 kilometres south of Laverton in the Eastern Goldfields region in Western Australia, the mine Sunrise Dam is has been in operation continuously since 1997 and is wholly owned by AngloGold Ashanti. In its development stages it was considered to be world-class, being the largest gold deposit in the Laverton gold mining district in the Yilgarn Craton of Western Australia. Its location can be viewed in Figures 4.2 and 4.3, which show its location within the Yilgarn craton and Laverton gold district, respectively. Open pit operations were conducted from 1997 until 2013, while the current underground workings have been operated since 2003 (Hill et al., 2014). Currently operating at a depth of around 600 meters, Sunrise Dam is one of AngloGold Ashanti's shallow gold mines in comparison to its South African operations.

4.5.2. Location and Resources

The operation Sunrise Dam lies in the Eastern Goldfields province of Western Australia within the Laverton Greenstone Belt (LGB). This district has attracted significant attention over the last decade, as shown by the

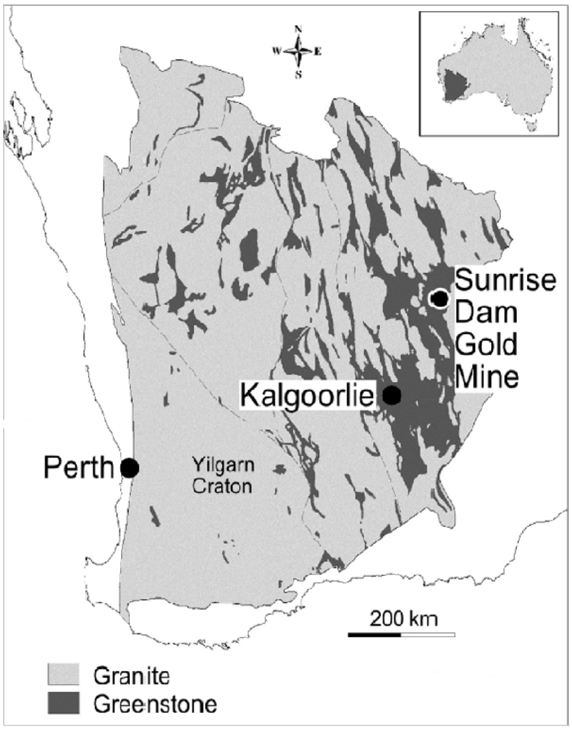


Figure 4.2: Sunrise Dam's location within the Yilgarn Craton, adapted from Hill et al. (2014)

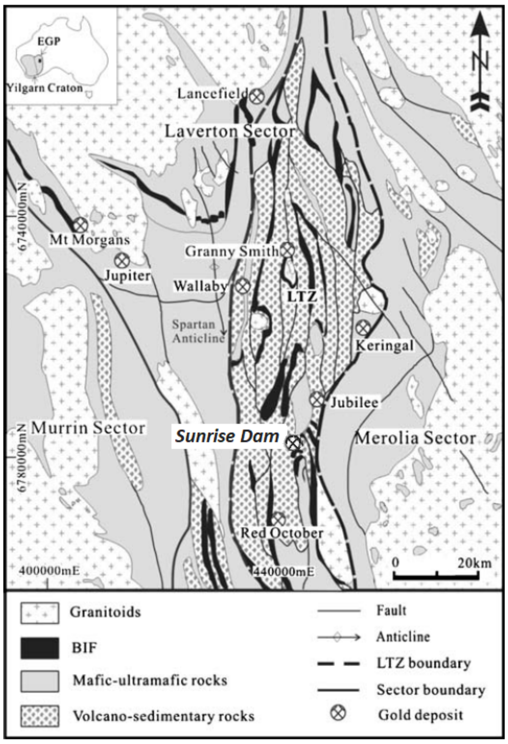


Figure 4.3: Close-up view of the Laverton gold district, adapted from Mair et al. (2000)

discovery of world-class deposits Sunrise Dam, Wallaby and several other minor gold deposits (Sung et al., 2009). Sunrise Dam is the largest deposit with some 6.59 Moz gold poured to-date. Addtionally, it still has resources and reserves totalling up to 4.5 Moz, with potential of up to 5.9 Moz with average grades around 2.04 ppm Au (AngloGold Ashanti, 2016). The operation has its own processing plant that produces a concentrate with gold as the sole product. In Figure 4.4, an satellite image of the general mining area can be viewed, with the processing plant marked in the middle-bottom of the image. In Figure 4.5, the marked section can be examined as a close-up of the processing plant with description of its various assets.

Figure 4.4: Satellite Image of Sunrise Dam mining area

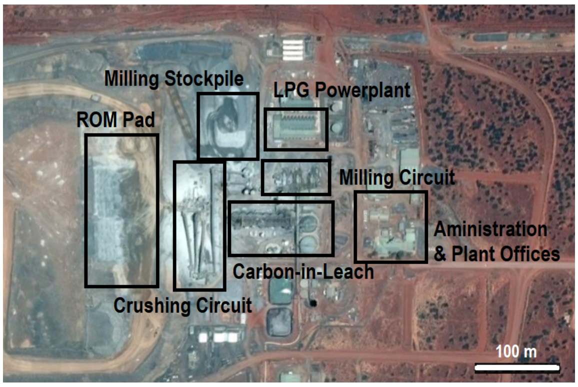


Figure 4.5: Close-up view Sunrise Dam Processing Plant

4.5.3. Ore body Geology

The orebody is hosted in a structurally complex Archaean greenstone belt, which has undergone metamorphism of lower-mid greenstone facies. The host sequence to Sunrise Dam has an upper layer of turbidite sedimentary rocks dominated by BIF and iron-rich shales (Hill et al., 2014). The intermediate sequence consists of metavolcanic and volcanoclastic rocks with mafic extrusive and intrusive rocks. The sedimentary rocks are intruded by doleritic dykes and sills as well as ultramafic rocks, while rhyodacite porphyry intrudes both the sedimentary as well as the volcanoclastic sequence. All ore lenses are centred on a series of parallel, NE-trending shear zones that dip at an angle of around 30°. These gentle dipping structures are characteristic of many of the orogenic gold orebodies in the Laverton Greenstone Belt (Sung et al., 2009), and these shear zones carry the majority of gold found in the deposit. grade variability is high even over short distances. A cross-section of the deposit can be viewed in Figure 4.6.

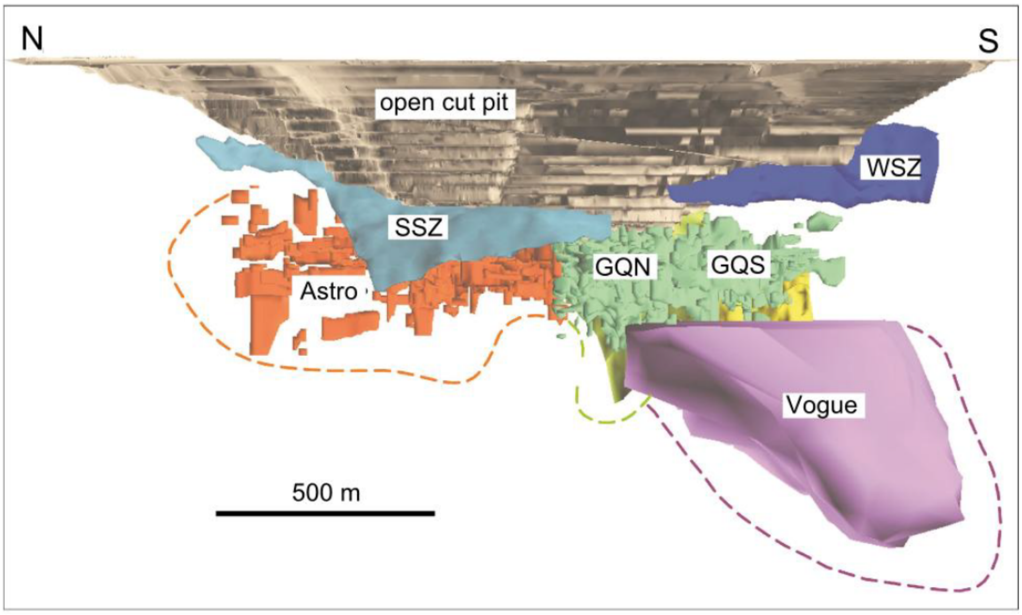


Figure 4.6: Cross-section of the Sunrise Dam ore deposit divided into its respective ore zones, as adapted from Hill et al. (2014).

The mineralization is hosted in arsenopyrite as "invisible gold", meaning nano-particles and/or lattice bound, in pyrite both as "invisible gold and in micrometer-sized inclusions of native gold, as electrum or Au(Ag)-tellurides (Sung et al., 2009). The ore lenses consisting of structurally complex vein systems have been formed over four distinct mineralizaton stages (D1 through D4), which were influenced by multiple events of fluid flow leading to repeated alteration and mineralization. Of these, Brown et al. (2002) estimate stages D3 and D4 to have occurred 2,670-2,650 MA. Pyrite is the main ore in all veins, while arsenopyrite is found mostly in structures formed during D4. Ore grades found in arsenopyrite average 562 ppm with a maximum of 5,662 ppm, while the average grade in arsenian pyrite is 1.6 ppm (Sung et al., 2009).

4.6. Organizational requirements

In order to align the piloting of critical control implementation to long-term company strategy, interviews with (senior) company officials were conducted in Johannesburg, South Africa and Perth, Australia as well as at SDGM itself. These interviews were conducted using the methodology specified in Section 3.1 and the functions and locations of these employees can be viewed in Appendix D. The success of occupational health & safety (OHS) strategy depends on the willingness of line managers to take a leadership role with regards to OHS risk and champion its implementation (Costella et al., 2009, Pillay, 2015). The safety department is there only to facilitate this process. The goals of these interviews were therefore twofold:

1. Assess possibilities for critical controls to be integrated into long-term systems strategy
2. Create a platform for active involvement and discussion amongst senior stakeholders

In twenty-six separate, one-on-one interviews the possibilities and limitations of critical controls were discussed with employees ranging from operator to company executive. Out of these discussions, the requirements throughout the organization were identified. These were subsequently amalgamated in five main goals, which will be discussed in the next five paragraphs. Together, these were used as the main requirements set forth by AngloGold Ashanti for the developement of the Critical Control Management System (CCMS). To these requirements is strictly adhered during design and implementation phases, thus successfully defining the key elements required for adaptation by stakeholders.

4.6.1. Keep it Simple, Stupid or "KISS"

First and foremost, all layers of the organization desire a simple, straightforward system. This goal for systems design aligns closely to the acronym “KISS”, short for Keep it Simple, Stupid. This principle has been attributed by some to Kelly Johnson, who was a lead engineer at Lockheed Martin Skunk Works, and others to a U.S Navy project in the 1960’s. Whatever its origin, this need for a simple system is corroborated by literature, stating the effectiveness of large, complex safety management systems is often diminished through sheer size (Costella et al., 2009). The necessity for a simple system that is introduced companywide at AGA is very real. When assessing the level of education of Basotho migrants moving from Lesotho to South Africa to work in mines, it was found none had completed primary education (Maphosa and Morojele, 2013). Another study by AMCA Inter-consult LTD (2012) for Terre Des Homme found that only 29% of migrants in Tanzanian mining districts had completed secondary education, while 2% said to have gone on to college. This principle also resonates with the Human Factors theory stated in Section 2.1, where systems prevent humans interacting with them from making decisions through their inherent complexity. In order for the system to work, it has to work for everyone. This can only be achieved through inherent simplicity, both in design and in use.

4.6.2. Weave critical controls into the cloth of the business

As was discussed in Paragraph 2.6.3, critical control management should be integral in the organization. Everyone ought to participate in its use and become aware of what it does on a day-to-day basis. Essentially, it should become second nature to all AGA employees. In order to make that happen, everyone should be introduced to critical controls. Such a process is not completed instantaneously. Rather, gradual yet persistent change is the preferred way forward. Build up knowledge, and expand.

4.6.3. Integrate broader sustainability approach

A second aspect identified during the interviews is the possibility for integration of other sustainability disciplines. While the safety department is currently the leading discipline for critical control thinking, the application of critical controls can be just as impactful for managing risks of the business with regards to the environment, security of operations or health of its employees. Especially when dealing with environmental issues, long-term complications derived from acid mine drainage or inadequate closure can lead to significant damage to environment, assets and reputation.

4.6.4. Observe cultural differences in implementation

As a third requirement, added to the necessity for possible integration is the abundance of different cultures on-site, be it in language, safety maturity or professionalism. The system should allow for local conditions to be a factor in the integration of site-level critical control applications. This includes creating understanding and making the implementation of critical controls manageable and suited to local circumstances. Without support from the organization and especially senior company officials, the outcomes of Critical Control Management will be less effective (Domingues et al., 2017).

4.6.5. Assure data integrity

Developing a system to monitor and assess critical control data could prove an exercise in futility if the data that goes in the system is not correct. Any data coming out of the system will then include systemic errors which will limit the value of the output. To assure this, steps should be taken in the data input phase to assure the validity of data. Because the data goes through multi-stage analyses within the BI environment, data acquisition and entry are identified as the process steps with the most significant potential for both systematic and random error.

4.6.6. Minimize impact on business

Monitoring critical controls is not the only process that is in place at SDGM to manage risks. Operators do risk assessments of hazardous jobs (JHA’s), have an assessment program to investigate hazards called SLAM and do a small assessment each time they do a new job called the Start Work in Control (SWIC) (AngloGold Ashanti, 2015). All these processes have an impact on the business through improving safety, yet costing time to complete. Relevant stakeholders within AGA senior management explicitly requested to forego development of new processes. This limited the scope solely to the modification of existing processes, something that delivered the intended result in the end.

5

Systems Design

In this chapter the design of the Critical Control Monitoring System (CCMS) and its subsystems will be discussed. Because not all subsystems are within scope of the project, the potential for future integration of these items will be discussed as well. The chapter is divided up into three parts. First, the overarching system and its requirements and functionalities are examined. Next, the subsystems relating to data acquistion are discussed and the way they need to be integrated as to cover all critical controls applicable. Last, the design of the BI environment is explored into which all of the data acquisition subsystems filter through.

5.1. Considerations

Integration of critical control management within AGA's business processes can not be achieved instantaneously. Instead, it will be a gradual process that depends on the capability and willingness of the organization at large to adopt it. Tracking the maturity of each of the sites and regions assists senior management in developing strategies for support. This maturity journey has been made into a model that gives an indication what the organization should be doing in order to make the next step to full critical control management. The model used was originally developed for sustainable operations integration by Machado et al. (2017) was applied. Although the methodology mainly focuses on manufacturing industry, the authors see the potential for use in other industries as well. The model is slightly adapted in Figure 5.1 to reflect the inclusion of safety into the domain of sustainable operation.

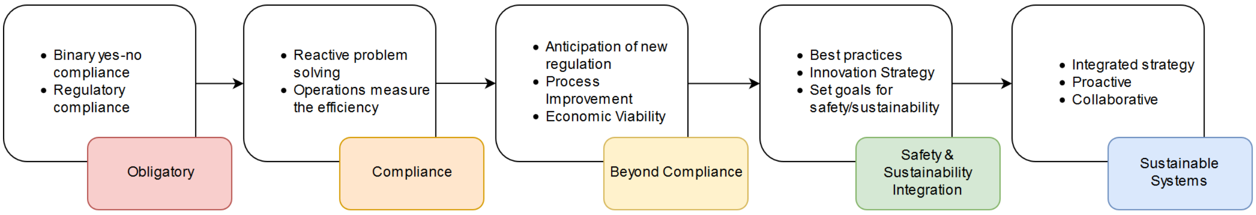


Figure 5.1: The maturity model developed by Machado et al. (2017) to identify steps necessary to achieving thte operation of sustainable systems

The first step in the maturity model has already been achieved at Sunrise Dam. This was accomplished through the application of an extensive safety management system tailored at transparency towards regulators. In order to assess how SDGM is performing in terms of safety or other sustainability disciplines, its compliance towards company goals should be measured. The CCMS will form the basis for the sustainable systems approach combining performance measurement, process improvement, best practices and integrated strategy for risk management on-site. Combining the implementation of CCMS in other sites with the model in Figure 5.1 will allow stakeholders to measure progress of implementation and simultaneously assess scalability of the system. Machado et al. (2017) identify several implications for the design of the CCMS based on the maturity model and sustainable operations management (SOM) capacity:

- Lean and green operations
- The need for a sustainable system
- Practical application of an information system

Integrating lean and green operations is quantifying metrics within the sustainability disciplines that function as key performance indicators for a company. Instead of measuring the statistics for incidents and injuries, the CCMS provides opportunity for moving towards pro-active measurement. This transition of lagging to lead indicators should be embraced by senior management in order to succeed within the company. In its design, the CCMS should therefore incorporate the capability for senior management to understand the issues their relevant sphere of influence is facing.

Safety is the leading discipline within AGA for implementing critical controls across the company. Other aspects within the broader context of sustainability follow closely behind. That means the CCMS should be open to implementation and integration of the other sustainability disciplines. This development is already foreshadowed by bow-tie modelling of environmental, health and security disciplines at the corporate level. In time, this data should be run through the CMS as well, generating a comprehensive overview of all sustainability critical controls.

The information generated within the CCMS should be available to the relevant stakeholders and therefore enable informed decision-making at any level of the organization. This requires functional knowledge of the user interface and the implications of data at every applied level in the organization. Not only that, the system itself should also be maintained by employees of AGA and that requires sufficient understanding of the back-end in order to maintain and update the system if necessary.

5.1.1. Data Features

In order to move forward with design of the overarching CCMS, the nature of data within the system needed to be assessed. The data that flows into the system will be generated out of every level within an operation. Unless every person working with critical controls works within the same system, flexibility should be guaranteed to accommodate a person's working environment. The Performance Standards set out by the global safety team are based on closed questions. This made data handling very straightforward as the binary nature leaves little room for interpretation. The data itself is not manipulated until the analytics stage, in which time-dependent analysis will be applied to ascertain trends in critical control performance. While the primary data is binary, some Performance Standards require extra evidence to be submitted in order to comply with validation of the controls. This data provides a quality assurance process before the data is entered into the wider BI environment.

Although critical control data is binary, other data sources consist of a different make-up. An example of this is data recorded for incidents on-site. These risk assessments, investigations and other data. Therefore, flexibility should be built into the BI environment in order to cater not just to additional bow-tie data, but also other related data. Potential sources of data for the BI environment can be incident related data, HR statistics, maintenance registers or production figures.

5.1.2. Information Flow

On top of general considerations and the nature of data, a closer look had to be taken at what exactly needs to go in and come out of the system. At the very base of data acquisition are the critical controls. Their performance has to be recorded at certain frequencies and entered into the system. After combining the data, analytics should be used to continuously monitor control performance. Based on those measurements, stakeholders ought to make decisions positively affecting their sphere of influence. Here, two different stages within the wider implementation context can be identified, which can be viewed in figure 5.2.

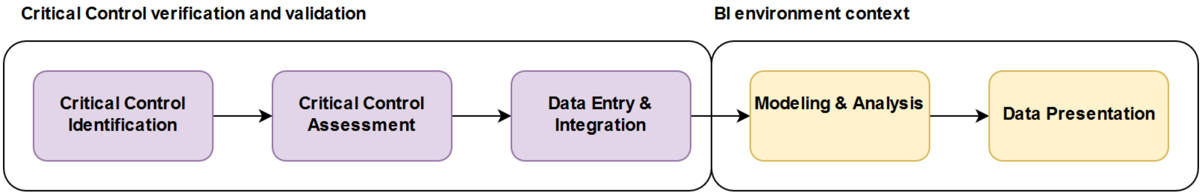


Figure 5.2: Overall flow of critical control data represented in process steps, as adapted from (Gandomi and Haider, 2015)

The process follows the same steps as are often used in big-data projects (Gandomi and Haider, 2015). By dividing the data flow into these two separate stages, several things are accomplished. First off, it allows flexibility with regards to data acquisition in the critical control stage. This flexibility is needed due to the heterogenetic nature of critical controls and their validation steps. Every level of the operation should participate in order to weave critical controls into the fabric of business. It is also one of the main steps within the requirement for mindful leadership set out to become an HRO as discussed in Paragraph 2.2.5. Now, the data input for the EMS generally follows the same data flow. Both systems enter the BI environment in the data integration phase.

5.1.3. Risk Application Landscape

At AngloGold Ashanti, bow-tie modelling software is only one of many systems present within risk management. It is central to the critical control approach, thus it is easy to see why such a system could help support CCMS. Not only does it categorize the Bow-tie models for all of its operations, the publisher of the software package in use at AngloGold Ashanti is also trialling a concept version for auditing critical controls as a data gathering process. The data obtained in those audits is then aggregated in a web environment where basic dashboard functionality can deliver insight into the performance of critical controls. Both of these applications are therefore considered key to the design of a CCMS at AngloGold Ashanti.

In this paragraph the goal of identifying other systems that could potentially support CCMS in the overarching risk management structure within AngloGold Ashanti is discussed. The landscape in which all of these applications function is characterized similarly to the structure of BI environments discussed in Section 3.3 in order explain their respective roles. The overall landscape is divided into applications that primarily gather data, aggregate it, serve a data warehouse function or facilitate reporting and can be viewed in Figure 5.3.

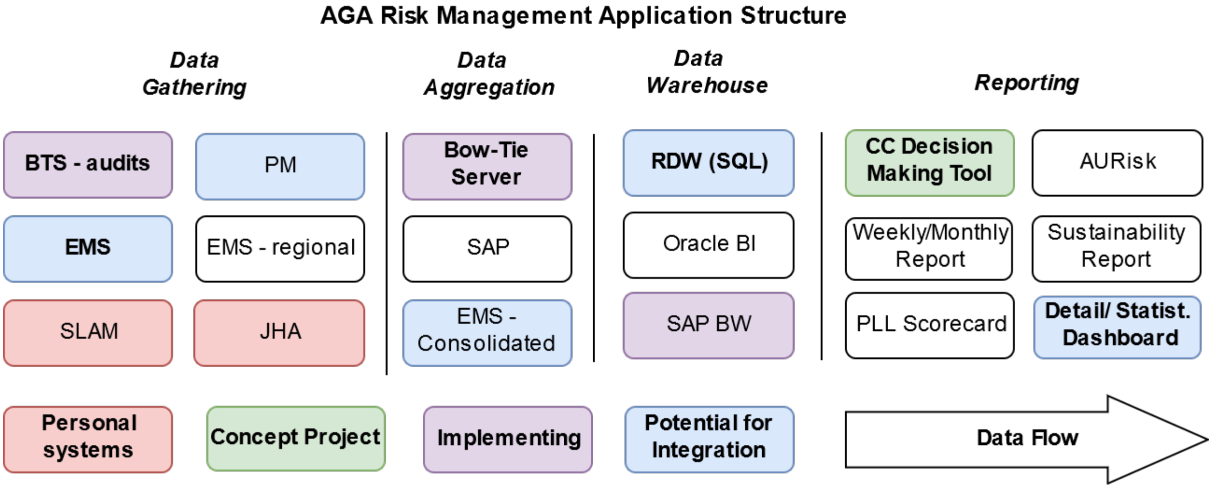


Figure 5.3: The landscape of relevant applications used at AGA in order to manage or categorize risk.

An overview of the application landscape in Figure 5.3 was developed during the course of this research and divides the flow of data into four sections. Through separation of the different applications by their nature, systems that had potential for integration into the CCMS were identified. One of the systems found during this analysis was the Event Management System (EMS), marked on the data gathering level. All incidents that happen on-site at SDGM, whether it be safety or otherwise, are recorded within the EMS. Significant and high-potential incidents are effectively a lagging indicator for critical control performance. Inclusion of incident statistics was therefore deemed to be a valuable tool for assessing whether the implementation and application of critical controls made a noticeable difference in safety performance. Although the potential for results is limited within the scope of research, inclusion should be trialled to explore possibilities for CCMS implementation at a larger operation.

The Regional Data Warehouse (RDW) for the Australian operations of AGA provides the opportunity to use ready-made BI infrastructure to host the BI environment necessary for the CCMS. Through the RDW, all potential critical control sub-systems within the Australian context can be integrated. This makes inclusion of the EMS within CCMS also more straightforward.

Within the risk management reporting structure, dashboards could be integrated through the RDW in order to give employees a bird's eye view of their day-to-day performance issues. By inclusion of critical controls into these dashboards, awareness is created throughout the company. Added benefit here is that reporting of figures on risk management, which is already required through corporate standards, can then be done in a familiar environment with little process interruption.

5.1.4. Systems That Are Out Of Scope

Other systems that could potentially be included in CCMS but are currently out of scope are Planned Maintenance (PM), EMS - Consolidated and SAP BW. Planned maintenance and SAP could potentially use the same companywide application. Additionally, BI capability is included to form a single application capable of performing data gathering, aggregation, BI and reporting in one go. However, the SAP infrastructure had not been implemented during the design phase of the project and was therefore removed from scope. How the system could potentially be integrated in PM will be discussed in Section 8.1 of Chapter 8, Discussion.

5.2. Critical Control Validation

Every person views a critical control differently. Their view is determined by their experience, job title, hierarchical status and/or education. That means no single view is necessarily perfect. Effort should be put forward to assess critical controls from different perspectives. By doing so, a comprehensive view of a control's performance is determined. The validation questions within the Performance Standards were set out with a similar approach. They were set up to cater to different layers within the company hierarchy, but were not designated as such. The following list of validation questions are applicable to the critical control of emergency stop button & trip switches related to equipment safeguarding:

1. Is a system in place to inspect, maintain and record all emergency stop and/or emergency trip switches/pull wires in use on site?
2. Is a system in place to ensure modifications and changes to work environment are assessed to verify additional requirements for emergency stop and/or emergency trip switches/pull wires?
3. Are operational tests routinely carried out on the emergency lanyards and stop switches with records maintained?
4. Are emergency stop and/or emergency trip switches/pull wires positioned conspicuously and within immediate reach of operators?
5. Are all operators familiarised with lanyard or stop switch activation and response to the activation alarm?

The Performance Standards apply these questions to the validation of a critical control. By themselves, the questions are quite comprehensive and have inherent expectations formulated in the yes or no answer. This way, criteria relating to the control all have to be met or otherwise result in a non-compliant entry. At the design phase of the project, neither the roll out nor the designation of relevant personnel for answering these questions had been conducted. That posed quite a challenge as the Performance Standards number around 540 verification questions in total. The dimension of frequency had also not been incorporated into the Performance Standards, so design of the critical control monitoring system had to include these aspects into the greater design.

5.2.1. Integration with company hierarchy

As stated in paragraph 4.6.2, one of the core requirements of this project is to integrate critical control monitoring and thinking throughout the entire company hierarchy, from operator to executive. Operators, supervisors, superintendents and managers all need to be aware and participate in maintaining critical control integrity. If they do so, significant incidents resulting in severe injuries or fatalities will be minimized. The nature of validation steps in the Performance Standards provides an opportunity to match questions to appropriate levels within the company hierarchy.

Because the validation questions were already in the final drafting stages, little could be done in terms of developing the questions themselves. Instead, questions could be matched to the relevant abstraction level in the organization. Going back to the different perspectives of personnel on-site, an operator is more likely to look at a single part, while a manager is more concerned with the running of entire processing plants. Mirroring the questions to relevant personnel was thus about finding that overlap where the nature of question matches the detail in an employee's daily work. In line with "KISS", three levels within active operation where defined:

1. Operators
2. Supervisors
3. Managers

That operators needed to be one of the categories, if not the main category, is without any doubt. Mindful leadership is about understanding what "front line" personnel experience, and it is these men and women that encounter the hazards on daily basis. Building their awareness is perhaps the most important goal with regards to implementation of critical controls. The need for inclusion of management has already been thoroughly discussed in Paragraph 2.2.5, but there is one extra category that was needed to cover the entirety of operations. Between operators and management sits an intermediate step. The employees in a supervisory role understand the tasks at hand, but also have knowledge of the processes that facilitate day-to-day work. While operating on a slightly less abstract level than a manager, these employees carry out an important role in being the conduit from management to operator, and back. This division of hierarchical levels corresponds with the reality gradient set out by Pillay (2015). This idea applies to mining safety systems and assesses the gradient from work imagined to work performed. The categories are explicitly kept on a fairly broad level. This will ensure they also work for other operations once the system is duplicated there. It is then up to an operation to classify who sits in a front-line, intermediate and managerial role.

5.2.2. Matching validation questions

Now the three main levels have been established, a methodology has to be applied to match the questions in the Performance Standards to the hierarchy categories. To do this the level of abstractness inherent to the questions was used. In order to manage operational safety effectively, a system is needed. Such a system is subsequently governed by processes that apply procedures to safety controls, alarms and interlocks (SCAI) (Hochleitner and Roche, 2017). This relates to the hierarchy within the company in that managers generally look at systems holistically, supervisors understand procedures and the overlying processes, while operators are mostly concerned with carrying out the task or procedure. The sought after levels of abstractness in the questions can thus be categorized as:

1. Procedure/Task
2. Process
3. System

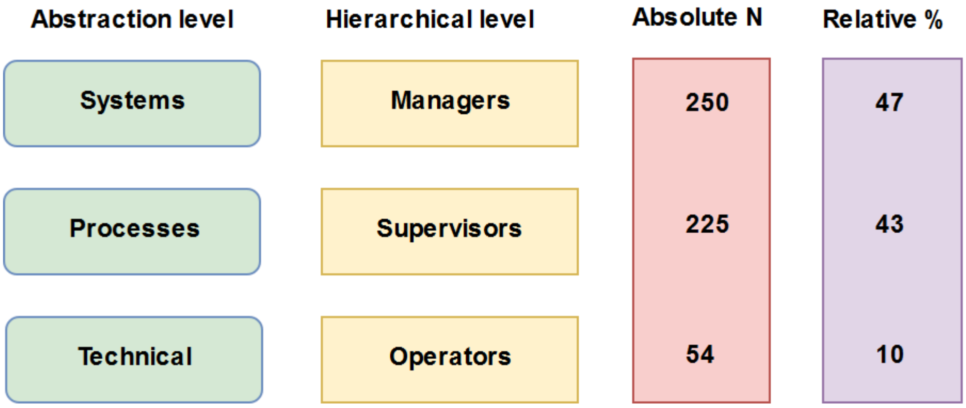
To understand how this methodology was subsequently applied to the validation questions in the Performance Standards, the example questions in Section 5.2 are assessed. These can be viewed with keywords determining the hierarchical level highlighted in the following list:

1. Is a **system** in place to inspect, maintain and record all emergency stop and/or emergency trip switches/pull wires in use on site?
2. Is a **system** in place to ensure modifications and changes to work environment are assessed to verify additional requirements for emergency stop and/or emergency trip switches/pull wires?
3. Are operational tests **routinely** carried out on the emergency lanyards and stop switches with records maintained?
4. Are emergency stop and/or emergency trip switches/pull wires **positioned conspicuously and within immediate reach of operators?**
5. Are **all operators** familiarised with lanyard or stop switch activation and response to the activation alarm?

The first two questions are matched relatively easily. Both discuss overarching systems that ensure emergency stops function on site, the first being a maintenance system and the second a Management-of-Change (MoC) system. The third question is less straightforward as it refers to "operational tests", perhaps implying that operators should answer this question. Yet the key aspect here is the word **routinely**, which indicates that this questions is about a process. That puts it firmly in the domain of supervisors. If one looks closely, question three is the same as the first, yet one level of abstraction lower. The fourth question is indeed an operator level question. It refers to a visual inspection that could and should be done by an operator. The last question is not about the task of familiarization, but the process to familiarize all operators. This means it is yet another supervisor level question.

5.2.3. Overview of Results

The methodology stated in Paragraph 5.2.2 was applied to all Performance Standard validation questions. Due to the use of different levels of abstraction, incorporating questions within the categories was achieved without exemptions. The resulted in a distribution as can be seen in figure 5.4.



Abstraction level	Hierarchical level	Absolute N	Relative %
Systems	Managers	250	47
Processes	Supervisors	225	43
Technical	Operators	54	10

Figure 5.4: Overview of levels with both absolute and relative number of Performance Standard validation questions

During the course of this research, the model in Figure 5.4 was created based on the division of hierarchies as noted by Pillay (2015). Immediately noticeable is the discrepancy between the amount of manager and supervisor questions on the one hand, and operator level ones on the other. A positive outcome of this distribution is the ample opportunity for inclusion of line management into the process. While 54 questions on the operator level might appear to be an insignificant number compared to the other categories, one dimension has not been taken into account as of yet: the frequency of assessments. This factor was still unknown at the design stage of the project. As discussed in Paragraph 2.1.1, a system will fail when the underlying processes stop working. By changing the frequency of assessments per level, over-prescription of safety audits can be prevented.

5.2.4. Missing dimension of validation questions

While operator level questions were designated through the use of procedures and tasks, a distinctive feature was found in the nature of these questions: they were more focused on the technical aspects of safety than on operator behaviour. Below some examples are listed that detail the nature of these questions:

- Are all permanent anchor points identified by clear markings for effective identification by persons required to work at height?
- Are all flow rate devices positively identified and flow direction indicated?
- Is a quarantine bin provided and used for unserviceable or untagged rigging equipment?
- Is the operator's console safely isolated from the remotely operated loader?

By failing to fully drill down to the behaviour of operators, critical controls are not completely integrated into the business. Therefore, another dimension needed to be added in order to make sure all layers of the organization are adequately made aware of critical controls. This last layer is that of operator behaviour.

In order to remedy this, 140 extra validation questions were specifically developed on that very level. That means the total amount of validation questions is around 670 and still subject to change. These additional validation steps were developed with the safety department of SDGM and focused on three things:

1. What control affects an operator personally?
2. How can we build awareness of these controls to the operator?
3. In what way can we integrate the assessments of these controls in daily work?

These extra validation steps are seen as the last step towards becoming a fully integrated, critical control managing company. While this is a step that every operation should take eventually, for now it is merely a way to go above and beyond what is expected at AngloGold Ashanti. The nature of these questions is quite different to those on the technical level. This can be seen in the following examples:

- Are you hydrated and have you eaten a meal prior to starting work?
- Have you verified the isolations in place with the isolations officer?
- Are you aware of the steps to take in case a PRV starts discharging into a working area?
- Is a licensed Dogger or Rigger present prior to commencing your lifting task?

The questions on the behavioural level are fairly straightforward. They action the operator to think about the controls possible, questioning if they are put in place and what steps to take if one fails. By answering these questions, operators are not impeded in their work while still building awareness. When taking the operator behaviour questions into account, another picture arises around the distribution of questions amongst the different levels. This can be viewed in Figure 5.5 where the model of Figure 5.4 was extended to reflect the addition of a behavioural component to the PS questions.

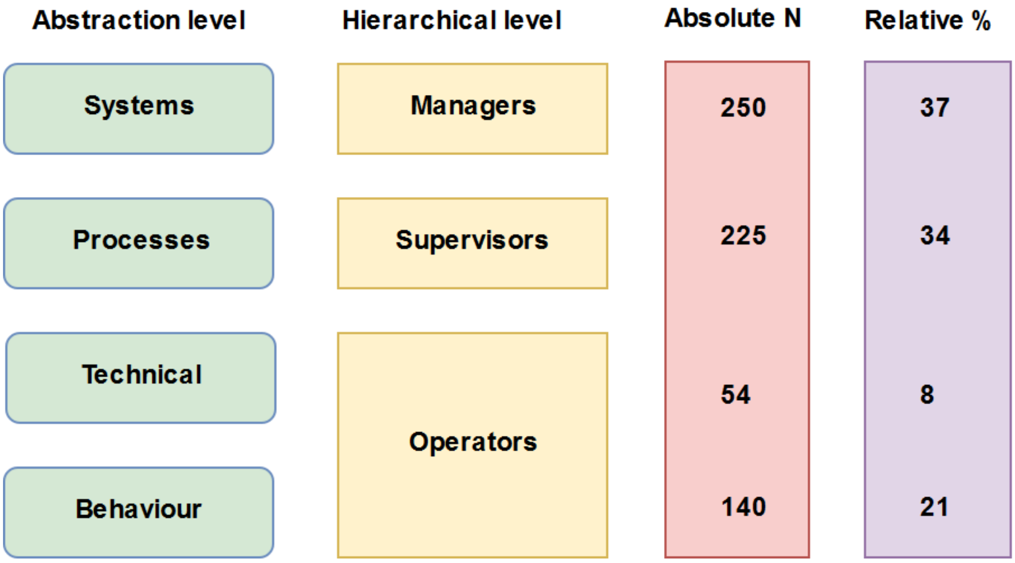


Figure 5.5: Distribution of Critical Control validation questions amongst the company hierarchy levels

The distribution of questions among company hierarchy is much more equal, with 37, 34 and 29% total for each of the hierarchy levels. This reflects the fact that everyone ought to participate in critical control monitoring. The inclusion of these questions into a business process was out-of-scope for the thesis project. However, the questions will be adapted at SDGM in a peer-to-peer process called Safety Observations in which the operators review each other during hazardous tasks. Not to blame or assign guilt, but merely to become aware of critical controls and identify possible behavioural errors. This reinforces the concept of a just culture as set out in Paragraph 2.2.3 as one of the tenets of an HRO. The roll out of that system will be conducted end of 2017, beginning of 2018.

5.3. Working Environment

One of the main issues with underground operations is the fact that wireless connectivity is seldom available, if possible at all. While tele-remote operations are applied when extracting ore from stopes, Wi-Fi connectivity is often left to be desired. While some mines might offer that kind of capacity, an integrated system that works for all of AGA's operations should be capable to work with off-line capability, if desired. This is essential for the operators that go into the most hazardous sections, which are often also the deepest levels, and conduct their work in a safe manner. While hierarchy in SDGM is relatively flat, this is also because of the small size of the operation. In some of AGA's South African operations more than 10,000 operators work in a single mine, meaning that supervisor and manager roles are conducted at least partially if not completely underground.

5.4. Summary of design implications

The division in questions into three employee levels is already indicating the fact that three separate processes are necessary to facilitate the evaluation of critical controls within an operation. What these look like will be discussed in the next chapter. It is clear that the processes will have to take the following aspects into account:

- Levels within company hierarchy
- Frequency of assessment
- Working environment and off-line capacity

As was discussed in Section 1.5 of the Introduction, addition of an operator-based process is the only level that is within scope for development during the project. However, potential integration with processes catering to supervisors and managers should be taken into account. This is where the data-flow model comes into play. Because the assessment of critical controls is separated from the BI environment, room is created for multiple assessment processes. In order to keep the system simple, only three levels of assessment were distinguished. Within the wider data application landscape, multiple systems have been identified that could potentially be integrated with CCMS in order streamline development. However only several of those are of interest to the immediate project, which are:

- Event Management System
- Regional Data Warehouse
- Detailed (Board) Dashboards

The inclusion of these systems into the CCMS enable assessment of incident registration as a lagging indicator though the Event Management System. BI capacity is enabled through the Regional Data Warehouse as it provides an online, SQL-based platform for storing arrays of data from a multitude of systems. The use of dashboards decreases the learning curve for end users and allows possible integration of multiple interfaces, i.e. together with maintenance data.

5.5. CCMS Architecture

In order to make sure all flows of data could be integrated, a systems infrastructure model was developed during this research based on the BI and OLAP framework set out by (Al-Aqrabi et al., 2015). The infrastructure model was made to include the initial data input process to capture the entire to-be engineered data infrastructure and can be viewed in figure 5.6.

The systems infrastructure adheres both to the organizational requirements set out in Paragraphs 4.6.1 and 4.6.6. It clearly shows the dependencies in terms of data flow. If a survey method is not developed, no critical control data can be presented within the bow-tie environment, ultimately leading to an empty dashboard. However, the method or process for data generation is independent of the overarching design. This means that whatever process is deemed suitable at an operation, it can still be adapted into the CCMS. This allows the system to be scalable to other operations and therefore gives an answer to the second research sub-question in terms of data input.

Creating a survey method thus has the highest priority when implementing the CCMS at SDGM. When that is accomplished, data should be drawn from the bow-tie environment into the regional data warehouse,

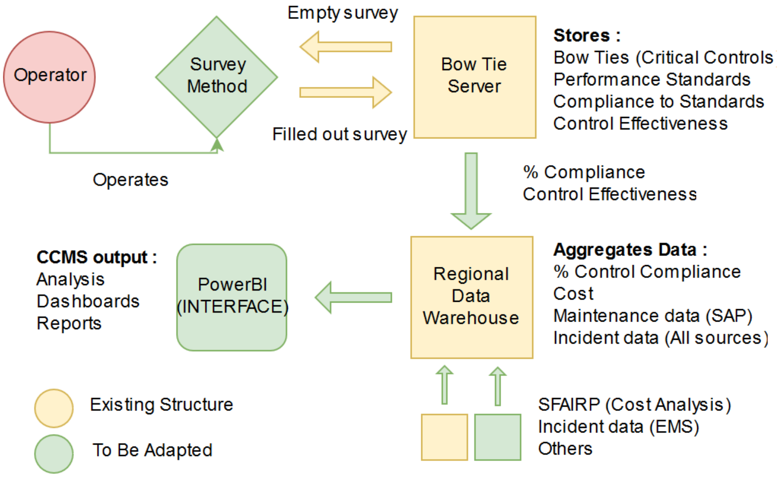


Figure 5.6: Systems infrastructure for the CCMS project at Sunrise Dam Gold Mine

where data integration with EMS and other sources is achieved. When a data flow to the Regional Data Warehouse is established, an interface can be created to truly enable critical control monitoring. The interface should then contain a back-end and a separate front-end. The back-end allows members of the global safety team to tailor the dashboard to relevant issues found in AGA operations. The front-end for employees should be tailored to the sphere of influence of the respective employee.

In the design shown in Figure 5.6, integration with the Event Management System has been included. This is not only a demonstration of technical capacity, it also allows monitoring of incident data starting from the implementation of CCMS at SDGM. Reflecting on the way in which AGA wants to go above and beyond of what is expected of a company, as discussed in Paragraph 4.1.7, this design accomplishes several things. It allows real-time auditing of non-conformities, systemic incident investigation and assessment of critical controls while being scalable to other operations. When implemented, it provides AngloGold Ashanti more control of their working environment.

5.6. Design remarks

The current data infrastructure was explicitly designed as a short to medium term solution with application in less automated environments. For an environment with a higher degree of automation in relation to the average IT infrastructure of AGA operations, a more advanced process could potentially remove intermediate steps for more efficient data flow. This optimization problem is discussed in further detail in Section 8.1 of Chapter 8, Discussion. There, the existing data infrastructure landscape at SDGM will be explored more thoroughly to come up with a more streamlined, long-term systems design.

6

Implementation

In this chapter, the implementation of the Critical Control Monitoring System is discussed. It examines all aspects necessary for taking the design developed in the previous chapter into the operational environment at Sunrise Dam Gold Mine (SDGM). First, the strategy applied to fulfil the required steps and build the system is discussed. Systems implementation is subsequently treated in the following sections. As the implementation carried out during the project was the first of its kind, lessons learned during this study are discussed last. These can then be applied to ensure a successful outcome at all other AngloGold Ashanti operations.

6.1. Strategy

Simultaneous with piloting the CCMS, Performance Standards were rolled out at SDGM. Because these specified exactly what needs to be assessed and reviewed on a control level, they provided a framework in which to set-up control monitoring. Adopting these questions however, meant that now around 540 new audit questions became part of the work that needs to be done on-site. Before any critical controls could be weaved into the fabric of the business, Performance Standards needed to be reviewed, accepted and adapted. Afterwards, operational processes could be assessed for integration. Once a suitable target was found, the rest of the implementation was carried out according to the methodology set out in Section 3.3. The implementation strategy formulated to develop critical control monitoring on site can be summarized in the following steps:

1. Adopt corporate Performance Standards on-site
2. Identify compatible business processes for critical control assessment
3. Adapt business process(es) to include critical control assessment
4. Integrate processes in Bow-tie software to reflect multi-level assessment of controls
5. Import and model critical control data in data warehouse
6. Code measures for control performance
7. Develop dashboards with data models for relevant stakeholders on-site

It should be noted that some steps taken ran partly simultaneously to accommodate availability of AGA employees during the various stages and time steps of the project.

6.2. Adoption of Performance Standards

In order to pilot critical controls monitoring on site, the first step in the process that needed to be taken was to integrate the corporate Performance Standards and their requirements on-site. Without those, no assessment metrics for the critical controls could be developed. Although the validation questions provided a good starting point for an assessment tool, nothing in the Performance Standards was stated about the frequency they have to be applied. As the validation questions number over 540 separate instances, there was a need to limit the impact of these questions on business processes. Should all be subjected to a daily assessement, more than 189,000 assessments ought to be carried out on-site on a yearly basis. To get an idea what might be a good number of assessments, the example of Rio Tinto (2017) can be taken. As a company it conducts 1.3 million assessment over more than 60 sites, thus averaging some 20,000 audits per site. Deciding how many might be necessary depends in large part on the characteristics of an operation. Being a small-size, shallow gold mining operation, a frequency ought to be designed that provides regular input yet is not over-prescriptive.

To achieve this, a frequency assessment was done based on the hierarchical levels of the questions. This hierarchy has already been extensively discussed in Paragraph 5.2.1. On the supervisor level, SDGM already carried out an own validation process with the help of so-called Critical Control (CC) Champions. These were designated out of their respective departments and championed a single Major Hazard Standard. Championing such an MHS meant doing quarterly audits similar to the Performance Standard validation questions. The CC champions were generally located within the hierarchical level of experienced supervisors to managers. However, it was found that managers would often delegate their championing tasks to superintendents. As such, the conduct of these assessment was carried out completely on the supervisor level.

The interval for the supervisor level critical control monitoring process was kept on the same level to reflect the system already in place. These assessments were trialled simultaneously to this research in the third quarter of 2017 as part of quarterly evaluations. Together with an implemented operator process, they formed the core of critical control data for this study. The quarterly evaluations are sent out as audit forms to the relevant stakeholders who are then accountable for their completion. In order to complete an audit a significant amount of evidence with regards to critical control functioning is required. The additional information is use to validate that the process audits use a more representative sample to measure their performance.

6.2.1. Frequency for manager level questions

Regulations in the United States specify that systems audits should not exceed an interval of 3 years (Satish and Crow, 2014). To comply with OHSAS 18001, which is the leading standard in Australia, annual audits are conducted by a third party. The standard itself however does not specify any figure for internal assessments done by a company. Other authors specify that each organization has to set its own auditing interval according to its own needs. In line with "KISS" and organizational goals specified in Paragraphs 4.6.2 and 4.6.6, frequency for manager assessments was set at yearly intervals. The following factors were used to decide on the annual frequency:

- Size of the operation
- Operational culture
- Site specific hazards

Weighing heavily on the frequency for annual audits is the fact that small sized mines like SDGM only have a narrow top layer of departmental managers. When the CCMS is duplicated to other mines, a re-evaluation of the frequency assessment will have to be carried out to match the operational environment of the mine. While there is a drive to push safety performance to excellence at SDGM, much of that momentum stems from the safety department itself. In order not to lose traction with regards to the implementation of new systems, cautious integration should be applied. SDGM is a shallow gold mine with good ground conditions and its safety track can already be considered better-than-average or even good for Australian standards. Therefore employees might feel that the auditing process becomes to constrictive when increasing the frequency to bi-annual or quarterly and thus lose faith in the overall approach.

6.2.2. Frequency of operator processes

Having stakeholders succesfully utilize the CCMS is one of the main goals of this project, reflected in sub-question 1 of the research questions. Operators on the shopfloor face high potential hazards on a daily basis, and they are therefore the main stakeholder with regards to the end product of the system. However, determining an appropriate frequency for operator processes was not as straightforward as those mentioned in the previous paragraphs. Control assessments have to be conducted during work on the operation itself, therefore downtime for auditing is limited. The Safety Observations process was designed to be minimally impactful itself. It only contains 8 to 14 closed questions per audit that relate to a single Major Hazard Standard. An audit using this process should not take longer than a quarter of an hour if no non-compliances are found. The goal of this process is to acquaint operators with critical controls through a peer-to-peer review process.

The over-saturation of safety assessments during work is the main concern in implementing a regular frequency to such a new process. Operators already have to fill out several processes during their work: the so-called SLAMS, SWIC's and JHA's. It is well understood that adding a process can lead to disgruntlement, if it detracts operators from doing their job while providing no clear benefit. The intended frequency of assessment as developed with the SDGM safety department is bi-monthly. Effectively however, that means operators are only exposed to the processes monthly as A and B crews alternate their work. Adding such a process was not in scope for this study as it goes against the requirements set by the organization, especially considering no new processes were allowed to be implemented on-site. The control monitoring process of Safety Observations goes above and beyond what is considered company standard. As such, it is carried out by SDGM on its own accord well after conclusion of this research.

6.2.3. Results of frequency assessment

Currently, three out of four layers have been discussed. Manager level questions are asked annually, supervisor questions per quarter, while operators are planned to have monthly safety observations. While the technical level have not been assessed yet, a balance can drawn up regarding the amount of audits done on a yearly scale. When all of the frequencies are matched to the amount of questions asked, 4,650 assessments are done at SDGM per year. Note that when the Safety Observations are subtracted from that figure, a mere 1,150 assessments are done. This is well below the average figure given for the operations of Rio Tinto (2017) and very much in line with Keeping It Simple, Stupid ("KISS"). By helping the operation understand the relatively low impact of assessments, a barrier was removed. What seemed daunting at first, now turned out to be a comprehensive system that on average only assesses a question every two months. As Safety Observations make up the bulk of assessments at about 3,500 audits, this just goes to show the commitment made at SDGM to achieve operational excellence. Without Safety Observations, the average frequency of assessments drops down to an assessment every five months.

However, the technical layer of the system has not been assessed yet. This will be done in the next Section, where it will become clear how much impact critical control integration can have. First, an analysis is conducted of the suitability of existing operator processes to determine which one is best suited to intergration of technical questions for critical controls. After modification of the related process, a final tally is made to demonstrate how CCMS manages to adhere to "KISS", assures data integrity and minimized impact on the business.

6.3. Control Integration in an Operator Process

The identification and implementation of a shop floor critical control monitoring process went through several iterative steps before integration was carried out. An initial study looked into employing an additional pre-start routine but this idea turned out not to be compatible with organizational requirements. Thus it came down to using processes at the operator level. To keep the scope of the project limited with regards to data acquisition, the goal here was to take a single process and modify to include critical controls. Operators at AngloGold Ashanti already have several procedures in place to assess safety, which makes targeting processes straightforward. These processes are:

- Start Work In Control (SWIC)
- Job Hazard Analysis (JHA)
- Stop and think, Look, Act and Manage (SLAM)
- Safety meetings
- Workplace Inspections (WPI)

Looking at the list above, one gets an understanding of the apprehension of adding yet another safety process. The first three processes are used on a daily basis, with the latter three being applied weekly or monthly, in the case of workplace inspections. Does one really need critical controls when so many processes have already been implemented? The answer to that question is yes. This project is about doing less while achieving more with regards to fatality prevention. The question then is, which of these processes can be best used as a data acquisition process for critical controls? In the next few paragraphs, a short description of each of the processes is given, as well with reasons for and against integration.

6.3.1. Start Work In Control (SWIC)

Whenever an operator changes his general working environment, he or she has to conduct a SWIC in order to make sure that all conditions for safe work are met. An example of such a switch in work conditions, is doing a spot check on a secondary crusher if a foreign element is detected. In such an example, a SWIC demands systems are isolated, supervisors are aware and that the right tools are selected for the job.

While the frequencies of SWIC's carried out is high, the changes in working environment do not specifically relate to high risk activities. As such it is difficult to assess what controls might be relevant in any change. Because operators are not familiarized with Major Hazard Standards or critical controls, it is unwise to rely on operator understanding. Essentially this process would have too much impact and too little direction. The upsides are significant awareness and adjustment to the relevant operating conditions.

However, there is no documentation process after a SWIC is completed. In order to gather data through SWIC's, operators would have to document the process, perhaps even multiple times per shift and afterwards deliver them for review. The potential of this process is purely in spreading awareness, much less in data acquisition around control performance.

6.3.2. Job Hazard Analysis (JHA)

Instead of only focusing on a change of scenery, Job Hazard Analyses are purposefully carried out to assess high risk activities. The assessment consists of documenting the hazards and controls required to carry out the work safely. When a routine activity is carried out, pre-made work instructions may be used instead of a JHA. The entire work team including the supervisor must review the JHA and sign off on it.

Contrary to SWIC's, a JHA explicitly details the controls needed for a job to be carried out safely. Additionally, there is a documented process that could be adapted for data acquisition. However, while a JHA specifies controls, nothing is done to assess their performance. Only if the controls were also checked beforehand could this process potentially help assess the effectiveness of critical controls.

The JHA does have potential for the identification of general hazards documented in the MHS. Whichever controls then relate to the MHS could then be made aware off during the JHA process. This potential has already been partially implemented through specification of critical controls in the JHA, if present. While the JHA is a pro-active process all review and sign off is beforehand, making the process have little potential for critical control monitoring.

6.3.3. Stop and Think, Look, Act and Manage (SLAM)

While JHA's focus on doing high-risk jobs within a controlled environment, the SLAM process focusses on mitigating high-risk situations when found on the shop floor. However, it is core an intrinsically reactive process. When looking back at the ALARP versus SFAIRP debate, such an approach is flawed in trying to implement, monitor and maintain controls. SLAM's do have purpose in providing operators the tools to get unexpected hazards back under control.

The benefits of the SLAM process are that it is tailored to the hazards found on site. As such data generated through the SLAM process can focus explicitly on control failures. The potential for SLAM's within critical control management thus lies with lagging indicators. When encountering a hazardous situation caused by failing critical controls, this should be documented though incident recording.

6.3.4. Safety Meetings

The second to last of the evaluated operator processes, a safety meeting is held for the underground crews every swing. As all underground operators worked on a 2 weeks on, 1 week off, they average about 4 safety meetings per quarter. Topics during the meetings focus on incidents and conditions on-site, as well as notable incidents within the province of Western Australia. If very impactful or similar to SDGM, incidents throughout the entirety of Australia could be made subject of the meeting. An example of such an incident was an operator who died of heat stroke while working in his jumbo alone. Although heat is not a problem at SDGM, it is common for workers to operate machinery alone in headings.

Like the SLAM, meetings tend to be on the reactive side of safety management. While specific controls may be discussed, no performance measurement is or can be done. The safety meetings do have potential for developing wide-spread awareness on critical controls or specific hazards.

6.3.5. Workplace Inspections

Throughout the entire mine, workplace inspections (WPI's) are carried out to assess general working conditions. The checks done are based off of a inspection sheet that leads an auditor through the relevant working area. Because the inspections can be quite extensive, research had already been carried in optimizing the path taken through the operation during auditing to reduce inspection time.

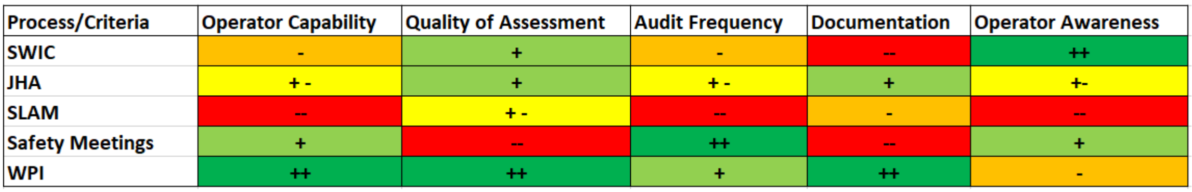
Workplace inspections are carried out by safety representatives who are elected by crews to represent them on HSE matters. They get time allocated to perform these inspections to fulfil regulatory requirements set out by the Western Australian Department of Minerals and Petroleum (1994). In effect this means that without inspections a mining site is not allowed to operate.

The safety representatives are briefed and consulted on all changes made to the site and get an accredited occupational health and safety course on top of their two year term. On the operator level, these employees guarantee the highest level of valid data when taking the site safety maturity into account. Only then can the validity of that on the operator level be guaranteed (Baybutt, 2014).

The inspection sheet itself contains closed questions and has to be uploaded to the EMS after sign-off and completion. This means a documentation process is already in place which could contain the status of critical controls checked throughout the mine. While potential for spreading awareness is lower than the other processes, it provides an excellent platform for checking control performance. Additionally, it is a pro-active process that checks all relevant, hazardous areas of the mine. As WPI's have a monthly frequency, it provides a steady stream of data that can be easily assessed on throughput and quality.

6.3.6. Selection

Out of all process identified, the monthly Workplace Inspections were considered to have the most potential for integration. It is pro-active, extensive, has a documented process and is a physical inspection of hazardous areas on-site. The deciding factor in choosing WPI's however was based on the competence of auditors involved in the process. On the operator level, safety representatives are the most skilled and competent personnel available for conducting a technical level audit of the controls. In Table 6.1, an assessment has been made about the most relevant decision factors relevant to selection of the process.



Process/Criteria	Operator Capability	Quality of Assessment	Audit Frequency	Documentation	Operator Awareness
SWIC	-	+	-	--	++
JHA	+ -	+	+ -	+	+-
SLAM	--	+ -	--	-	--
Safety Meetings	+	--	++	--	+
WPI	++	++	+	++	-

Table 6.1: Table lining out the decision variables and manner of scoring for each of the operator processes

Scoring within the table was determined through assessment of the descriptions listed above and the relative quality of the components for each of the processes. A double plus scores best, a double negative worst. The workplace inspections perform well on all criteria except general operator awareness. However this is more than compensated by the fact operator competency ranks highest, while each of the other criteria scores at least positive.

Based on this assessment, the workplace inspections were selected as highest scoring operator process for further adaptation of critical controls. In the next Section this process will be discussed extensively. What can be concluded from this selection procedure is the identification of criteria that have impact on the integration of critical controls into operator processes. This way the third research sub-question is answered not through the identification of one or more processes, but by development of a framework that helps an operation and its stakeholders decide for themselves what is most important in terms of critical control monitoring. This informs the decision for integration and thus generates both flexibility and scalability for the CCMS to other AngloGold Ashanti operations.

6.4. Modification of Workplace Inspections

While the workplace inspection process was deemed to have extensive potential for auditing, not all employees necessarily agreed on adding critical controls to the inspection sheets. A big concern here was that already extensive inspections might become too cumbersome. Should that occur, operators might apply a "tick and flick" process to filling out the inspection sheets, making the inspections effectively useless.

As doing less, achieving more through the utilization of a least-invasive system is one of the core goals during the project, a step of process optimization had to be applied. This approach centred on targeting existing questions for modification instead of just adding new ones. During this step it would also become clear that a significant portion of questions is duplicated in other processes, thus allowing for removal of questions not relevant to the inspection at hand.

6.4.1. Overview of the inspection process

Each month, 23 inspections are carried out across processing and maintenance areas, as well as any area related to the underground workings. Any above-ground workshop, in-pit limits or working area is also included. These inspections totalled 1909 closed questions on technical safety aspects on the mine. 18 out of 23 inspections are between 34 and 104 questions in length, with 2 being shorter and 3 longer. The latter category all exceeded 200 questions, which 212, 223 and 295 respectively. With such lengthy inspections, the apprehension of personnel to extend them is easily justified. The workplace inspections at SDGM were carried out according to a path moving the auditor along all relevant aspects of the mine site. The general areas assessed for the underground workings workshop can be seen in Figure 6.1

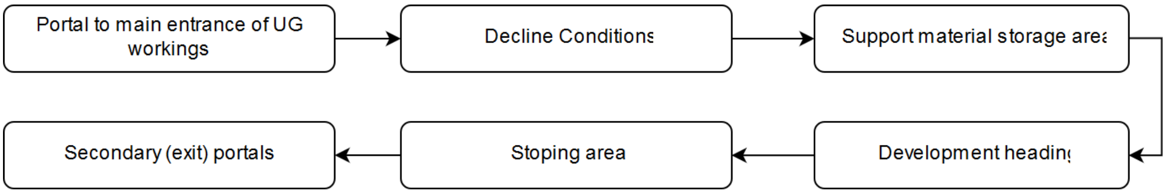


Figure 6.1: Flowchart for workplace inspection of underground workings SDGM

For each of these stages, a series of closed questions was asked to verify the state of the workplace. Because a significant amount of critical controls affect the workplace by themselves, the assessments could be made to include these to introduce control audits. The goal of the monthly inspection is not to repair defects when found, merely to note any faults or failures and send them through to the maintenance department.

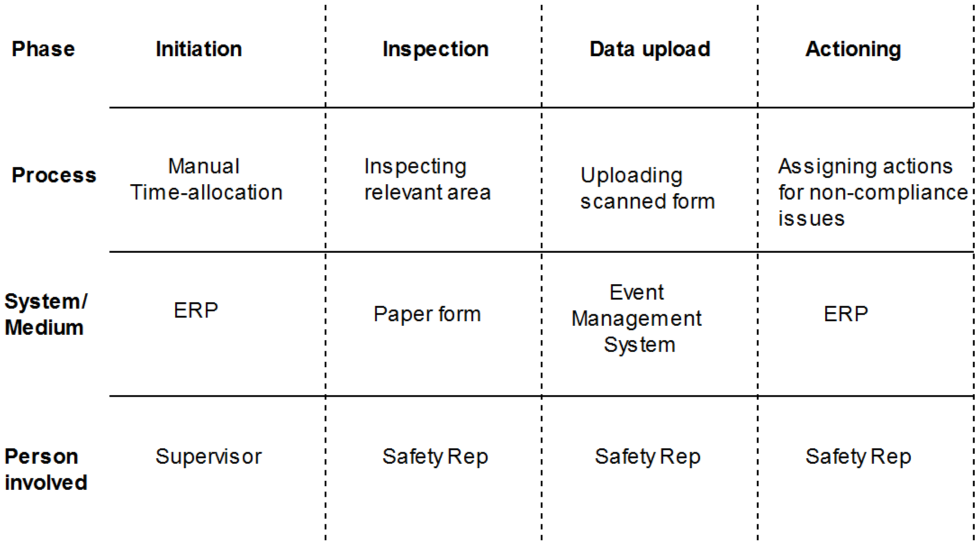
Although the goal is to do less, the inspection should remain complete. The reason the largest inspection is 295 questions is that it concerns the entire part of the plant involved in the multi-stage crushing of gold ore. In Figure 6.2, a picture can be seen of the crushing plant. This includes four separate crushers, seven conveyors belts and multiple take-up towers.

Figure 6.2: ROM pad with primary and secondary crushers and additional conveyor belts at SDGM.

The crushing circuit inspection is the most significant in terms of questions by a large margin. The underground workings inspection rivals its extent however. Not in the amount of questions, of which it has 72, but in time spent completing the inspection. The ore body at Sunrise Dam consists of several connected lenses which are accessed through six portals in the now unused open pit operation. Because of its high degree of dissemination and therefore also working areas, checking these environments takes a long time. Taking into account limited space and traffic, an inspection might take close to a full working day to complete.

6.4.2. Data acquisition for control monitoring

The closed questions used in the inspections made that applying critical control monitoring meant only modifying, adding or removing questions. This means that the nature of inspection forms remained unchanged. However, there was no way to extract the data efficiently from the process at that time. In order to understand how data acquisition was solved, the process behind the workplace inspections needs to be understood. In Figure 6.3, the steps behind assigning, doing and completing a workplace inspection can be viewed.



Phase	**Initiation**	**Inspection**	**Data upload**	**Actioning**
Process	Manual Time-allocation	Inspecting relevant area	Uploading scanned form	Assigning actions for non-compliance issues
System/ Medium	ERP	Paper form	Event Management System	ERP
Person involved	Supervisor	Safety Rep	Safety Rep	Safety Rep

Figure 6.3: Process steps with personnel and applications involved for workplace inspections

Although safety representatives (reps) get time allocated, this process is not automated but based on prevailing working conditions in the mine. It could be that their expertise is required elsewhere during non-routine tasks, and as such the time to do an inspection is fitted in between normal work. The allocation of that time is done by the operations coordinator or someone in a similar function. After time is allocated in the enterprise resource planning (ERP) system, the safety rep takes a paper form to the relevant working area and performs the audit. Next, the safety rep uploads the paper form as a scan to the event management system as proof the inspection has been conducted. Finally, based on non-compliances found during the inspection, actions are put into the ERP system for maintenance personnel to pick up.

6.4.2.1. Data Identification

In the workplace inspection process, two types of data are generated as output of the system. One is the scanned inspection form and the second type is the actions put out in the ERP system. Taking the systems design discussed in Chapter 5 into account, a link should be made to the bow-tie environment, so all critical control data generated is homogenous and can be pulled into the BI environment. Additionally, no other infrastructure was available to support bow-tie models and critical control data.

Unfortunately, neither form of data can be directly fed into the bow-tie environment. In order to process the scanned form, Optical Character Recognition (OCR) ought to be applied as an intermediary step. This technology is used in the South African operations of AGA, but was not viable as a solution for the CCMS project. Being the system that already stores the bow-tie models, the bow-tie environment was the foremost choice as a platform for data aqcuisition. However, input to the system is currently limited to audit forms detailing critical control questions. That means it is similarly not possible to route actions out of other systems into the bow-tie environment. Alternative routing the data streams will be discussed in Section 8.1 of Chapter 8, Discussion.

6.4.2.2. Data Extraction

So in what way can the inspection forms be put into the bow-tie environment? As discussed, audit forms can be distributed by e-mail to relevant employees for fill-out of critical control questions. In its most basic form, that would mean a safety rep would have to complete another process after uploading the form and putting out actions for maintenance. It is a solution that could work immediately, however it would include the addition of one more step to the inspection process.

Solving the data extraction problem this way has two important caveats however. For one, a safety rep that voluntarily looks out for the best interest of his co-workers has to complete another data acquisition step that does not generate attributable benefits for the individual in question. Squarely put, it means that after an 6-8 hour inspection, another process irrelevant to the operator has to be completed. That is a problem, as volunteering for such a role should not mean one is used as a data "mule".

The only result of transforming the role of safety representative into a data entry position is that those who volunteered will not continue, nor will their co-workers seek to get elected. The role of safety representative should be about looking out for your co-workers, with as little clutter around it as possible. That makes adding a process step after the inspection itself undesirable.

More of an overall business concern is the second caveat of this solution. In order to be able to receive audit forms, an employee has to have a purchased license. For a relatively small mine like SDGM that means 20 safety representatives require such a license, on top of all other processes using the auditing portion of the bow-tie environment. However for the scope of this project the focus will be solely on the licensing around the workplace inspection piece. A conservative estimate of required licenses for AGA globally would be around 500 licenses. At 2017 purchasing costs, solely the workplace inspection licensing would cost upwards of $100,000 dollars annually. For a process that is copying ready-made data into a question form delivered by mail, that is quite excessive.

6.4.2.3. Working Solution

The process itself however is not the issue. It scomes down solely to licensing and not having the safety representative bother with an extra data entry step. The scanned forms can be readily used to input the audit forms. These files are available on the EMS that can be accessed by safety personnel on-site. Instead of having all safety reps fill out an extra step, a member of the safety department can use the scanned files to import control data into the bow-tie environment using the audits. This solves two things: safety representatives no longer have to be concerned with an extra step, while secondly the licensing issue is reduced to one or two licences on-site. That reduces the process cost to a little over $7,000 dollar annually for all AGA operations.

This solution satisfies several other requirements and considerations set out in systems design. It maintains the capacity for offline work to be conducted underground or on-site. Secondly, it adds a data verification step in the input of this data in the bow-tie environment. Thirdly, through compounding the fill out of all workplace inspections in one go, the process can be optimized for speed and accuracy. Within scope of the project, the solution given was deemed the most cost-efficient, least impactful and most of all the simplest. That there may be a more efficient solution is not contested, rather their use and implementation requirements will be discussed in Section 8.1 of the Chapter 8, Discussion.

6.4.3. Critical Control Integration

Following from the previous paragraph, the forms on which to note the state of workplace inspections is the basis for further data processing. To implement critical control monitoring into workplace inspections, four process steps where defined that were repeated through several cycles:

1. Assess workplace inspections for the addition of potential critical controls
2. Integrate critical control validation questions in the monthly workplace inspections
3. Optimize workplace inspections for safety representative evaluation and subsequent data entry
4. Verification and validation of the monthly workplace inspections

As discussed in Paragraph 5.2.3, 54 Performance Standard questions on the technical level were identified. In principle, these should all be viable for physical inspection, as it involves personnel auditing the state of being of controls applied within the mine. Therefore, assessing workplace inspections for control integration will revolve in matching these 54 technical level questions to the inspections at hand. The questions span 40 out of 117 control applicable to SDGM and 100% of MHS present on-site. The questions themselves can be found in Appendix B, together with their parent controls and MHS listed in tables B.4 and B.5. Within the workplace inspections, three categories of questions are relevant to control integration:

- Questions that are the same as Performance Standard validation questions
- Questions that are similar to Performance Standard validation questions
- Questions that are irrelevant to control integration

The first two categories are relevant to the integration process itself. The last category might not be of use to critical controls, but it is an integral part of the workplace inspections. The first category is both the most applicable and the rarest. Out of 1909 questions, 20 were completely the same, and could thus be ear-marked for control integration. The more interesting category are those questions that are similar, but may differ in context or semantics from the use within the control standards. An example of a question similar to a critical control validation question is:

- Workplace inspection question : Are emergency stop and/or emergency trip switches/pull wires positioned conspicuously and within immediate reach of operators?
- Performance Standard validation question : Is the emergency stop button clearly marked and visible?

Like in the example, some workplace inspection questions are actually more specific than the related Performance Standard question. All monthly inspection questions similar to Performance Standard questions were categorized and in total, 252 questions were found that have a high degree of similarity to the PS validation questions. This result shows the potential for workplace inspections as a data acquisition process for critical controls: 272 out of 1909 or 14% is almost directly attributable to critical controls.

Next, the workplace inspection questions were related to their most applicable PS validation question. Out of that assessment, 48 out of 54 (89%) technical level Performance Standard Questions could be related. These 48 PS elements relate to 35 out of 40 (88%) critical controls on the technical level. If not applicable to the workplace inspection process there were three possible causes:

- The inspection task requires specific technological knowledge. An example of this is inspection of Pressure Relief and Blowdown Valves, which is covered by maintenance.
- The technical question involved a reactionary, non-standard hazardous task. The treatment of misfires concerns one such technical element.

The addition of maintenance into critical control management facilitates a perspective not necessarily attainable through monthly inspection routines. It adds a level of technical expertise to perform a more critical assessment of the integrity of physical assets. On-site, the maintenance department sets out a strategy to inspection, maintain and repair systems on site. Factors involved in setting up maintenance routines consist amongst others of OEM specifications, statutory requirements, FMECA analysis and operational conditions. Data on maintenance activities is routed through the PM system, of which the integration into CCM is currently out of scope. In a next step, integration of maintenance data could complete all unutilized Performance Standards questions to implement full critical control management. How this can be done is thoroughly discussed in Section 8.2 of Chapter 8, Discussion.

6.4.4. Addition of extra validation questions

Because Sunrise Dam has been in continuous operation since 1997, operators on-site have a thorough understanding of the capacities and limitations of the mine and its processing facilities. In lay-man's terms, that means personnel understand their working environment well, and are thus able to run the operation efficiently. For the workplace inspection process it means the relevant hazards are all categorized in some shape or form within the operation. However, not all hazards might be identified in any single place. Through cross-referencing the inspections and hazards encountered, additional questions could be marked for insertion through their similar nature of working environment.

This was done through a two-step process. First, potential questions to be integrated in all sections were assigned within the existing workplace inspections based on their relevance on-site. One such example was the existence of emergency stop button questions that were denoted within the grinding circuit inspection, yet not in the one applied to the crusher circuit. Questions relating to emergency stop buttons are relevant to both inspections, as both share the same type of conveyor belts. When checking on conveyor belts in the crusher circuit, emergency stop buttons were added for potential integration.

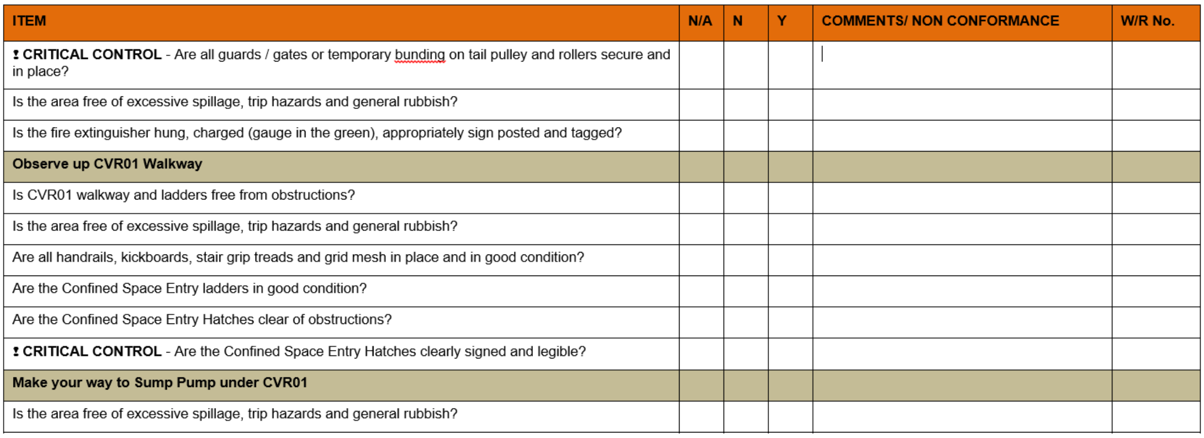
This process was conducted for all inspections, making two separate passes to take knowledge gained through all inspections once more. This was only the first step in the process of adding questions however. The second question consisted of doing all inspections in person with a safety representative to validate the addition of new critical control questions. This same process was used to verify and validate the removal of non-essential questions discussed in Paragraph 6.4.6.

The final result of this process was the addition of 61 critical control questions to the inspections. Combined with those previously found, this generates 316 critical control questions within the workplace inspections. As these are assessed on a monthly basis throughout the year, this amounts to 3,792 data points collected yearly. These questions can be found in Appendix B, within the mapping tool applied to identify the elements across the inspections in Tables B.1, B.2 and B.3.

6.4.5. Design of Inspection Forms

The second step in which errors around critical controls can be generated is after the actual inspections are conducted. When safety personnel transcribe the critical control data into the bow-tie environment, errors can be made when data is misinpreted. While the questions are answered either yes or no, the variety in critical control questions and hazards could potentially cause errors of judgement.

Adding the critical controls to the inspections should therefore include an easy data verification step for both personnel conducting transcription and possibly auditors. In order to conduct a least-invasive approach to changing inspections, the overall format was left in tact. An example of the layout of the inspections can be seen in Figure 6.4



ITEM	N/A	N	Y	COMMENTS/ NON CONFORMANCE	W/R No.
⧗ **CRITICAL CONTROL** - Are all guards / gates or temporary bunding on tail pulley and rollers secure and in place?					
Is the area free of excessive spillage, trip hazards and general rubbish?					
Is the fire extinguisher hung, charged (gauge in the green), appropriately sign posted and tagged?					
Observe up CVR01 Walkway					
Is CVR01 walkway and ladders free from obstructions?					
Is the area free of excessive spillage, trip hazards and general rubbish?					
Are all handrails, kickboards, stair grip treads and grid mesh in place and in good condition?					
Are the Confined Space Entry ladders in good condition?					
Are the Confined Space Entry Hatches clear of obstructions?					
⧗ **CRITICAL CONTROL** - Are the Confined Space Entry Hatches clearly signed and legible?					
Make your way to Sump Pump under CVR01					
Is the area free of excessive spillage, trip hazards and general rubbish?					

Figure 6.4: Example layout of the crusher circuit workplace inspection form

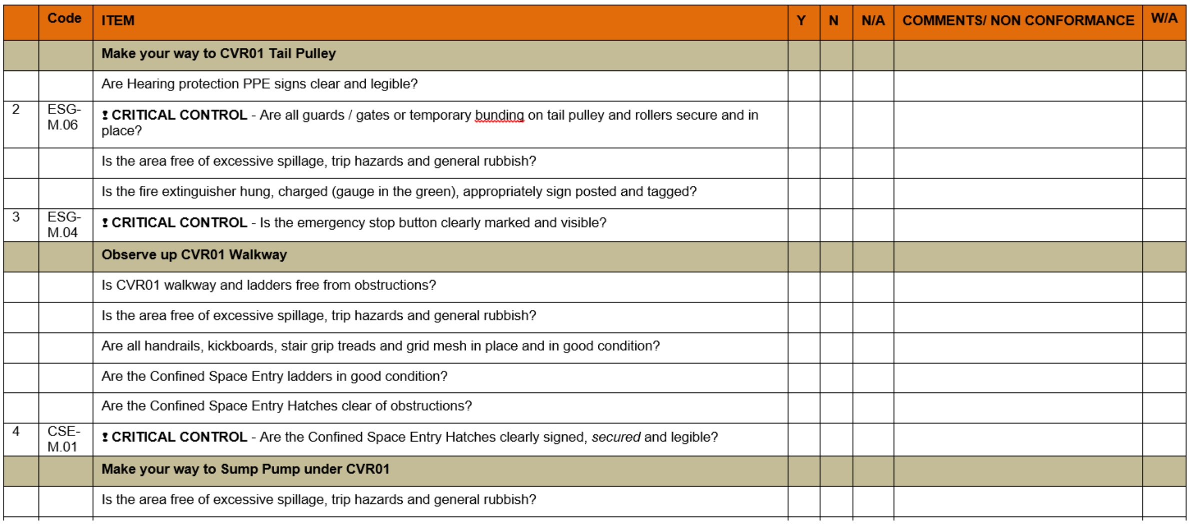
Several aspects of the inspection are clearly visible in the example shown in Figure 6.4. Entities that had already been identified as a critical control on-site are marked with an hourglass figure together with a bold marking of "critical control". The first question marked as such in the example does correspond with one in the Performance Standards set out by the global safety team, namely "Guarding of moving equipment" within the Major Hazard Standard "Equipment Safeguarding". The second such entity corresponds with the critica control "Confined Space Register" within the Major Hazard Standard "Confined Space Entry".

In the last column, "W/R" is specified. This denotes the work request set out to fix the deficiency. Because the work request itself is done through EMS, tracking of these requests can be drawn into the BI environment as well. Another aspect that is clearly visible is the sequential nature of the workplace inspection form. Before each section, the general programme of the inspection is specified. In the example, this is through two separate instances:

- "Observe up CVR01 Walkway"
- "Make your way to Sump Pump under CVR01"

These questions refer to Conveyor Belt 01 within the crusher circuit, specifying both the walkway next to the conveyor belt and a separate sump pump located under it. Both instances require no answer as they are merely pathfinding specifications that help the observer find his or her way. While two critical controls had already been marked for their nature, they do not correspond with the global Performance Standards at this stage. As such, the questions were aligned to the relevant critical control entities listed in Appendix B in Tables B.4 and B.5.

After aligning the questions to global Performance Standard entities, they were given a code to identify them within the bow-tie environment. Additionally, the critical control questions within the inspections were numbered. This was done to support data entry personnel in correctly transcribing the data, should multiple of the same critical control questions follow each other in sequence. The resulting changes can be seen in Figure 6.5.



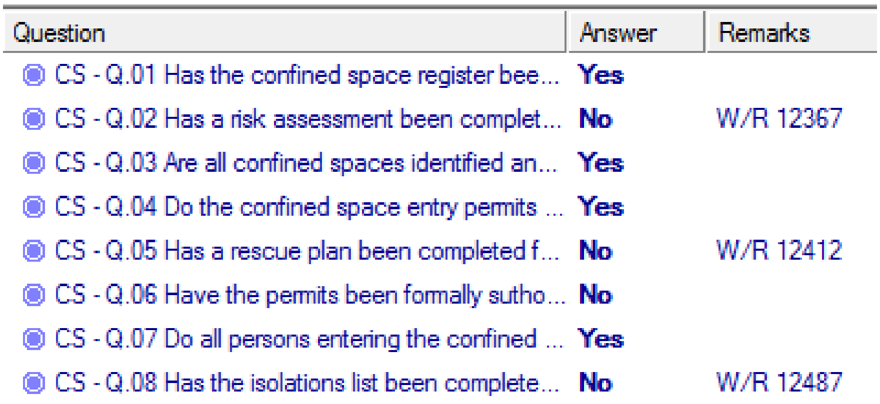
	Code	ITEM	Y	N	N/A	COMMENTS/ NON CONFORMANCE	W/A
		Make your way to CVR01 Tail Pulley					
		Are Hearing protection PPE signs clear and legible?					
2	ESG-M.06	! **CRITICAL CONTROL** - Are all guards / gates or temporary bunding on tail pulley and rollers secure and in place?					
		Is the area free of excessive spillage, trip hazards and general rubbish?					
		Is the fire extinguisher hung, charged (gauge in the green), appropriately sign posted and tagged?					
3	ESG-M.04	! **CRITICAL CONTROL** - Is the emergency stop button clearly marked and visible?					
		Observe up CVR01 Walkway					
		Is CVR01 walkway and ladders free from obstructions?					
		Is the area free of excessive spillage, trip hazards and general rubbish?					
		Are all handrails, kickboards, stair grip treads and grid mesh in place and in good condition?					
		Are the Confined Space Entry ladders in good condition?					
		Are the Confined Space Entry Hatches clear of obstructions?					
4	CSE-M.01	! **CRITICAL CONTROL** - Are the Confined Space Entry Hatches clearly signed, *secured* and legible?					
		Make your way to Sump Pump under CVR01					
		Is the area free of excessive spillage, trip hazards and general rubbish?					

Figure 6.5: Example of final design change of the workplace inspections

Several changes are visible in the example of final workplace inspection design. The critical control questions are numbered sequentially in the first column. Another change is the addition of a second column before the actual question that specifies with which entity it should be matched within the Bow-tie environment.

Thirdly, a new critical control question is added (no.3 going by the first column), that determines the status of the emergency stop button along the conveyor belt. The coding supports understanding of this entry through clarification of MHS in the first three letters, frequency in the second, and lastly which question specifically should be filled in. When examining the code applied to critical control question 2, it specifies (E)quipment (S)afe(G)uarding-(M)onthly.Question(06).

That does not mean that data entry personnel have to look up the questions. Instead, they are lined up straight below eachother, specifying both sequential number and code. The only task left then is to match each corresponding question. One such audit can be seen in Figure 6.6.



Question	Answer	Remarks
CS - Q.01 Has the confined space register bee...	Yes	
CS - Q.02 Has a risk assessment been complet...	No	W/R 12367
CS - Q.03 Are all confined spaces identified an...	Yes	
CS - Q.04 Do the confined space entry permits ...	Yes	
CS - Q.05 Has a rescue plan been completed f...	No	W/R 12412
CS - Q.06 Have the permits been formally sutho...	No	
CS - Q.07 Do all persons entering the confined ...	Yes	
CS - Q.08 Has the isolations list been complete...	No	W/R 12487

Figure 6.6: Example audit within the Bow-tie environment

The example audit in Figure 6.6 does not match the questions in Figures 6.4 and 6.5. However, the sequential nature of the questions is clearly visible with no questions irrelevant to critical controls clouding the data. Additionally, actions put out in the EMS can be added as remarked in the workplace inspections. Due to limited access to the audit environment of the bow-tie environment, an older example had to be used in which the sequential numbering before the questions had not yet been added and the MHS were still only coded by two letters. In the example in Figure 6.6, the questions refer to (C)onfined (S)pace-(Q)uarterly questions. Because those asked in the quarterly audits are only asked once per audit, the sequential coding of questions is already embedded.

Because the actions taken to remedy control non-compliances have a number that is noted in the inspection, the action can be tracked in relationship to the issue found. This enables a new avenue of approach into performance monitoring, as it also gains the capability to show how long it takes to close out a maintenance request. Based on the average close-out time, new priorities can be set if necessary.

6.4.6. Process Optimization

The process found at SDGM had been through multiple iterations, increasing its complexity beyond what was strictly necessary. During these iterations, questions were merely added without considering their duplicate use elsewhere. Because the process in its original form was considered somewhat cumbersome, a platform for changing the workplace inspections with employees was created through asserting the goal of achieving more, while doing less.

In line with “Lean and Green” operations as set out in Section 5.1 of Systems Design, the process was then optimized to make the workplace inspections as effective as possible. At the beginning of the project, the workplace inspections were found to be the product of years of small, incremental additions with little consideration for the overall usefulness of the process. This resulted in a bloated, cumbersome process. In order to fulfil objectives as set out by the requirements from AGA, the assessment of the process was used as a complete re-evaluation of the monthly workplace inspection process.

The re-evaluation was done with the intent of the safety representatives in mind. The questions in the workplace inspections were assessed according to the questions:

- Does this question add value to the level of occupational safety at Sunrise Dam?
- Is the question specific in its requirements for satisfactory answers?
- Is the question relevant for the current state of the inspections?

If any of these above requirements was answered unsatisfactory, the question was assessed for potential modification to fit the requirements set out above. If this was not feasible, the question was slated from the inspection. Questions related to hygiene in and around workplace areas were assessed not to be the task of safety representatives as these are already carried out by the business services contractor on site. Questions that did not satisfy the second requirement were for instance:

- Is the safety signage in place?
- Is the area well ventilated?

The first question does not make an accurate assessment, as a single instance of safety signage is enough to mark answer the question yes or sufficient. The second question requires the auditor to be completely knowledgeable on the ventilation requirements in different sections of the mine. Both types of questions were modified to include the specific demands of their respective locations in the mine.

Some examples of questions that did not meet the third requirement were all questions related to a battery charging station no longer in place. An entire inspection for a paste plant was withdrawn as the paste plant in question was no longer in use. The inspection was being done until that time, however. The result being an inspection filled out with all questions NA. Another entire inspection was removed as well as designating two entire inspections for full re-evaluation. Other questions withdrawn through the third requirement related to the assessment of operators in the workplace themselves.

After addition of the critical control questions and completing the re-evaluation of the workplace inspections on site, the new workplace inspections were validated with operators working in the various sections of the mine site through manual assessment. Through the validation process, small changes were made to the inspections to reflect the actual state of the mine. After completion of the verification and validation steps, the dataflow from finished inspections had to be drawn into an automated system for further analysis.

6.4.7. Resulting changes for process

After addition of the critical control questions and completing the re-evaluation of the workplace inspections on site, the new workplace inspections were validated with operators working in the various sections of the mine site through manual assessment. Through the validation process, small changes were made to the inspections to reflect the actual state of the mine. After completion of the verification and validation steps, the dataflow from finished inspections had to be drawn into an automated system for further analysis. The re-evaluation of the workplace inspections and integration led to:

- The removal of two entire workplace inspections
- Overall reduction in workload of 18% or net change of -341 questions
- Addition or modification of 316 critical control questions (21% of total remaining questions)

Because the net change of questions is negative, widespread support was generated for the integration of critical controls into the process. When assessing the 316 critical control questions in the workplace inspections, their potential for further quantitative analysis was assessed based on the spread of critical controls assessed across the mine site. The critical control questions in workplace inspections cover:

- 35 out of 117 or 30% of critical controls relevant to mine site
- These critical controls cover all MHS relevant to the mine site
- 37% questions relate to engineering controls, the rest (63%) being administrative controls.

Especially the last observation generated interest among senior AngloGold Ashanti officials, as the fraction of engineering controls is higher than was first assumed. In fact, it shows that the percentage of engineering controls is 2.5 higher than looking at the absolute number of different critical controls. For other operations and companies implementing critical controls, it means that the relative abundance and vulnerability of administrative controls only becomes an issue if the balance is not adequately redressed through a higher frequency of similar engineering controls. Additionally, the workplace inspection process now adds 3,792 data points on a yearly basis. This is more than three times the amount of 1,150 assessments that was estimated in Paragraph 6.2.3, thus given a much more comprehensive view of controls in place on the shopfloor.

6.5. Integration into bow-tie environment

While the workplace inspection feature an intermediate step with regards to data entry, both the supervisor and manager level questions can directly be utilized through the auditing part of the software. Once these processes are started, adaptation into the bow-tie environment is immediately possible and practical.

With the workplace inspection process however, adaptation into the bow-tie environment was more difficult. Although the environment allows audit forms to be sent out to any given user, any question is only allowed to be asked once in the form. This becomes a problem when controls questions have to be asked multiple times per inspection. Going back to the example with the crusher installation in figure 6.2, the same question has to be asked multiple regarding guarding of conveyor belts.

This issue could possibly be resolved by making separate questions for each of the control verification steps in the bow-tie environment. As SDGM already has 316 verifications, that would lead to thousands of different questions amongst all AngloGold Ashanti operations. To administrate such an amount of detail would be a job onto itself. Keeping in line with "KISS", using the same question multiple times allows reduction of 316 verifications into 48 Performance Standard elements. This in turn allowed for much more straightforward performance review against company standard.

For the company that distributes the software package, identifying this specific gap was seen as very valuable. Unfortunately they were willing nor able to adapt their audit forms to allow multiple inclusion of the same question within scope of the research. It is set on their internal timeline as a deliverable, yet no target could be given as to when this could be resolved.

The fact that data acquisition in the workplace inspection process is disconnected from the necessity for direct feedback into the system, allows storage of that data until the integration issue can be resolved. The identified process of Safety Observations could be implemented similarly to the quarterly and yearly audits, therefore not running into similar issues as the workplace inspection piece. As the quarterly audits were being implemented into the bow-tie environment simultaneously, that process could be utilized as feed to further tailor the BI environment to AngloGold Ashanti requirements. Any data generated during modelling and dashboard creation will thus primarily contain quarterly audit data.

6.6. Data Import and Modelling

During critical control integration of workplace inspections, importing data into the regional data warehouse was implemented through collaboration with the AGA Australia BI team. In order to do so, the servers on which the bow-tie environment is hosted were identified. After analysis it was found that data stored in the bow-tie environment was based on SQL, a Microsoft Database language which is also applied in the Data Warehouse. Importing critical control data therefore only required a request to be put out with the required level of access for the bow-tie environment.

After the data had been put into the data warehouse, the different matrices that were imported had to be related in order to make sense of the core concepts of a bow-tie model. Before that could successfully be done, a Unified Modelling Language (UML) model was made to better understand the nature and relationships and data within a generic bow-tie model. The reason for creating of such a model was that the system needs to be sustainable for further amendments, if necessary. Ensuring the system is easily understandable is a critical element of the life cycle cost of the system, as software maintenance consumes about 40-80% of the total software development cost (Fernández-Sáez et al, 2016). Of that cost, about 50% is spent on comprehension of the software (Bashir et al, 2016).

Model-driven Software Engineering has been demonstrated to improve efficiency and effectiveness in various studies (Brambel et al, 2012), with UML being one of the most applied methods in object-based modelling (Bashir et al, 2016). A UML class diagram denotes the cardinality between the different objects in the data. These UML associations are called object relationships, and can take on various forms. In the UML model created for understanding of the underlying data, only one relationship is used : one to many, denoted as 1 to 1 .. n or 1 to 1 .. n. An example of this relationship is one hazard being related to a variety of causes. Similarly to the bow-tie model itself, the hazard or top event is central to the UML model, which can be viewed in Figure 6.7.

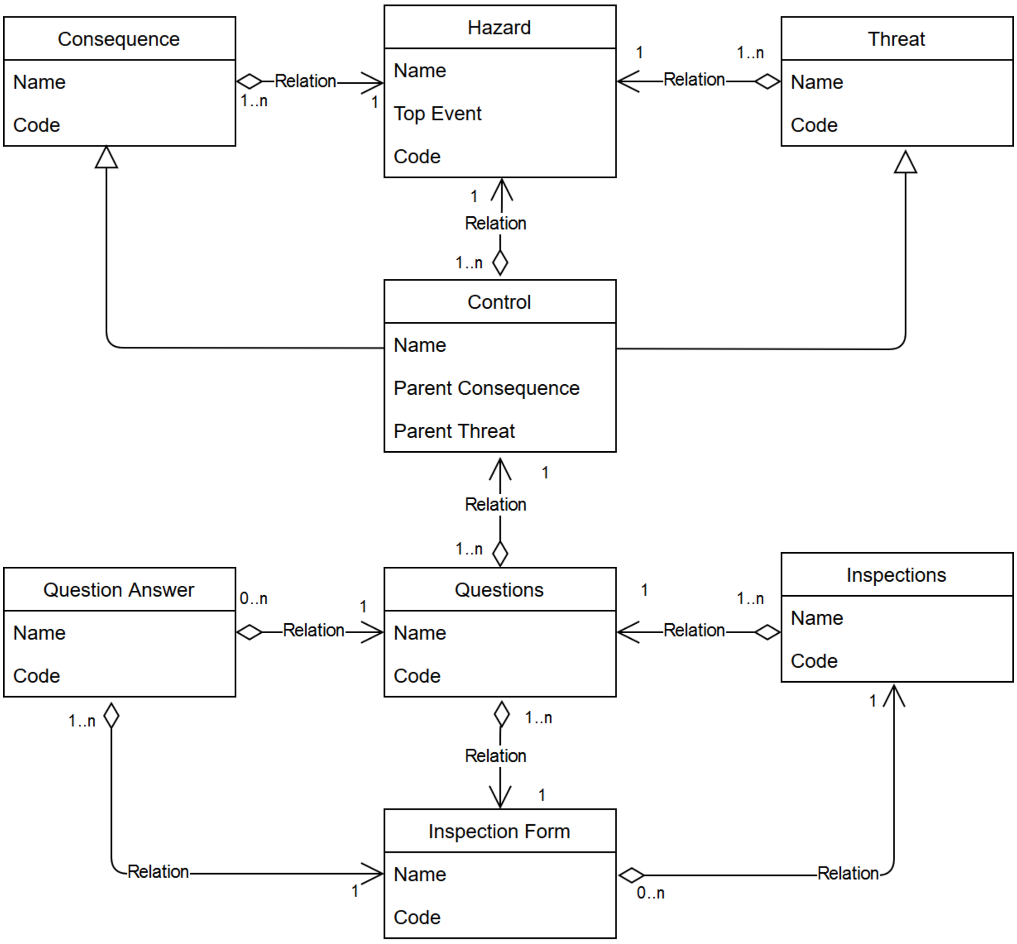


Figure 6.7: UML diagram detailing the relationships of arrays generated for bow-tie models

The UML diagram was developed specifically for relating bow-tie models and the audits that relate to them. The model in Figure 6.7 demonstrates the straightforward nature of the extracted arrays. Additionally, no distinction is made between the nature of inspections/audits and their respective questions. This means that once the data is generated in the bow-tie environment, it is immediately assessable as input for the BI environment. Once the audits allow not just singular questions but their repeated use, the data can immediately be forwarded to the dashboards.

6.6.1. Event Management System

During systems design, integration of the Event Management System (EMS) was targeted as a primary data source for a lagging indicator on critical control performance. Although the EMS was already integrated with the Regional Data Warehouse, no addition into the critical control BI environment was achieved. In order to make the data within the EMS applicable to critical control management, a slight change is required within the format of incident reporting. Both Australian sites have the capacity to add their own fields to incident registration, requiring such things as who reported the incident, to whom, when and where an incident took place. When a drop-down menu is added that specifies the Major Hazard Standard involved in the incident, the case studies that are done in Chapter 7, can be repeated for any newly generated data.

6.7. Dashboard creation for end users

Data analytics demonstrate the effortless way in which someone can drill down in the data generated through the critical control assessments. To do this, dashboards have to be generated based on measures in the data. Essentially, the data has turned into a series of pivot tables which can now be manipulated to suit the users' wishes. An example of a dashboard generated for users can be seen in Figure 6.8.

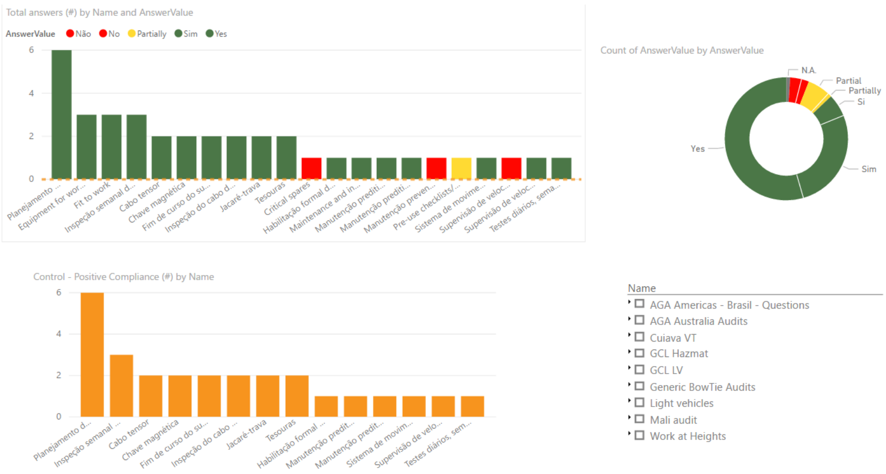
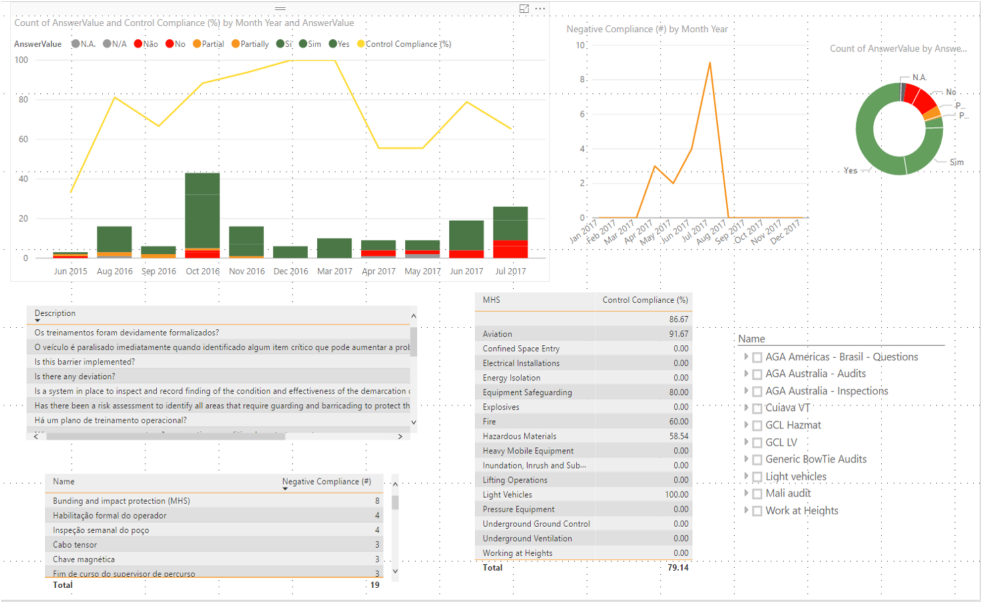


Figure 6.8: View of a BI dashboard demonstrating amount of positive compliance, relative compliance and all answer values

Based on the selection of the control with the largest number of absolute non-compliances issues, the non-compliance trend for this control can be shown within the domain of a single department. This allows a department to immediately focus on that control, while tracking progression of the trend in with which the data moves. An example of a control and its selected implications can be seen in Figure 6.9.

By using a slicer function that can sort the data hierarchically within the organization, every single stakeholder can track his own non-compliance issues and set out actions to mitigate them. This allows for an evidence-based approach of solving operational risk on every level of the organization. Not only does it allow stakeholders to take action based on enduring trends or spikes in incidents, it also simplifies reporting with regards to critical controls. Any MHS or critical control compliance level can be immediately brought to the attention of auditors. As such, safety specialists and supporting personnel can help develop measures to specifically help local managers instead of only looking at the general data. Furthermore, any sudden increase in issues can be picked up to mitigate emergent risks. This is of particular importance in mining, as conditions in the mine change over time. Aspects that play a role in these changing conditions are for instance depth, ground conditions, water inflow and seasonality.



Description
Os treinamentos foram devidamente formalizados?
O veículo é paralisado imediatamente quando identificado algum item crítico que pode aumentar a prob
Is this barrier implemented?
Is there any deviation?
Is a system in place to inspect and record finding of the condition and effectiveness of the demarcation
Has there been a risk assessment to identify all areas that require guarding and barricading to protect th
Há um plano de treinamento operacional?

Name	Negative Compliance (#)
Bunding and impact protection (MHS)	8
Habilitação formal do operador	4
Inspeção semanal do poço	4
Cabo tensor	3
Chave magnética	3
Fim de curso do supervisor de percurso	3
Total	**19**

MHS	Control Compliance (%)
	86.67
Aviation	91.67
Confined Space Entry	0.00
Electrical Installations	0.00
Energy Isolation	0.00
Equipment Safeguarding	80.00
Explosives	0.00
Fire	60.00
Hazardous Materials	58.54
Heavy Mobile Equipment	0.00
Inundation, Inrush and Sub...	0.00
Lifting Operations	0.00
Light Vehicles	100.00
Pressure Equipment	0.00
Underground Ground Control	0.00
Underground Ventilation	0.00
Working at Heights	0.00
Total	**79.14**

Name
- ☐ AGA Americas - Brasil - Questions
- ☐ AGA Australia - Audits
- ☐ AGA Australia - Inspections
- ☐ Cuiava VT
- ☐ GCL Hazmat
- ☐ GCL LV
- ☐ Generic BowTie Audits
- ☐ Light vehicles
- ☐ Mali audit
- ☐ Work at Heights

Figure 6.9: Working Example - View of a BI dashboard demonstrating amount of positive compliance, relative compliance and all answer values

6.8. Implications for other sites

The integration of critical controls into the workplace inspection process can be considered successful for SDGM. Its implementation has provided an offline capacity, operator based, low-level technical inspection process for critical control management. These three aspects provide ample potential for integration in other sites. Workplace inspections are required within mining regulations in Australia, South America and South Africa, with varying degrees of requirements in continental Africa. As such, these processes are already available for potential integration. Through use of existing, offline infrastructure and a low license structure, once it is implemented it provides extensive data for little expense. The key here is "after implementation". For a relatively small operation like Sunrise Dam, it took one person 2.5 months to implement the process. Main cost associated with the implementation of critical controls will thus be around the use of a safety specialist assisting with integrating critical controls into existing processes.

Implementation of critical control management at other sites should use a phased approach. Although changing operations for the better, resistance to change remains a constant, as noted for AngloGold Ashanti in the context of its South African mining operations (Robbins, 2010). In terms of adopting critical control management, integrating the workplace inspections per site would be the best option with respect to changing the existing situation as actual process optimization can be realised. However, due to the current inability of the bow-tie environment to adapt the used form of inspections into the system, other operations are advised to move forward with quarterly audits first.

While it implements another process, its coverage of 225 Performance Standard elements covers 41% of the entire required company standard. Through quarterly updates, trends in system behaviour can already be noted a half year after implementation. Additionally, critical control awareness is raised on the supervisor level, which benefits both subsequent manager and operator learning.

7

Case Studies

Two separate case studies were conducted to ascertain the potential for critical control monitoring and safety decision-making at Sunrise Dam Gold Mine. Additionally, these serve as a validation study for use of incident data as a lagging indicator for critical control performance, as specified in research sub-question 4. The case studies both target a single Major Hazard Standard with one focusing on underground Ground Control and the other on underground Fire. Within the scope of these hazards, the case study on Ground Control focuses on incident prevention and thus preventative controls. Contrarily, the case study on underground Fire focuses on reactive controls, specifically the critical control Aqueous Film Forming Foam (AFFF). It is the only reactive critical control in the MHS for Fire, and one of the only engineering critical controls on the reactive side of any bow-tie model within the scope of SDGM. The goal of both case studies was to look into systemic issues potentially affecting critical controls, while providing guiding principles for other studies in this domain.

First, the scope of both case studies is discussed. Next, the case study for underground Fire is examined. Subsequently the different aspects related to prevention of Ground Control incidents underground are assessed. Finally, lessons learned from both case studies will be drawn up into a conclusion relating the effectiveness of critical controls back to the incidents studied.

7.1. Scope

In this chapter incidents over a 5 year time period from July 2012 until July 2017 will be assessed. The incidents related were obtained from the Event Management System based on keyword searches and subsequently filtered on relevance. The data is used to validate the CCMS put in place with the goal of improving risk management. Therefore systemic and emergent risks are the focus of investigation. In order to implement the presented level of analysis in the BI environment of CCMS, the relevant MHS should be linked to an incident. Addition of this feature is technically feasible in incident reporting. It is even possible to add failure of specific critical controls to an incident, unfortunately this could not be achieved during the scope of this research. However, to use such a system efficiently means that relevant personnel should be knowledgeable in MHS's and their implications. Furthermore, where adding the correct MHS to an incident is a relatively straightforward decision, finding the correct failed critical control requires a lot more knowledge.

7.1.1. Underground Fire

With respect to the incidents related to underground fire, 57 instances of incidents were found in the aforementioned time-period. These include both actual and potential incidents. It is important to keep in mind that these 57 instances could have led to a fire, but might have been reduced to near misses due to adequate response and controls in place. The specific pathway in which AFFF is applied can be seen in Figure 7.1.

In the bow-tie model, AFFF is a critical control mitigating the possible consequence of damage to equipment. All other pathways can be viewed within the entire right half of the Bow-tie model in Appendix C in Figure C.3. While another pathway after the top event regarding underground fire focusses on potential human injury, none of the incidents within this case study have triggered the use of other critical controls such as rescue chambers. The scoping on AFFF keeps the area of investigation confined to the immediate area of the affected vehicle, something that will prove useful in the elaboration of the case study.

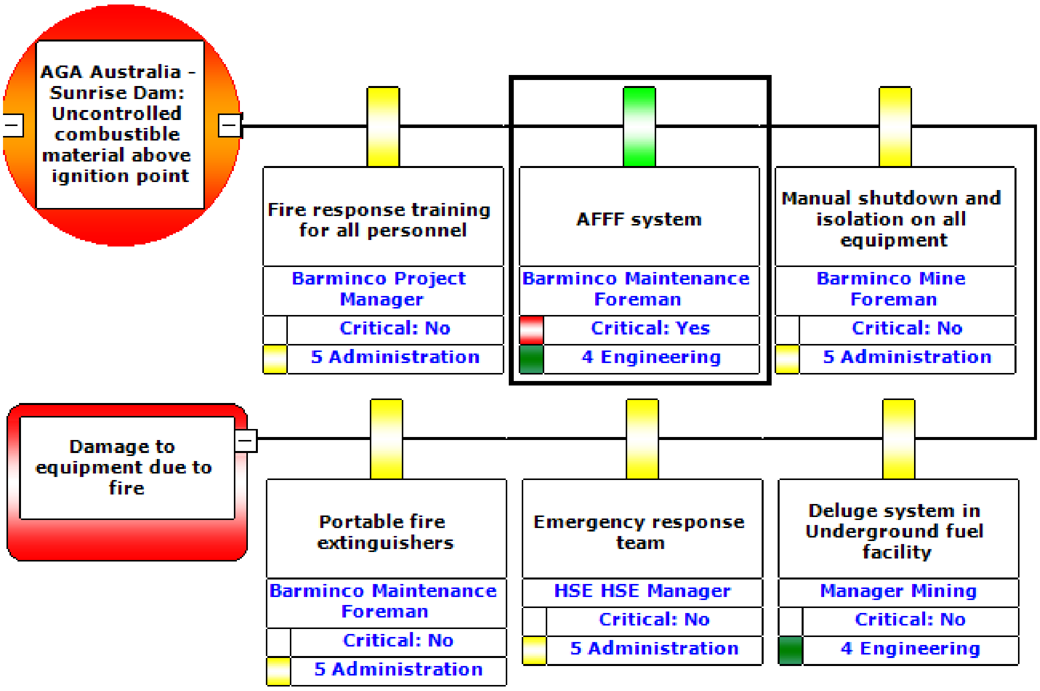


Figure 7.1: The pathway from top event until consequence in which AFFF is applied

7.1.2. Underground Ground Control

While underground fires are relatively easy to classify, ground control issues can be considered a broader category of incidents. This case study contains 74 instants that (potentially could) have impacted ground control within the mine. This research is dependent on the data submitted in the incident reports. Like the learning organization in HRO's, near-misses are reported. How many incidents go unreported could not be established. Instead of looking at only one critical control after a top event as in the case of UG fire, the entire left hand side of the Bowtie diagram for Underground Ground Control is examined. Because the model assessed is rather comprehensive, merely the critical controls and the main causes within the model will be assessed. The full model up until the top event for Ground Control can be found in Appendix C in Figures C.1 and C.2.

7.2. Case 1: Underground Fires at SDGM

As discussed in paragraph 2.4.2, operational safety risk is the product of probability and consequences of Material Unwanted Events (MUE's) within AngloGold Ashanti mining sites. Thus the risk experienced over the past five years can be described as the probability of all underground fire events and the aggregate of all related consequences. To quantify the exact amount of risk experienced by AngloGold Ashanti with respect to underground fire would require establishing a measure for probability of all related incidents. This is out of scope for the case study.

Instead this case study focussed on doing an analysis of all underground fire incidents within the mine to pinpoint target areas for improvements in firefighting capacity. Essentially only the right hand side of the bow-tie diagram was examined, with extra attention paid to the effectiveness of the critical control Aqueous Film Forming Foam (AFFF). Using data gathered over the last five years and a half several assessments were made with respect to firefighting capacity, AFFF and its applicability, fire sources and predictions regarding escalation. Additionally, other critical controls were assessed to give an indication of the expected effectiveness of the entire model with regards to mitigation of underground fires at SDGM.

7.2.1. Aqueous Film Forming Foam

To understand why Aqueous Film Forming Foam (AFFF) is the focus of the case study on underground fire, one has to look at the causes of underground fire within the scope of SDGM. All but two of the 57 instances were caused by a form of vehicle malfunctioning, such as liquid on spraying on hot engine parts after a line burst. Similar results are corroborated in a study by de Rosa (2004). Because the source of fire in all cases at the mine was a vehicle, the scope is limited to combating vehicle fires with the help of AFFF. If the AFFF system on the vehicle was not used or was not effective, recommendations are made to what controls might replace or support the AFFF system in containing and quelling instances of fire.

7.2.2. Risk: Potential for Underground Fire

Because it is the right hand side of the bow-tie diagram that is of interest, probability of the incident is not as much the focus as is the potential severity of the incident. As Hansen and Ingason (2013) have demonstrated, it is not unfeasible for a drilling jumbo without petroleum-based fuel to burn up beyond all repair using solely the hydraulic tank, lines and tires as fuel. Some incidents reports found have incidated that AFFF was needed with the help of three handheld fire extinguishers, pointing in no uncertain direction to the timely reaction of operators and their prevention of a worse outcome.

As stated in Paragraph 5.1.3, incidents on site are registered with a potential and an actual outcome as part of an obligatory risk assessment done to review the incident. A scatter plot for the potential incident severity plotted over the last five and a half years can be seen in Figure 7.2.

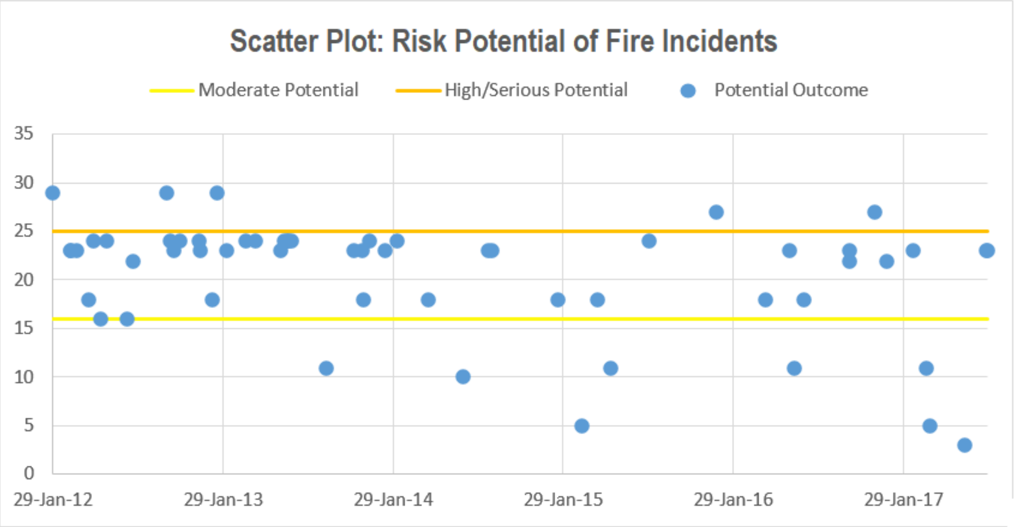


Figure 7.2: Risk scores attributed to the incidents plotted as scatter against time frame of case study

It shows two trends that have occurred since January 2012. First is a trend that the relative frequency of incidents has decreased severely until 2015 and has since picked up again slightly. The second trend revolves around a relative decrease in the severity of incidents. The three incidents with the highest potential (29 or major) all occurred in 2012 or January 2013.

On the absolute scale of the AGA risk matrix, 29 is on the second to highest consequence level indicating a fatality or multiple severe disablements, a financial loss of 10-50$ million dollar and/or serious adverse media/public/NGO attention. Something that illustrates the relative decline in incidents as well as decreasing severity is when the scatterplot is aggregated as a 6 month moving average scale over 1 month increments, which can be viewed in Figure 7.3.

Because no data is available before January 2012, the moving average only starts to be valid after July 2012. The Y-axis represents a relative risk score reminiscent of, but not equal to the values in the AGA risk matrix. The value for the moving average curve has been achieved through the use of a one-sided 6 month moving average (Hyndman, 2011). Often used for uncomplicated forecasting, such a formula was deemed adequate for indicating total risk exposure for any given moment in time based on the incidents in the six months before it.

The equation used above is the same as the one used in the case study for fall of ground incidents. This allows establishing a relative severity between the two cases in terms of overall impact on the underground mining operation. What can be seen in Figure 7.3 is the rising potential for underground fires until a high point of 33.1 on April 10th 2013, rapidly declining until a low-point of 2.9 on March 9th 2015 almost two years later. After the low-point there is a slight increase again hovering somewhere in the 10-16 range. In order to establish what the causes of these trends are, the incidents will have to be examined more closely.

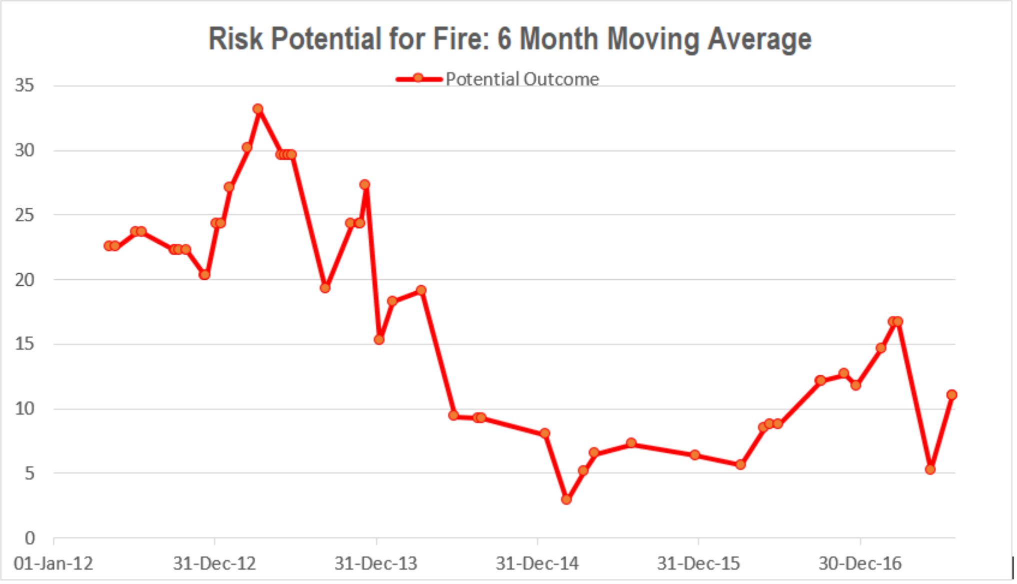


Figure 7.3: Moving average curve of potential risk score for fire incidents over the time-frame of case study

7.2.3. Causes of Fire incidents

As discussed in Section 7.2, all but two incidents originated from the malfunctioning of a vehicle in or with potential to be in the underground workings. Further specifying the origin of the fire will require determine several factors, being the following:

- Vehicle Type
- Fire Source
- Fire Type

The fire type is of special concern here, as it is both a determinant in the ultimate potential of the incident as well as an important aspect with regards to applicable firefighting methods.

7.2.4. Vehicle Types

In Figure 7.4, a distribution of the different vehicles in the incidents can be seen.

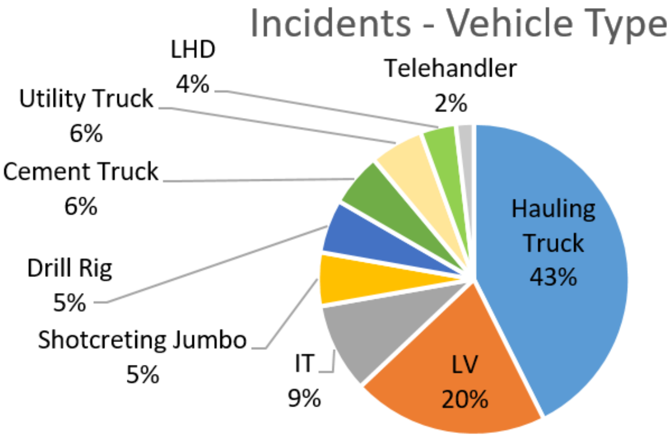


Figure 7.4: Distribution of vehicles as a fire source at SDGM

Together, underground hauling trucks, light vehicles (LV's) and integrated tool carrier's (IT's, a multipurpose front loader) account for 71% of all underground fire related incidents on-site. Utility trucks and cement trucks account for another 12% of the incidents, with the rest of machinery (16%) is mainly used in or near production areas. To illustrate how vehicle types as a source of fire have changed over time, vehicle categories have been plotted as areas under the moving average graph as shown in Figure 7.3 to illustrate their respective significance over time in Figure 7.5.

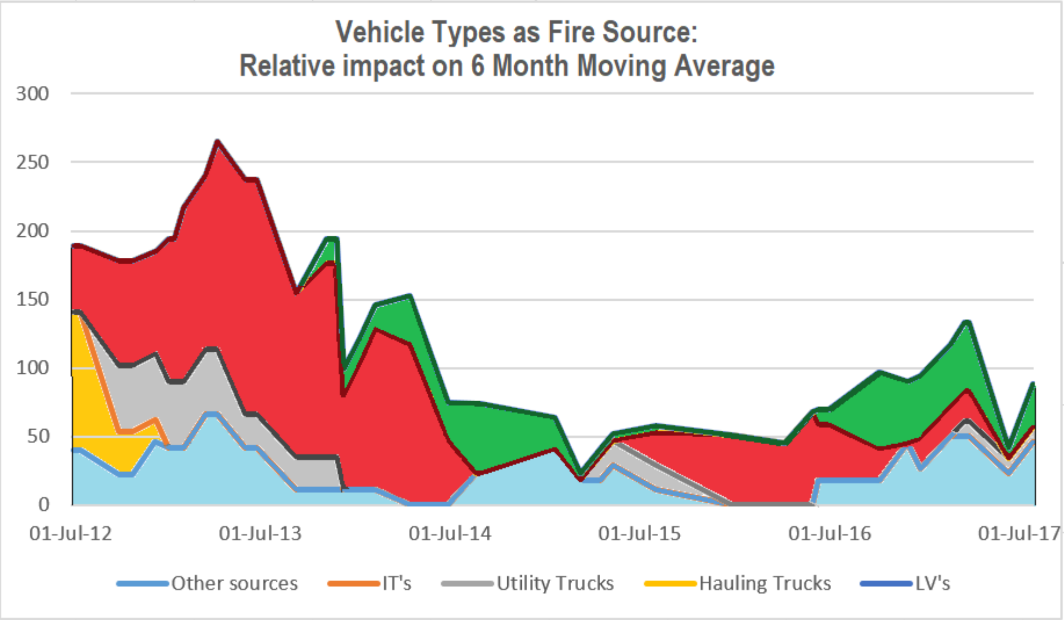


Figure 7.5: Vehicle types as contributing to moving average risk score for fire

Evident from the plot in Figure 7.5 is that in 2012 a significant fraction of the vehicle types used underground was subject to one or more incidents concerning fire. Contrarily, 2013 shows that a significant portion of incidents was solely due to underground trucks. The decrease seen from April 2013 until March 2015 in the aggregated risk score in Figure 7.5 can therefore be largely attributed to the elimination of IT fires and the extensive decrease in fires on underground hauling trucks. The increase seen from March 2015 until mid-2017 can conversely be attributed to a resurgence in underground hauling truck fires followed by an increase in fires on LV's.

The decrease in underground hauling truck related incidents has in part been due to a re-evaluation of the supplier and vehicle type and phasing out the fleet for a new, less fire-prone hauling truck type. It goes to show that a sequence of incidents in close succession can at partially lead a company to evaluate their entire fleet choice. A similar fleet change has not been one of the main factors in either the decrease in IT fires as well as the increase in LV fires. To get a better understanding of the incidents, not only the type of vehicle but also the source of fire has to be examined.

7.2.5. Sources of Fire

In 52 out of 54 vehicle related fires on-site, a cause was established as part of the investigation for reinstatement of the vehicle. The two cases where a cause could not be established were both LV's, a source of fire that will described in more detail after underground trucks have been examined. The goal of this paragraph is to establish if sources of fire differ significantly across different vehicle types. The types of vehicle that will be examined with regards to the fire source are underground hauling trucks, LV's and IT's. Within that scope, underground hauling trucks will be first discussed being the largest source of incidents on site.

7.2.5.1. Underground hauling trucks

To identify if there is an underlying cause for multiple similar incidents, a reliability block diagram (RBD) for a hauling truck will be used to categorize the different incidents involving underground hauling trucks. The reliability block diagram used to categorize the different failure modes can be seen in Figure 7.6.

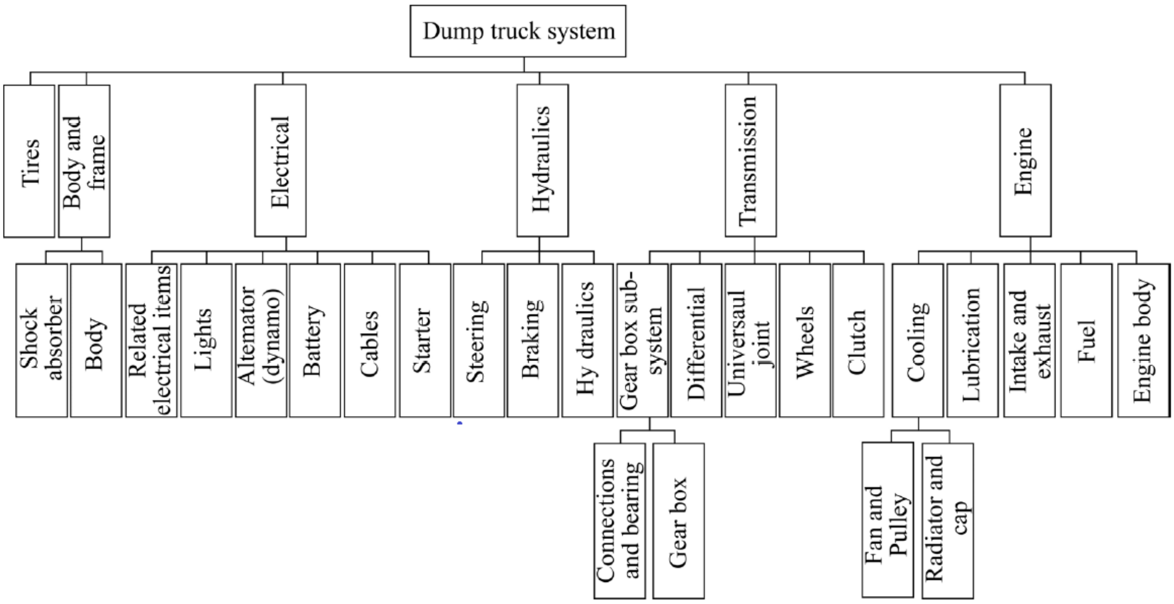


Figure 7.6: The reliability block diagram for an underground hauling truck showing the different subsystems of the vehicle, most notably the engine and its subsystems.

The diagram in Figure 7.6 has been adapted from a study into the productivity improvement of open pit mining equipment (Morad et al., 2014). Essentially a reliability block diagram functions as a fault tree analysis in identifying common failures of machinery leading to critical failures. Although the vehicles studied in the case study might not feature the exact same sub-systems, a more detailed approach is not required as all fire sources correspond to one of the sub-systems listed in the RBD. The resulting causes are then super-imposed on a RBD that only contains the relevant branches in Figure 7.7.

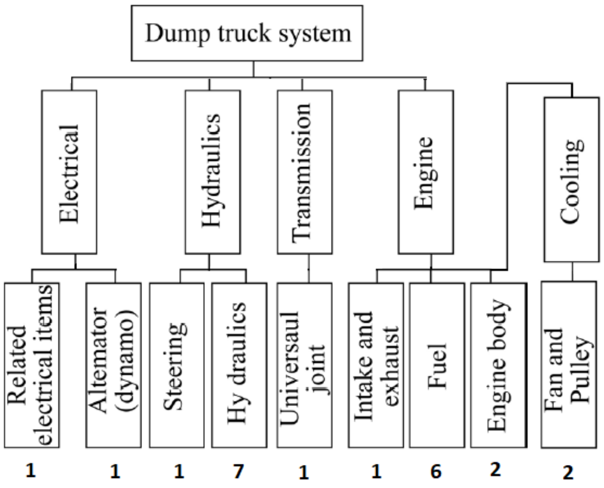


Figure 7.7: Failures super-imposed on RBD for underground trucks

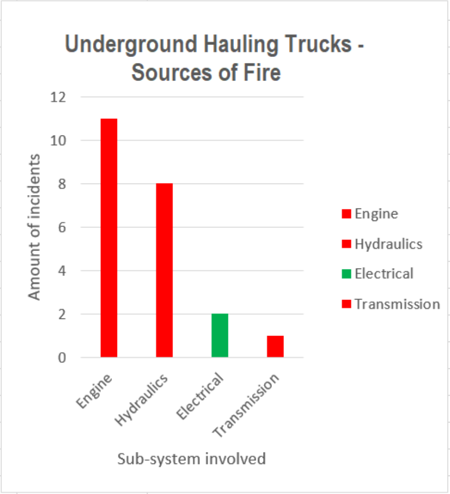


Figure 7.8: Bar diagram showing the discrepancy in fire sources on underground trucks

Figure 7.8 shows that all but three causes lead back to either hydraulics or engine failure. The red sections of the bars indicate that the source was a Class A or B fire, meaning a flammable liquid or solid. The green section indicates a Class C, electrical fire. Failures with a fuel, hydraulics or steering line are indicated with a dot and account for 13 out of 19 engine/hydraulics failures, or 60% of total underground hauling truck failures. Other sources of fire only account for one or two incidents over a 5 year time scale. Finally, only two of all underground truck incidents were caused by an electrical source.

7.2.5.2. Light Vehicles

The only category that was not explicitly built for mining are light vehicles (LV's). These are often durable 4x4 off-road pick-ups or passenger cars. For simplicity's sake, the same reliability block diagram used for underground trucks is applied to the sources of LV fire incidents. When the causes are super-imposed over the RBD in Figure 7.9, it becomes clear that the source of incidents is mostly due to failure of electrical components as shown by the corresponding bar colour in Figure 7.10.

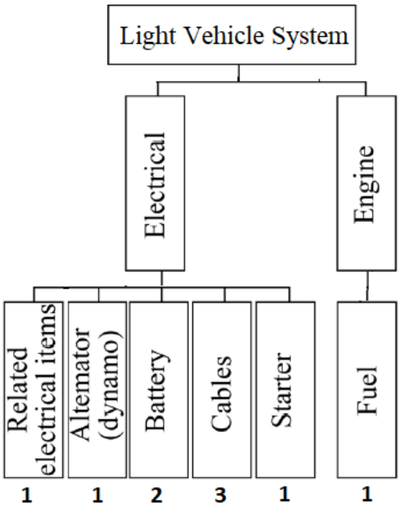


Figure 7.9: Failures super-imposed on RBD for LV's

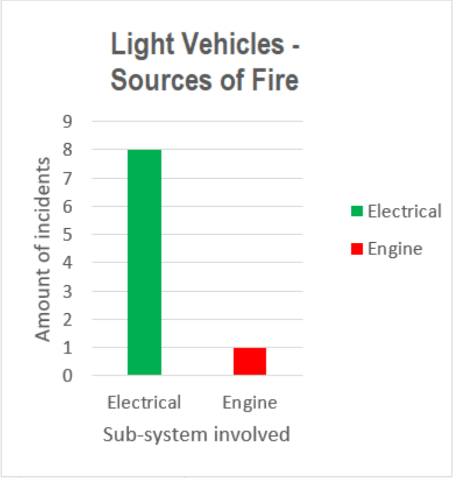


Figure 7.10: Bar diagram showing the discrepancy in fire sources on LV's

The significant portion of electrical fires directly impacts the effectiveness of AFFF, which is typically not rated for fighting electrical fires.

7.2.5.3. Integrated Tool-carriers

The last category of investigated fire sources is that of the integrated tool-carrier. When taking a closer look at the incidents, three of the instants were due to broken coolant hoses, one due to the air filter being incorrectly fitted and one due to damage to the AFFF system itself. No RBD is strictly necessary to demonstrate fire sources, as all causes for IT related fires originate within the engine block.

7.2.6. Types of Fire

What has become clear with regards to the origins of fire on all investigated vehicle types is that the fire source differs significantly per category. Both trucks and IT's face a majority of B class fires, which originate from combustible liquids such as diesel, coolant and hydraulic fluid. These types of fires are most effectively put out when the AFFF is able to apply a smothering effect through creation of a aqueous film across the pool of fire (Hetzer et al., 2014). LV's however face mostly C class fires originating in electrical circuits. Essential to fighting C class fires is de-energization of the circuit involved as well as using a non-conductive agent such as carbon dioxide. The difference between A/B and C class fires across vehicle types can be viewed in Figure 7.11.

The bar chart in Figure 7.11 shows that LV's face significantly more electrical fires than other types of vehicles. If LV's are more prone to electrical fires could not be determined from literature.

7.2.7. Outcomes of Fire Incidents

The most prevalent vehicle types and failure modes have now been established. This will help support the assertions made in the outcomes of the events and the effectiveness of measures developed to combat these incidents. None of the incidents categorized as relevant for this case study caused a fire to be uncontrolled for any significant amount of time. Hansen (2017) demonstrates that similar vehicles have been entirely lost as a result of unattendance. In SDGM, no such cases were recorded and in all cases the operator on-duty was able to quell the fire before it escalated beyond his or her control. This is also a sign of competency with respect to the operators involved at SDGM.

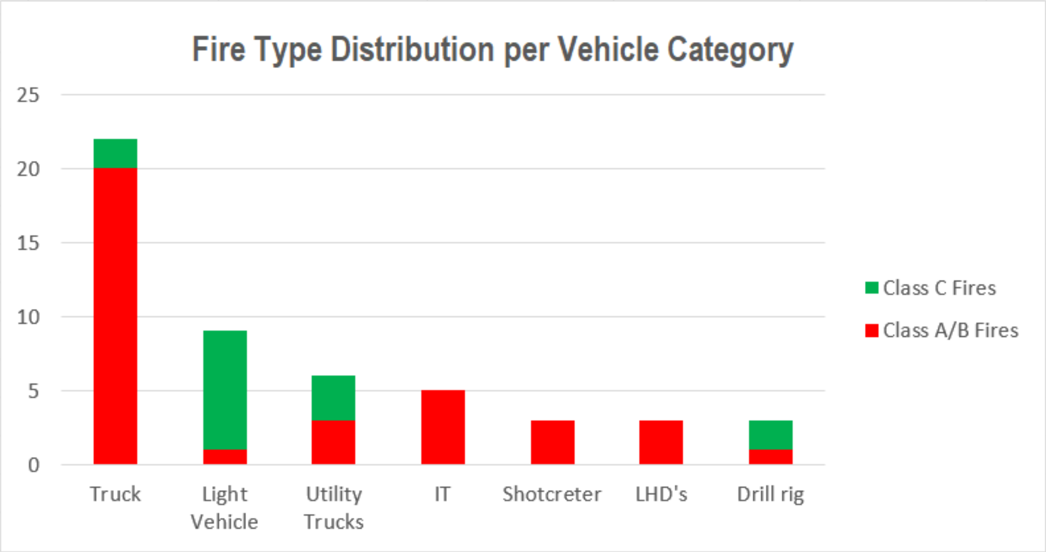


Figure 7.11: Fire types as plotted across vehicle types

Subsequently, no injuries were sustained during any of the incidents in this study. This is reflected in the actual outcome as given in the risk assessment accompanying the incident reports:

- Insignificant: 23
- Minor: 28
- Moderate: 1

Similarly to the risk curve presented in Paragraph 7.2.2, the actual outcome of the events can be plotted as a 6 month moving average curve over the last 5 years which can be seen in Figure 7.12.

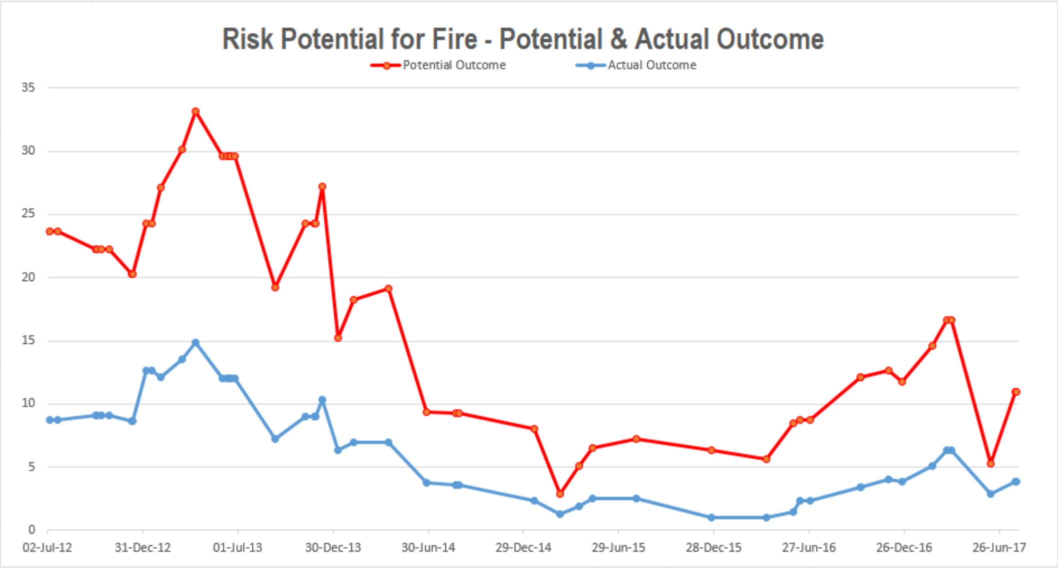


Figure 7.12: The 6 month moving average curve of actual impact plotted against potential impact

The graph in Figure 7.12 shows that the actual impact has been reduced by an order of magnitude. This is expected as it relates to the risk matrix score given in both instances. As the potential for an outcome does not change, movement on the risk matrix is only vertical as discussed in Paragraph 2.4.3. The graph demonstrates another possiblity in terms of risk quantification. Because the absolute amount of risk reduction is known, attributable factors can now be used to indicate relative importance of mititgation factors. Naturally, operator conduct is one of, if not the most important factor at play. Other things that may be influenced by human behaviour include usage of a fire extinguisher, disconnection of the battery or engine, self-extinguishing, or the use of AFFF.

7.2.8. Potential for escalation

That is not to say a severe incident cannot happen. In a study by Hansen and Ingason (2013), two underground vehicles were ignited to measure heat release rates of the subsequent fires. In both instances a Class B fires was the primary source. Any fire of a similar nature therefore has at least some potential of leading to a complete burning of the vehicle. Unfortunately, no conclusive data was available to investigate the risk potential of electrical fires.

As the vehicle types involved have changed over time, so have the fire causes. In Figure 7.13, the type of fires has been projected as area under the graph in Figure 7.3 to indicate what the potential for each of the different fire sources was for the last 5 years.

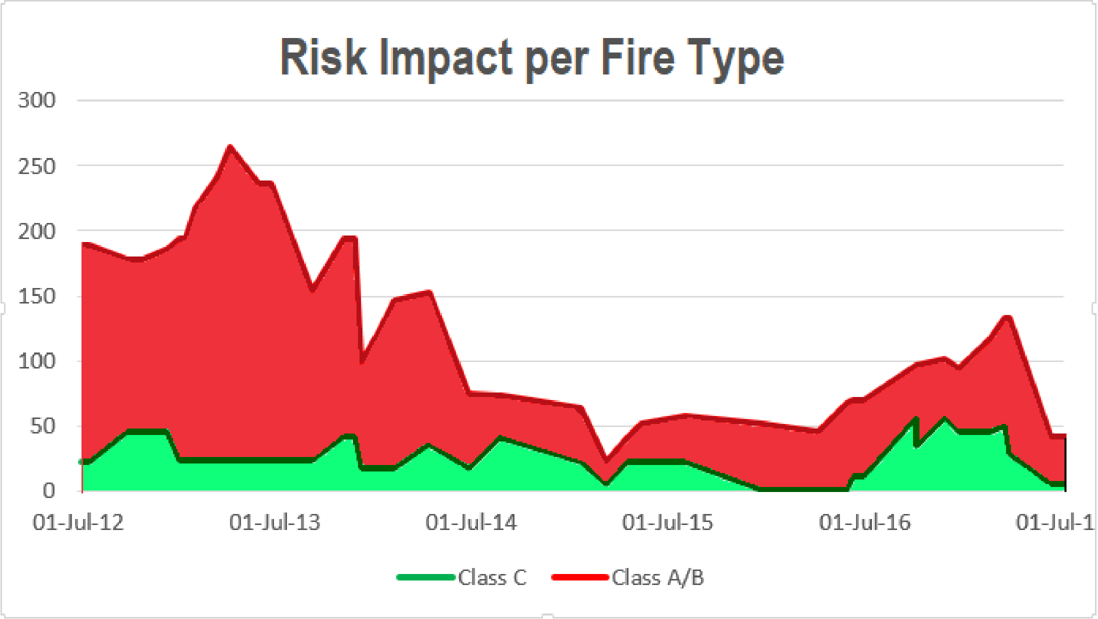


Figure 7.13: Fire types plotted as a 6 month moving average at SDGM

If the fire class is then related to the critical control AFFF a measure of its potential effectiveness over time can be assessed. This is done by first assessing what the actual effectiveness of AFFF was in incidents in which it was used. In incidents where only AFFF was used, it was the single measure that reduced the incident from its potential to its actual outcome. Again, the risk score can be superimposed on the risk score to visually quantify the risk reduction achieved through use of AFFF, which can be seen in Figure 7.14.

Additionally, there are the incidents where AFFF was used in conjunction with other firefighting methods, primarily dry chemical powder extinguishers. Of these incidents there is not enough detail to ascertain exactly how much of the firefighting was due to AFFF. What is clear however, is that AFFF alone was not able to completely put out the fire, thus at least partially failing in its task. This can be added to the moving average curve as a zone of medium confidence in the control.

There is a last category of incidents where the AFFF could have been used, but was not used due to whatever circumstance dictating the response at the time of the incident. This is only the case for Class B fires across the different vehicle types. These incidents can be classified as a zone of low-confidence. For the purpose of this study these were not quantified in the figure as to overstate the significance of this portion of risk reduction. Together, these give the potential for the use of AFFF within SDGM over the last 5 years, and can be viewed in Figure 7.15.

The diagrams above show that AFFF has played a significant part in risk reduction. The effect can be quantified as the area for each of the different confidence zones, being:

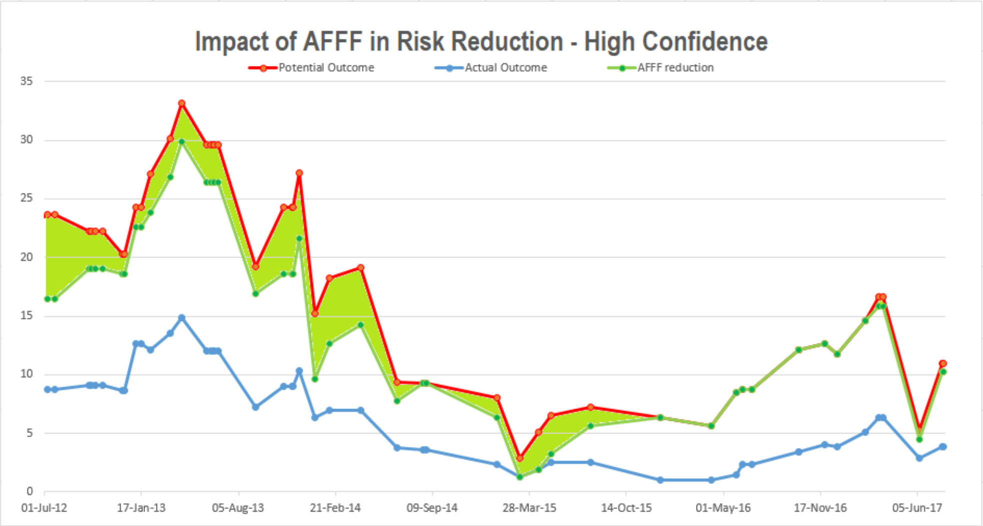


Figure 7.14: AFFF reduction with high confidence over time-frame study

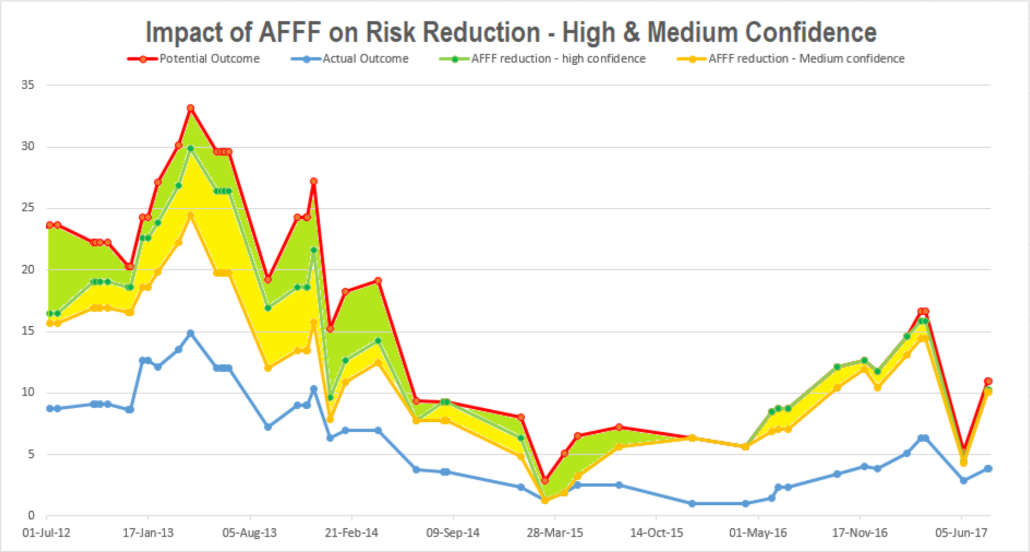


Figure 7.15: AFFF reduction plotted with confidence zones over 5 year time-frames

- High: 14.3%
- Medium: 12.0%

Together this represents a little over a quarter of total risk reduction. Perhaps the more interesting thought however, is the fact that the potential for risk reduction through AFFF has also changed over time. Figure 7.16 shows that the relative potential for risk reduction, using both the compound and the individual confidence classes shows a decline when moving from 2012 until 2017.

The major cause of this is the change of a majority underground hauling truck fires to LV fires and the difference in fire types across these vehicles. That is where associating costs and possible benefits with regards to critical controls comes into play. The fleet size has remained the same over life of mine in the timespan examined in this case study and so have the AFFF systems. This means that the costs associated with the control also remained the same. One of the reasons for this is that diesel powered, turbo-charged vehicles rated above 125 KW have to be equipped with an AFFF system under Australian law (Department of Minerals and Petroleum, 1997). Therefore capex and opex have remained the same while (potential) effectiveness has gone down.

This is the issue with fighting symptoms instead of the underlying issue. Only after the fire has started

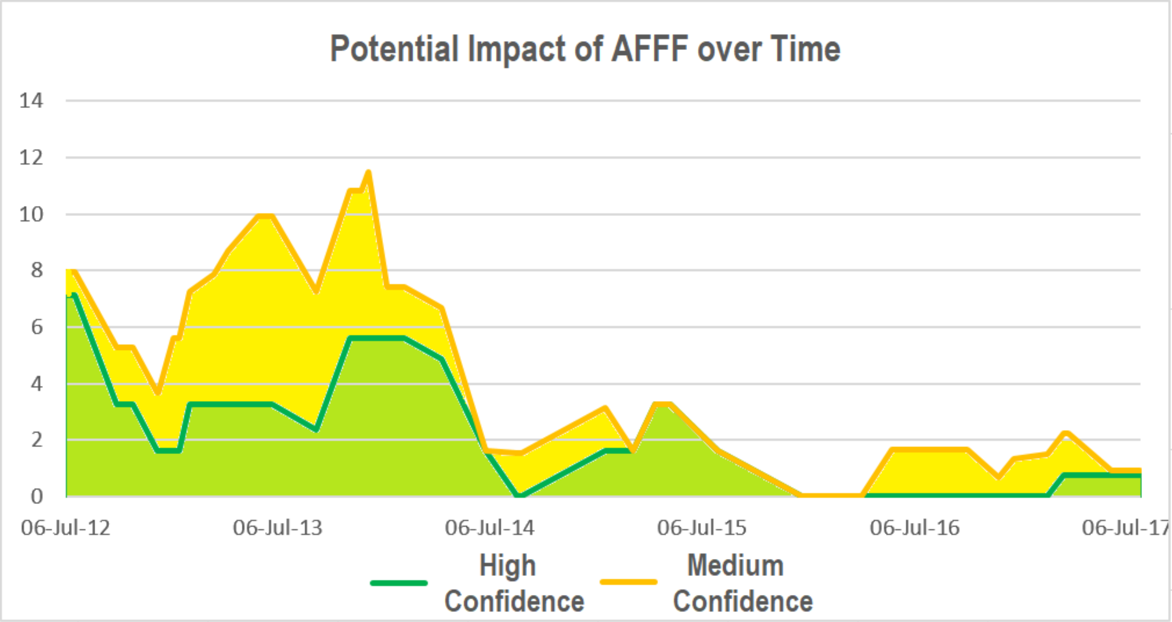


Figure 7.16: Potential of risk reduction for high and medium confidence classes of AFFF

will the AFFF be used or remain unused, demonstrating its effectiveness in the process. Especially solutions that are not in a way “one-size-fits-all” like rescue chambers, the one-dimensional side of controls has to be considered. The only engineering critical control in the Major Hazard Standard for Fire is a method of fighting class A&B fires on underground vehicles, regardless of their proneness to these kinds of fire.

7.2.9. Discussion of other (critical) controls

If we look back at Figure 7.1, the only critical that prevents a loss of control fire event from escalating to "damage to equipment due to fire" is the AFFF system. In this paragraph a brief discussion is presented reflecting on the "critical" nature of the control.

Looking back at the definition given in Section 4.3, the AFFF does qualify as a critical control. It mitigates MUE’s, prevents event escalation and can be used for multiple risks. That is, it can be applied in class A and B fires. But when a portable Dry Chemical Powder (DCP) Fire Extinguisher is examined, it factually does the same. Both are operator activated, yet a DCP extinguisher also applies to class C electrical fires. Arguably, the presence of a DCP extinguisher should then be qualified as a critical control as well. Comparing effectiveness of both systems, the DCP extinguisher participated in 26 of 57 incidents, often assisting where AFFF was not effective. In 19 cases, the AFFF worked as intended. A case can be made that a DCP extinguisher is more effective, has more purpose and can be used at all affected areas. However, the distinction has to be made that while the AFFF works automatically, the operator has to physically approach and fight the fire to use the DCP extinguisher effectively.

However, none of both controls matter if not for intervention of the operator present. In all but one cases at SDGM, the operator on duty was the first to notice the signs of fire. This is thus a key element of figrefighting on underground machinery: it is the operator that is the first and most important line of defence. This is alluded to in the bow-tie model, where fire response training for all personnel is listed as an administrative, non-critical control.

As discussed in Section 2.3, this is a misconception often had in the building of bow-tie models. The training does not actually prevent escalation of fires. Instead, it is a tool which validates that the control will work, when depended on. Consciously or not, putting "fire response by operator" literally in the bow-tie model might rub stakeholders the wrong way. It is a way of saying: "if the machine catches fire, we expect the operator to try and deal with it". The emphasis here is on trying. Meaning, an operator is responsible nor accountable for quelling the fire. Should the situation require retreat due to excess heat, an operator is expected to move away from the scene.

However, the pathway discussed controls mitigating damage to assets, not human injury. It must be concluded that in this pathway, operator response is without a doubt the most important control. While defined at AngloGold Ashanti as an administrative control, literature shows that AFFF, DCP extinguishers and operator fire response could fall in the same category of socio-technological controls (de Ruijter and Guldenmund, 2016). Until an automatic fire suppression system is fitted a true engineering control is implemented. Then the question remains if it is applicable to the fire and the location at hand. In a way, reactive critical controls will always remain a form of symptom killing instead of addressing the "true" issue. As the underlying issues change in the operation, so does the potential and thus value of a critical control.

7.3. Case 2: Underground Ground Control

The case study on underground ground control will focus on prevention of incidents and thus the left hand side of the bow-tie diagram developed for SDGM. The potential of this approach lies in the fact that the aim becomes eliminating the cause of incidents, instead of solely fighting symptoms of the underlying causes. The goal of this chapter is to look past the immediate incidents and, like the previous case study, develop ideas on the patterns influencing incidents. The analysis will focus on the critical controls in place and ways in which these can be used more efficiently. To accomplish that, a risk pattern will first be established for the timeframe from January 2012 until July 2017. Secondly, the incidents relevant to ground control will be assessed in separately designated categories. Lastly, probable causes will be specified within each of the incident categories.

As the bow-tie model for ground control is quite extensive, the full extend of the left hand side of the model can be found in Appendix C. The identified causes of ground controls issues within the model are as follows:

- Unsuitable Mine Design
- Less than Adequate ground support
- Drill and Blast practices
- Excavation interaction
- Rock mass characteristics
- Discrete geological features
- Seismicity
- Pit wall Integrity
- Access to non-active areas

The identified causes form an exhaustive list of possible ways in which ground control could be negatively impacted. In the next few paragraphs, categories of incidents will be discussed as found at SGDM. Although these might not directly relate to the causes listed, the case study will conclude with an analysis of their adequacy. Like fault tree analysis example on strain burst in Figure 2.2 in Chapter 2, intermediate causes will be used to explain some of the underlying issues.

7.3.1. Risk: Potential for underground Fall of Ground

Like the incidents related to underground fire, all incidents involving ground control have a risk rating attached to them in terms of their risk potential. Using the same methodology used in the previous case study, the potential risk score of the underground ground control incidents is plotted as a scatter plot in Figure 7.17. In this scatterplot, no pattern or trend is clearly distinguishable. That would imply that as opposed the fire incidents, ground control has improved nor deteriorated significantly since January 2012. The only noticeable effect is the notion that the frequency of incidents exceeding the threshold for "high potential" have increased since January 2015. To identify if the frequency of incidents has increased, a 6 month moving average line is plotted in Figure 7.18, applying the same methodology as used in Figure 7.3.

As opposed to Figure 7.3, no trend is distinguishable from the moving average curve. As with the underground fire incidents, a major change did take place during the timeframe in which the data was gathered. In early 2013, a change was made to using fiber shotcrete instead of unadded shotcrete. The change was made after issues with the adhesion qualities of the shotcrete applied before that time. It should follow that shotcreting incidents have thus decreased since, something which can be explored through examination of causes related to fall of ground.

7.3.2. Causes of Ground Control incidents

Within the case study a wide variety of incidents have been classified as related to ground control. All 54 instances were at least partly due to the fact that ground control integrity was impacted. This led to a variety of incident categories, where all of the incidents in one category are related in nature. These categories are:

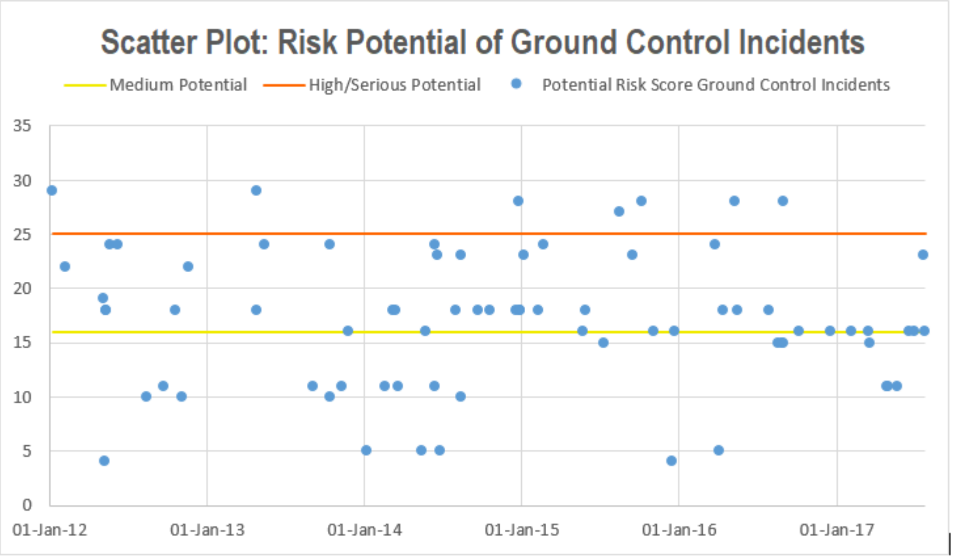


Figure 7.17: Scatter-plot of the risk potential of fall of ground incidents at SDGM

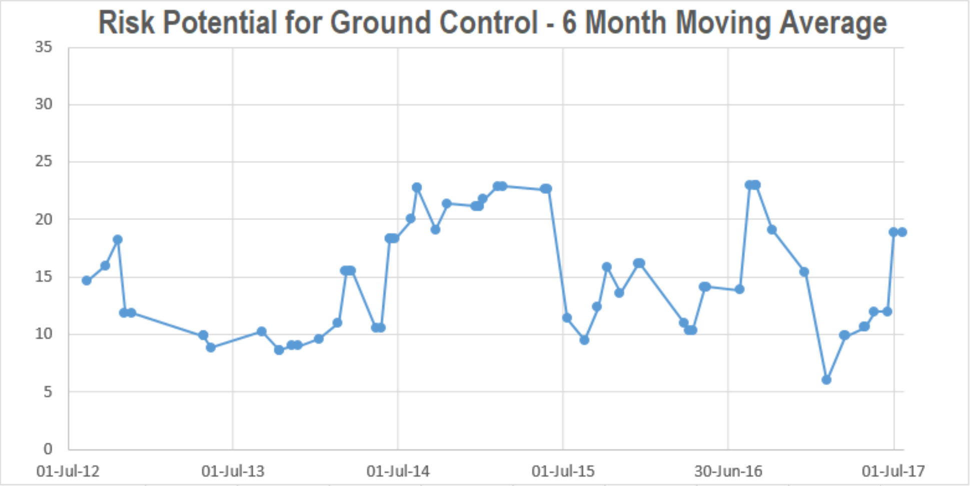


Figure 7.18: Fall of ground incidents plotted as a 6 month moving average at SDGM

- Scaling: 15
- Stope Rilling: 15
- Unplanned Breakthroughs: 10
- Shotcreting Application: 9
- Supporting Operations: 8
- Operator Procedure 3
- Impact through blasting 3
- Build-up of salt 3

Through assessing the separate categories, cause analysis can be done to indicate if the loss of ground control was precipitated by design or changing conditions. To see if trends can be identified on a yearly basis, a graph was made representing the different incidents categories which can be seen in Figure 7.19.

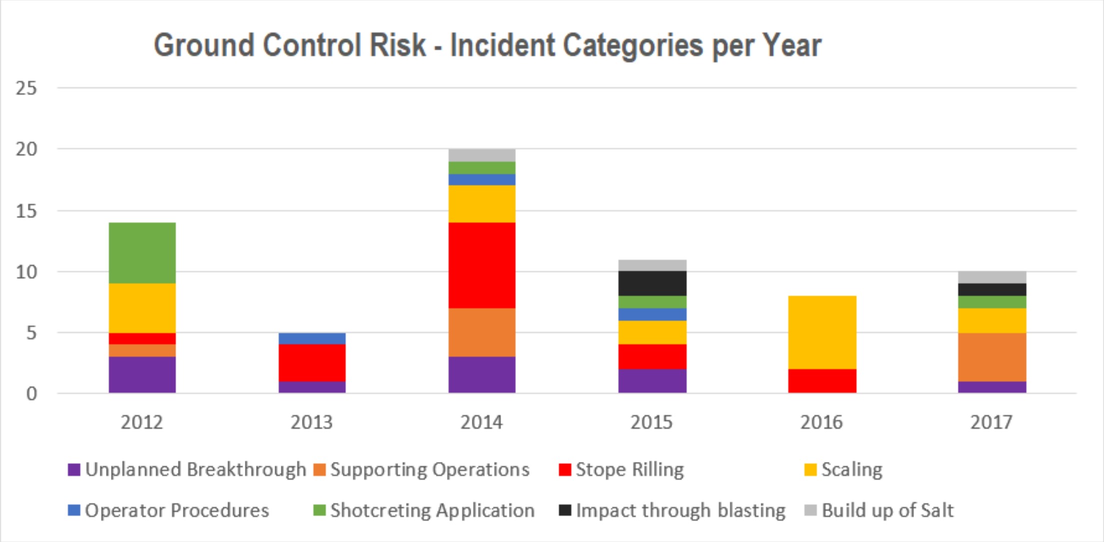


Figure 7.19: Ground Control incident categories plotted per year

Within the graph, no specific upward or downward trend is identifiable. A slight decrease however can be seen when looking into shotcreting application, which moves from 5 incidents in 2012 to 1 incident in 2016 and 2017 together. It is important to understand that some of the incidents are considered an acceptable loss, as controls have been put in place to maximize value extracted elsewhere. This is especially the case for stope rilling, which will be discussed second. First however, incidents related to scaling activities are examined. Thirdly, shotcrete application and supporting operations will be discussed, as they are individual categories but with significant overlap. Finally, several minor categories are reviewed.

7.3.3. Scaling

The single most impactful category with respect to ground control issues at SGDM is that of scaling incidents. A technique used to check for loose rocks before continuing operations underground, scaling is one of the most hazardous tasks required in any mine. The purpose of scaling is to make sure rocks do not unexpectedly come down when performing supporting operations under newly exposed rock. This process is usually carried out mechanically at SDGM using hydro-scaling.

With a jumbo a high-powered jet of water is used to clear any loose rocks from the relevant face. However, manual scaling is still carried out at SDGM as part of surveying rock conditions. All but four incidents listed in this category involve these manual scaling activities carried out to assess local rock conditions within the mine.

Close to a quarter of all ground controls incidents would be eliminated if scaling issues could be resolved. Therefore a closer look into the underlying trends and patterns is necessary. In Figure 7.20, scaling incidents are plotted per year against the areas in which the incidents occurred.

What can be seen in Figure 7.20 is that scaling incidents concentrate in the GQ and Dolly/Vogue sections of the ore body. Except for 2013, scaling incidents have occurred over the entire time-frame from 2012 to 2017. As scaling explicitly targets less supported or unsupported areas, it could follow that the likelihood of ground instability during scaling is higher in areas with poor ground conditions. According to the geotechnical department at SDGM, the only area where conditions are noticeably worse than else is at the bottom of Cosmo East. This area is in the middle-bottom of the image in Figure 7.20. Unfortunately, no detailed maps of geological features were available at the time of study. It is therefore uncertain if localized geological features have played a role in causing incidents.

It could be theorized that local ground conditions are not the underlying issue that is causing scaling incidents. An assessment of the impact of scaling incidents concluded that 9 out of 15 cases specified an injury to have occurred while another two incidents have falling rocks hit scaling operators. Furthermore, two more incidents have rocks falling dangerously close to operators or in places occupied a short time-frame ago. In total, 11 out 15 times a rock made contact with two additional near-miss incidents. The reason this category is considered more significant than stope rilling is that scaling incidents represent the only category

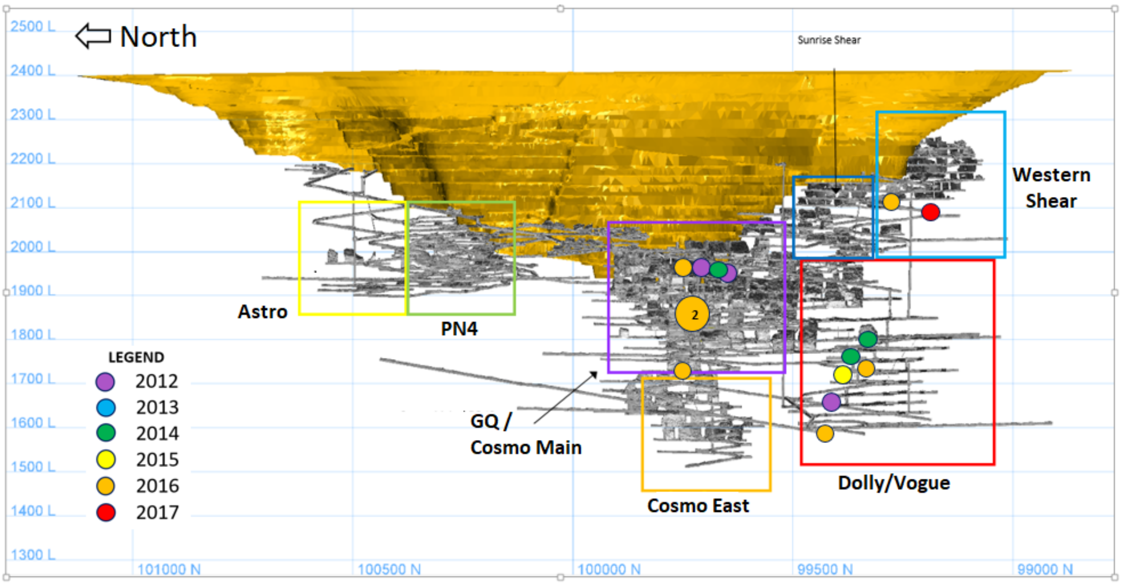


Figure 7.20: Scaling incidents mapped per year within the underground workings of SDGM

of incidents leading to injury.

To see if critical controls cover these scaling incidents, the relevant pathways in the bow-tie model can be examined. None of the pathways in the greater model explicitly cover scaling, however two relate to the partial cause of scaling incidents: Rock Mass Characteristics and Discrete Geological features. The bow-tie pathway for Rock mass characteristics can be seen in Figure 7.21.

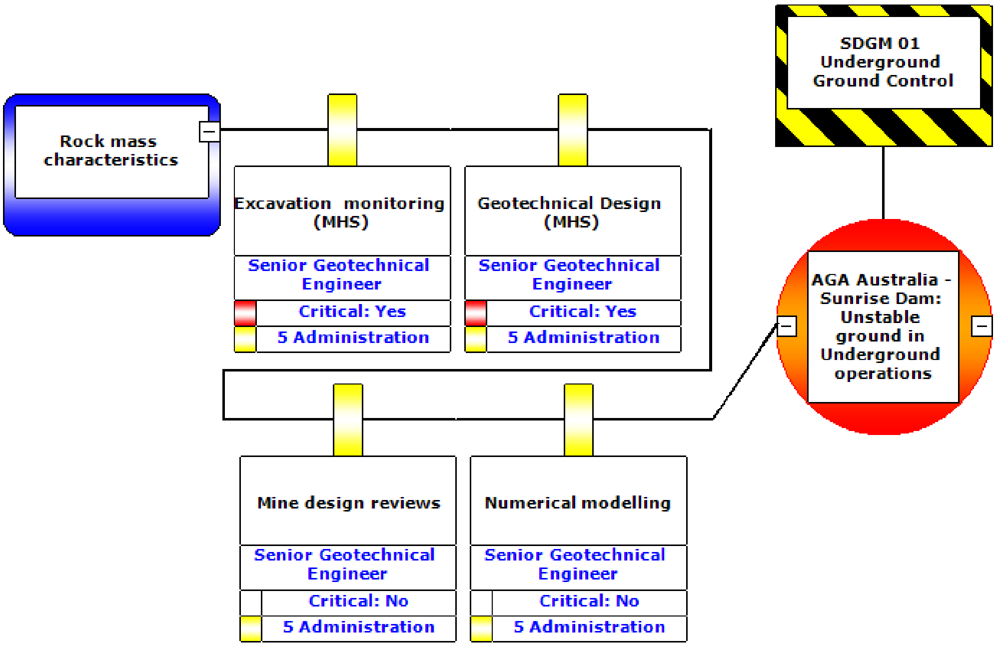


Figure 7.21: Bow-tie pathway for rock mass characteristics as a cause of ground control incidents

In the pathway of Figure 7.21 two critical controls are present. The first, which is called excavation monitoring, deals with holistic mine planning, having surveying systems online that monitor rock mass behaviour as new parts of the mine are opened. It deals with having people who perform surveillance being adequately trained. This is the category of employees that is involved in scaling elements: surveyors, geologists and development operators. In Figure 7.22, the bow-tie pathways for discreet geological features can be viewed.

While the bow-tie pathway in Figure 7.22 features structural interpretation as a control, it is not catego-

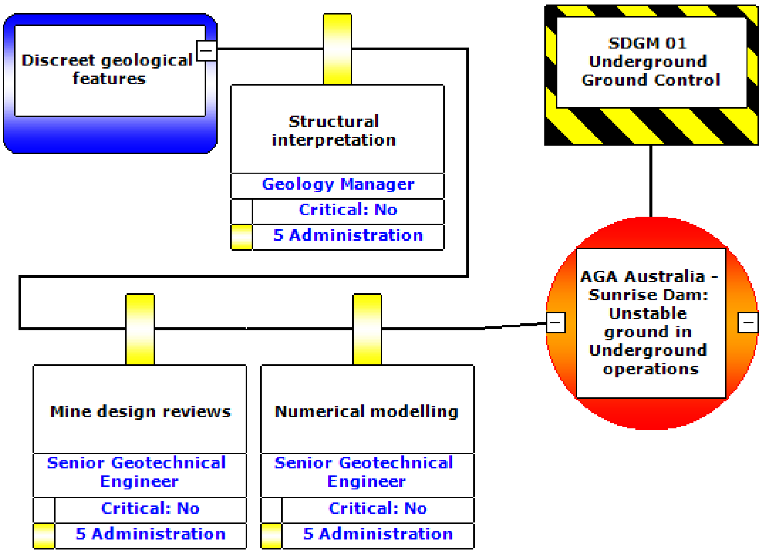


Figure 7.22: Bow-tie pathway for discrete geological features as a cause for ground control incidents

rized as a critical control. As such, no Performance Standards have yet been drawn up at a Group level to reflect the nature of this control.

Because the incident registration did often not specify details nor is it the goal to assign blame, no cause relationship was attributed to specific operators. One possible solution to eliminating these hazards is removing the need for operators to be physically at the face. If this is not a viable solution, re-training of personnel might help operators detect hazardous situations. While this is already specified in the Performance Standard related to the critical control "Excavation Monitoring", specification on scaling and other surveying procedures might clarify what training has to be given. The high rate of injuries and hits could suggest that operators find it difficult to disseminate what is standard scaling procedure and what constitutes an incident. Agreeing to report incidents when in doubt might facilitate a more detailed look into why scaling takes up such a significant portion of ground control incidents.

Should the verfication questions within the critical control Excavation Monitoring also contain an assessement of training programmes on scaling proficiency, this incident category could be monitored. However, that is currently not the case and could be something that would add value to a next iteration of control monitoring.

7.3.4. Stope rilling

This paragraph is concerned with the phenomenon of stope rilling, which is the case of 15 out of 66 or 23% of ground controls incidents. Stope rilling is the phenomenon of a fall of ground within the confines of an active stope. As the ore body of SDGM is extracted in hard rock conditions, geotechnical properties of the surrounding rock allow for blasting of large open stopes. Dimensions often exceed 20 meters in every direction leaving a significant gap on which the overlying layers of rock press down. As the stresses on walls of a cavity underground face increasing pressure with increasing size, these cavities face much more than average pressure compared to the rest of the underground workings.

Combined with the fact that these stopes are not supported means that every so often, a part of the stope collapses. This does not imply there are negative consequences, if right precautions were taken beforehand. If no personnel was present at the time of rilling and it was limited to the confines of the stope in question, this event posed no threat to operational safety. The way this is solved in SDGM and many other underground mines globally is the use of remote Load-Haul-Dumpers (LHD's). These machines are operated by personnel sitting as far as is practical and the teleremote system is capable.

Limiting stope rilling to the cavity itself is achieved by the construction of a bund where the drift meets the stope. The only other procedure that has to be applied within the confines of the stope other than extracting the ore is measuring stope dimensions as a result of blasting. This is done through a cavity monitoring system (CMS) on a telescopic arm. An example of the use of a telescopic arm can be seen in Figure 7.23.

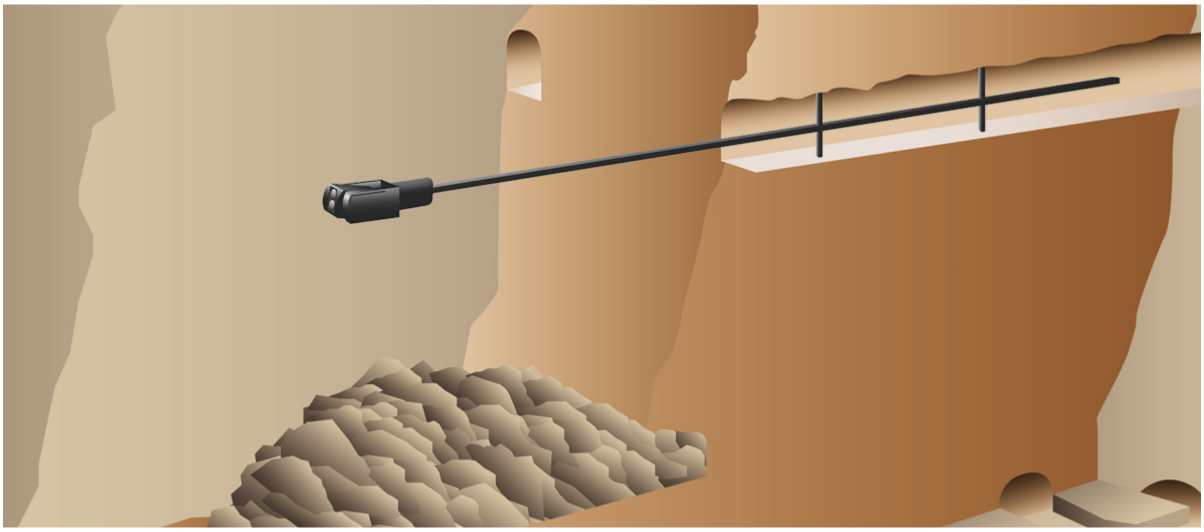


Figure 7.23: Cross-section of a telescopic boom for a Cavity Monitoring System

An operator can control from across the bund on the side of the drift. With regards to fall of ground incidents, this is one of the most hazardous tasks underground. Due to the close proximity to the stope confines, rocks might still impact operational safety when rolling over the bund.

In order to get a better understanding of stope rilling at SDGM, all incidents classified as such have been heat mapped in Figure 7.24. As only the relevant level is recorded in the incident reports, heat spots have been accumulated when occurring on the same level and year. Furthermore, heat spots have been drawn on the right level according to the expansion of mining areas per year.

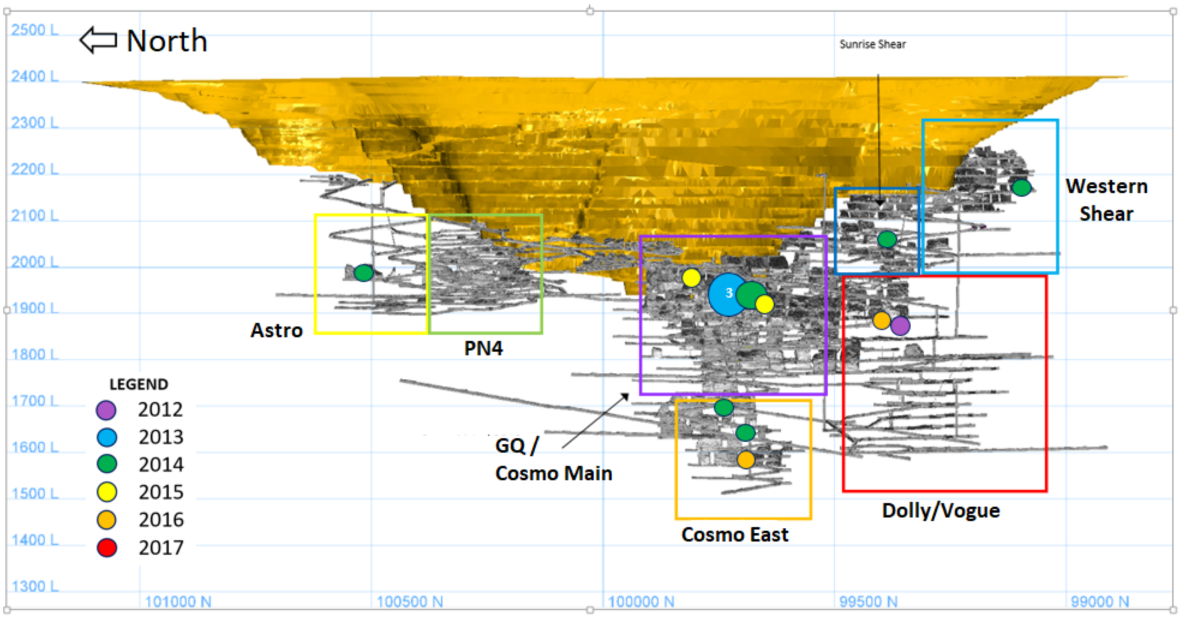


Figure 7.24: Heatmap of stope rilling incidents across case study time-frame

The area impacted most during 2013 through 2015 are the GQ 1900-2000 levels. This area is where full underground production commenced in 2013, increasing tonnage after closure of open pit operations. The high frequency weakening towards 2016 having no 2017 incidents in 2017 might point to a more mature mine design process taking place over the years. While rock mass characteristics might play a role, another cause for these incidents that has been specified is Unsuitable mine design. In Figure 7.25, the pathway for unsuitable mine design in the greater bow-tie model can be viewed.

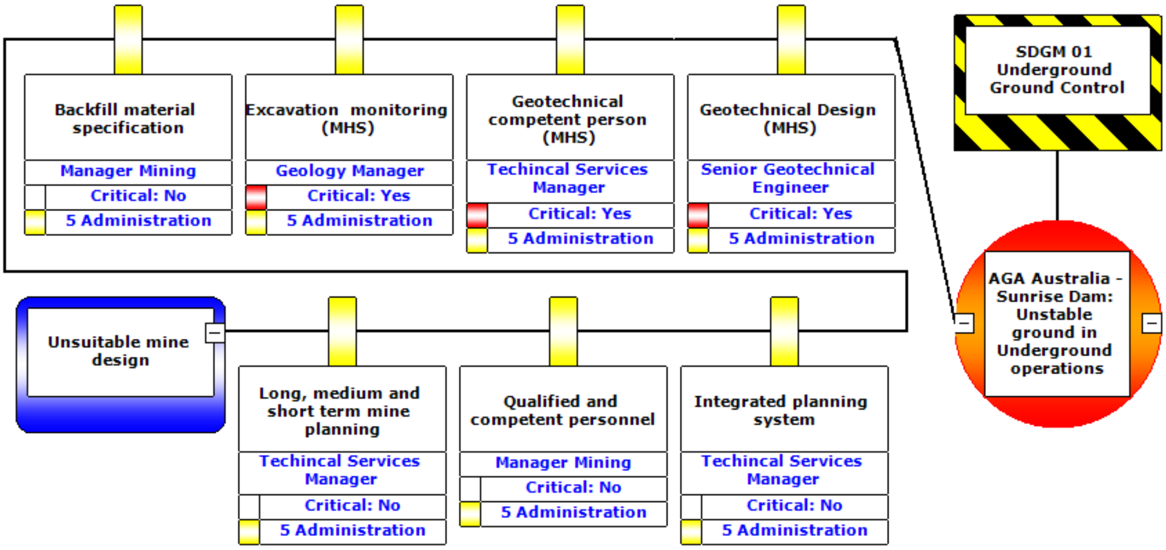


Figure 7.25: Pathway for Unsuitable mine design in the ground control bow-tie model

Similar critical controls as in the previous pathways can be viewed again: Excavation Monitoring, Geotechnical Design and Geotechnical Design. Apart from the critical controls noted in Figure 7.25, "Long, medium, and short term mine planning" is one of the controls that may have had significant impact since SDGM has turned to an entirely underground operation. Working in concert with sound geotechnical design, stope rilling incidents have decreased since monitoring these instances in 2012. However, a low probability of stope rilling could well have been included by design and/or mine planning. This could however not be verified during research into the subject while on-site.

If the critical control Remote Loading is fully functioning, stope rilling will not be an issue with regards to operational safety if operators do not enter the confines of stopes.

7.3.5. Unplanned Breakthroughs

Long hole drilling is an essential step of mining operations at SDGM. In order to create a free face needed for blasting, a so-called V30 hole drilled. This is the first step in extracting a new stope as it provides the blasted material room to expand to when the explosives are set off. In Figure 7.26, a diagram of this V30 hole or slot raise is presented.

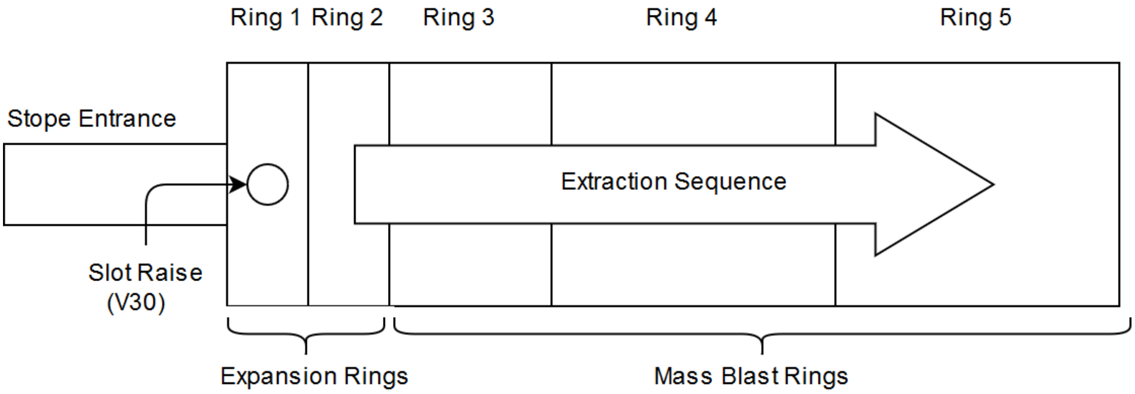


Figure 7.26: Top view of cross-section of a sublevel stope with a V30 slot raise

In the blasting sequence in Figure 7.26, after the longhole is drilled subsequently rings 1 and 2 are fired. After significant room is created within stope, mass blasts fire the majority of stope material. The slot raise is at least as high as the stope, often exceeding the requirements. Risk management wise, it is cheaper to drill slightly ahead than risk a misfire of the expansion rings. If that occurs, significant production delay could be incurred.

Drilling slightly ahead is not always without consequence however. If the drilling operator is not aware of an opening is present above the stope, an unplanned breakthrough can occur. This is what precipitated in ten incidents across the timeframe of the case study. Although procedural error is at the base of such a breakthrough, a pattern may be established using similar heat mapping like the previous ground control categories. The unplanned breakthrough incidents can be viewed in Figure 7.27.

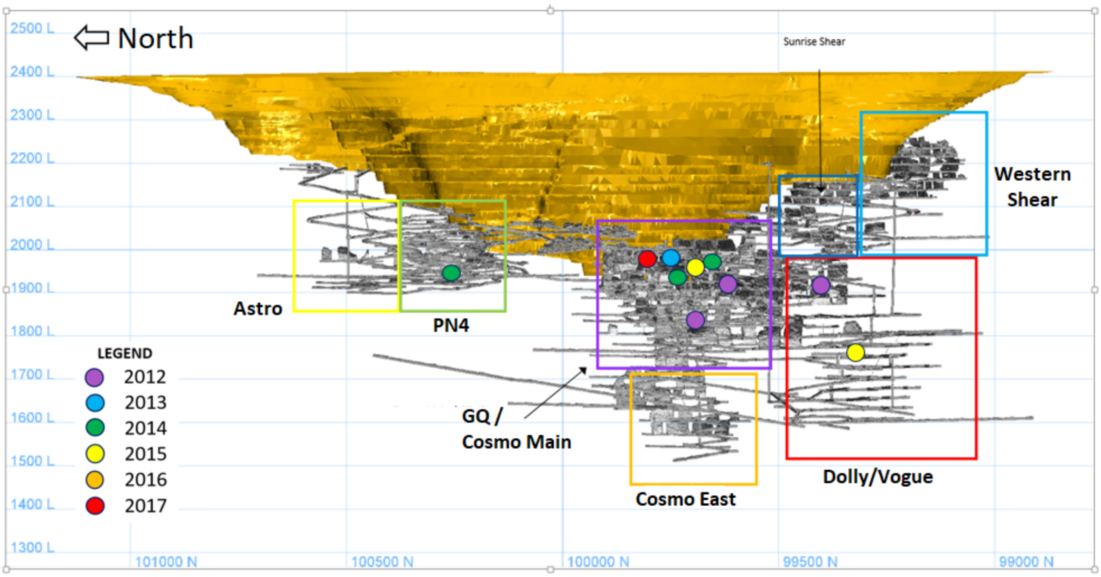


Figure 7.27: Heatmap of unplanned breakthrough incidents at SDGM categorized per year

What can be established from Figure 7.27 is that since 2015, only one incident in 2017 has occurred. Additionally, most incidents were precipitated in the GQ orebody, which was excavated early into full underground production and it is one of the most developed underground areas within the mine. Combining these factors could point to a relatively high pressure underground environment where drifts on intermediate levels might not have been indicated on drilling plans. This can be corroborated by the downward trend in breakthroughs, indicating a increasing level of maturity with regards to production processes.

Similar to the bow-tie pathway for unsuitable mine design in Figure 7.25, better collaboration between geotechnical design and mine planning could explain why unplanned breakthroughs are trending downwards. Another bow-tie model pathway of interest when dealing with breakthroughs is that of Excavation interaction, which can be seen in Figure 7.28.

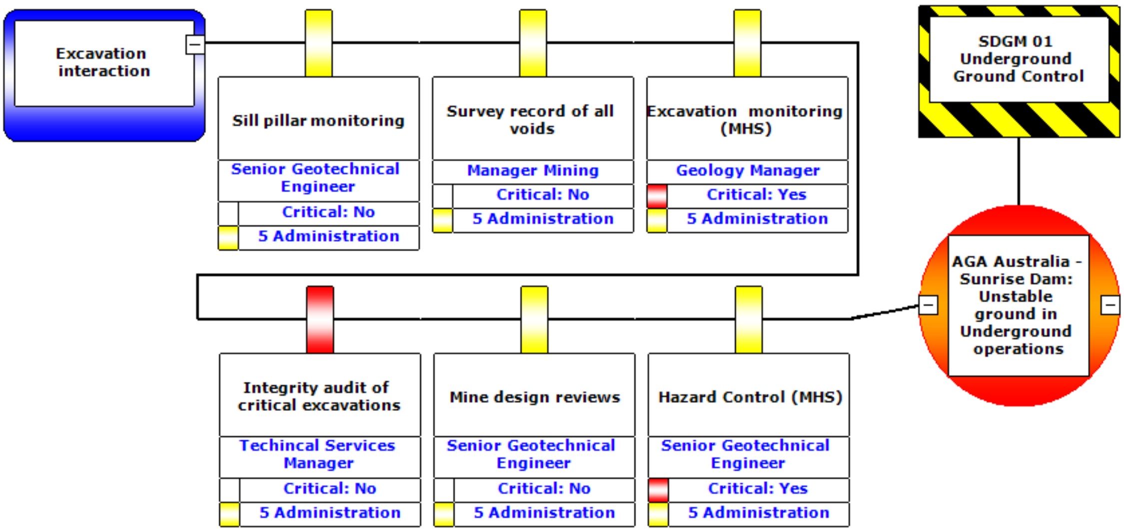


Figure 7.28: Bow-tie pathway for excavation interaction extracted from the greater ground control model

Apart from Excavation monitoring, another critical control in the pathway in Figure 7.28 is that of Hazard Control. This critical control focuses on the identification, demarcation and communication of geotechnical hazards. While it is not relevant to unplanned breakthroughs, this control might however be a more effective tool in preventing scaling incidents.

Although it is not a critical control, Review of Mine Design is the most important factor in the prevention of unplanned breakthroughs. In order to cover this discrepancy within critical controls, a verification step might be applied to Excavation monitoring. This step verifies acknowledgement of potential interaction between mining areas in mine planning. If correct design is implemented and an operator is aware he or she is not to drill past a denoted length, only operator conduct remains in the way of truly preventing unplanned breakthroughs.

7.3.6. Supporting Operations

In this paragraph, incidents during general supporting operations are considered. As can be seen in Figure 7.19, supporting operations incidents have known two years in which multiple incidents have occurred: 2014 and 2017. If the supporting operations incidents are examined more closely, seven out of eight incidents are clustered around a similar part of the orebody. The area in which these incidents are clustered can be seen in Figure 7.29.

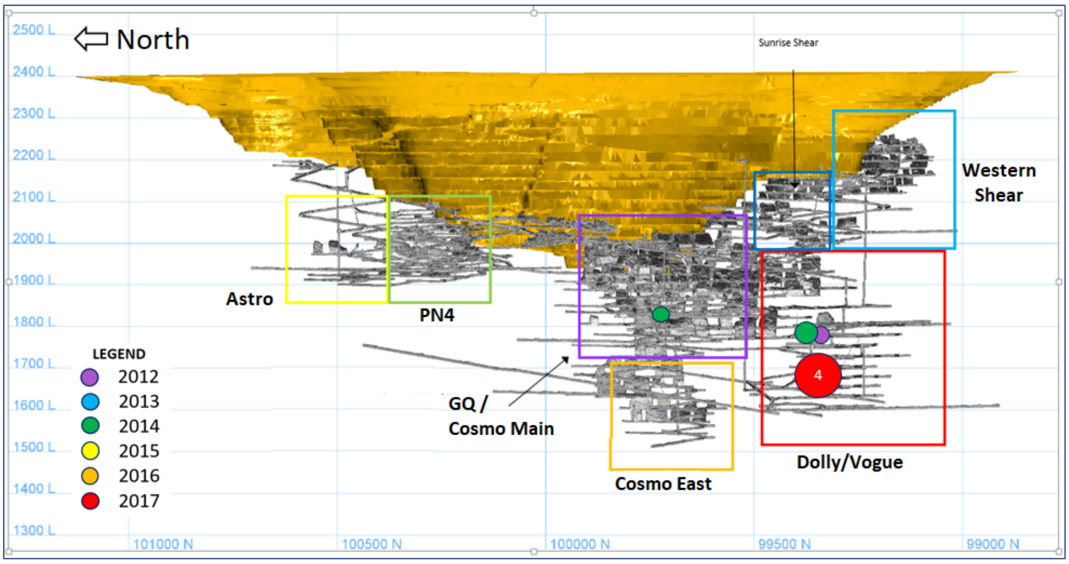


Figure 7.29: Heatmap of supporting operations incidents across case study time-frame

The slightly larger green ball in the Dolly/Vogue orebody represents two separate instances. The clustering of 4 incidents in 2017 represent four similar instances in which ground conditions precipitated a rock fall during remote supporting operations. Ground conditions can differ significantly across an orebody, which is not unlikely in Sunrise Dam as slocal features demonstrate strong structural variation over short distances (Hill et al., 2014). As a new part of the orebody get developed, these changing conditions affect the way in which supporting operations can conduct their work. If the blasted area remains the same while conditions get worse, the integrity of ground that needs support will decrease.

The pattern established at SDGM gives a similar impression with regards to these changing conditions. Unfortunately, assessment of geotechnical data could not be included in the scope of research. In the bow-tie model for ground control, a pathway is explicitly made for development of new mining areas: drill & blast practices. In Figure 7.30, this pathway can be viewed.

What is noticeable about the pathway on drill and blast practices is that no critical controls are present. In the pathway two controls apply to the aforementioned supporting incidents: blasting practices and face preparation standards. As several incidents have occurred after the face was already scaled, better face preparation might help resolve such instances. Effectively, this is the boundary on what is, and what is not a critical control. Looking at the potential for MUE's, incidents in the currently discussed category have not had any potential for severe injury let alone fatalities. As such it can be concluded that using remote machinery and extended booms is enough to maintain operational safety.

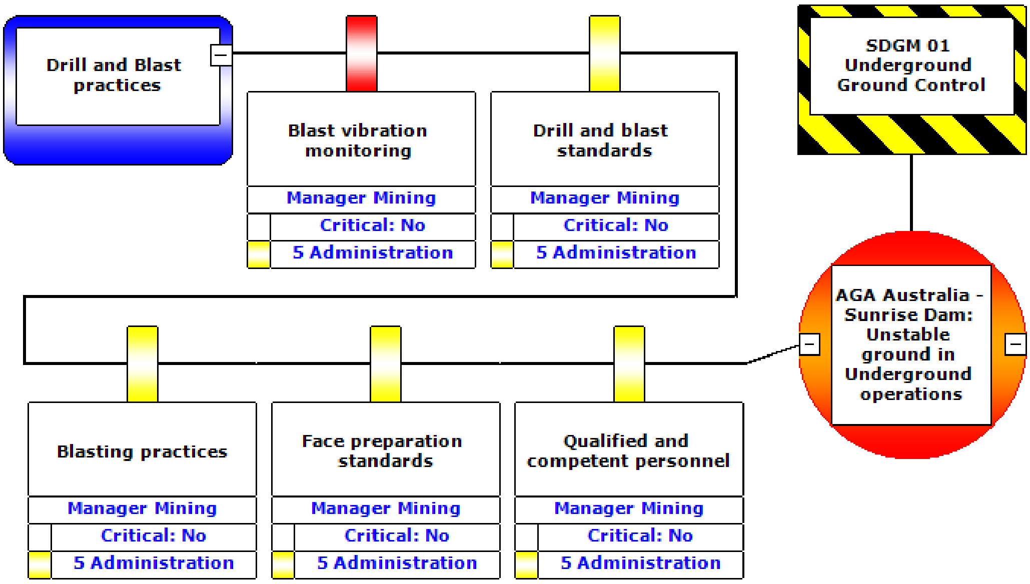


Figure 7.30: Bow-tie pathway for drill and blast techniques extracted from greater ground control model

7.3.7. Application of Shotcrete

The application of shotcrete and its subsequent integrity forms one of two lines of defence against fall out in non-stope areas of the mine together with roof and wall bolting. In Figure 7.19, it was demonstrated that incidents involving a loss of integrity with shotcrete have decreased from 5 a year in 2012 to 2 from the beginning of 2016 until half of 2017. Yet, categorizing incidents only on the involvement of shotcrete is merely pinpointing a symptom of several underlying issues. If the incidents are more closely examined, several contributing factors come to light. These factors are:

- Deterioration of shotcrete over time 5
- Poor quality shotcrete applied 3
- Impact due to nearby blasting 3
- Insufficient shotcrete applied 2

One or more contributing factors might be at play in any given incident, and study have shown shotcrete decays over time (Usman and Galler, 2013). Blasting as a contributing factor thus helps accelerate the decay of shotcrete integrity. Furthermore, a study by Mittermayr et al. (2012) on concrete liners of Austrian tunnels points to chemical reactions in a saline environment with sulphates present in the surrounding rock. Similar to the environment in the study by Mittermayr et al. (2012), the SDGM orebody features a porphyry vein system surrounded by alteration haloes dominated by various combinations of pyrite, dolomitic to ankeritic carbonates and quartz (Hill et al. 2013). Furthermore, the alteration is not symmetrically distributed around veins, and may be absent. Changing geotechnical properties of the rock could therefore be a source of shotcrete deterioration.

If these conditions are related to the bow-tie model for ground control, the most relevant pathway within the ground control model points to less than adequate ground support. It may have been adequate directly after application, but time-based deterioration and other outside factors have reduced its effectiveness. The pathway from less than adequate support can be seen in Figure 7.31.

The most extensive of the pathways in the ground control model, the pathway from less than adequate support to the top event, features ten controls. Two of those are designated as critical, the previously discussed Hazard Control and Ground Support Systems. When taking a closer look at the Performance Standard critical control ground support systems, it focuses mostly on preventing personnel from working under unsupported ground. With validation questions on signage and barricading, support work procedures and scheduled visual inspections, a wide range of topics is covered.

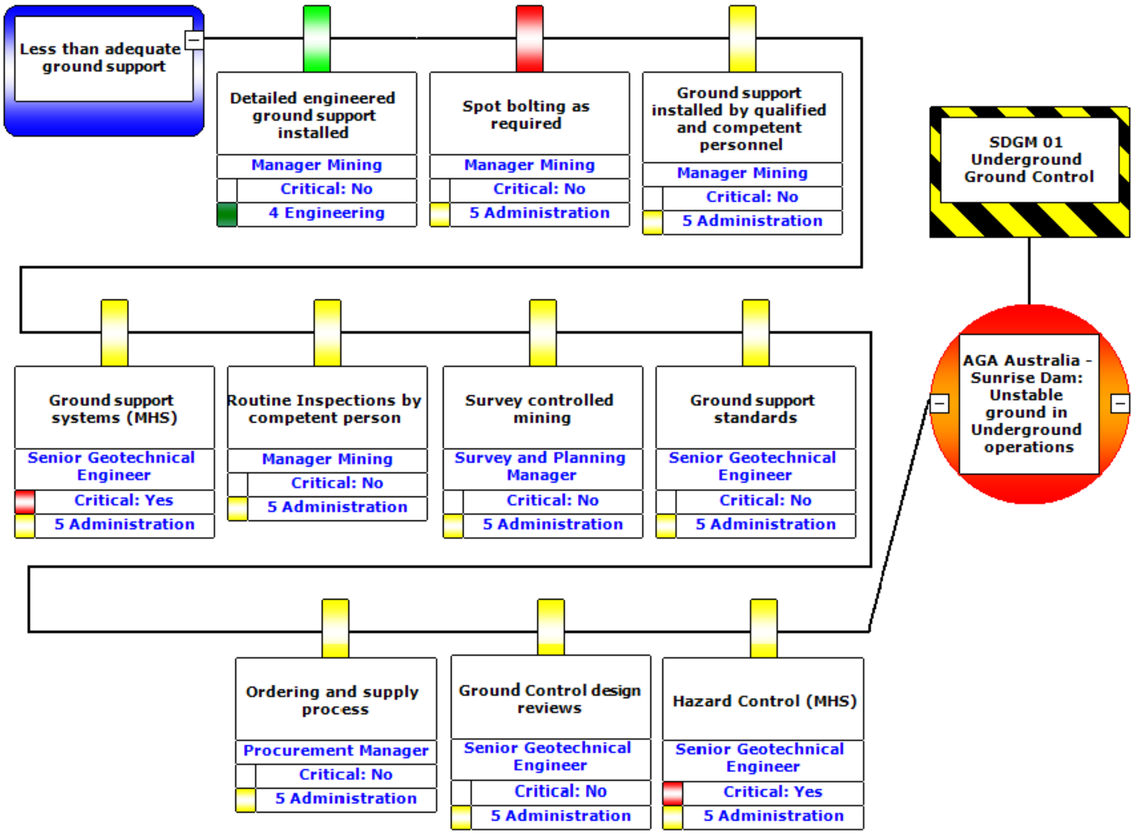


Figure 7.31: Bow-tie pathway with controls mitigating less than adequate ground support.

While inspection alludes to the issue, what is really missing from this pathway is maintenance of ground control, when needed. An inspection will not prevent ground support from failing, it is actually monitoring, repairing and maintaining support that provides mitigation. Short of an extensive maintenance programme, inspections ought to be conducted in older sections of the mine, especially if nearby blasting has the potential to accelerate support deterioration.

7.3.8. Other Incident Categories

The last three categories within ground control incidents at SDGM are Operator procedure, Impact through Blasting and Build-up of salt. Although these are minor categories, some conclusions can be drawn on incident prevention, especially with regards to operator procedures.

7.3.8.1. Impact Through Blasting

Interaction between open areas and blasting is a issue in mining when done in close proximity to other sections of the mine (Xia et al., 2013). As shotcrete deteriorates over time, blasting can accelerate the formation of cracks or continuous damage across the shotcrete. This can then subsequently lead to loss of adhesion and finally loss of support for the surrounding rock.

Closely related to the category dealing with the application of shotcrete, impact through blasting is something that can be checked fairly easily after explosives have been set off and the mine has been ventilated. In areas where shotcrete had been applied over five years before and nearby blasting takes place, extra geotechnical inspections might be prudent to verify continued integrity of ground support present.

Using the controls asserted in the pathway of drill & blast practices in Figure 7.30, the controls of vibration monitoring and blasting practices might be applicable to preventing accelerated deterioration of support. Like the category of shotcreting application, maintenance and inspection of shotcrete possibly impacted by nearby blasting could be the most effective way to mitigate impact through blasting.

7.3.8.2. Build Up of Salt

Because mining at SDGM is done in a hyper-saline environment, any flow of water contains suspended salt particles. When water trickles down the open pit works, salt is deposited along the benches of the open pit, as well as along openings within the pit walls. This leads to the last category of ground control incidents: an excessive build-up of salt. A problem arises when this build-up becomes unstable over a used mining portals. In three cases, sizeable salt blocks have come down.

In the first two cases, the blocks landed close to where an operator was standing moments before. In the last instance, the rock was caught by meshing suspended across the mining portal. Being a reactive control, it performed when depended on. In order to prevent salt build-up from causing incidents, hydro-scaling could be used periodically to remove any excess salt from active areas within the open pit.

As the open pit areas are not actively mined anymore, any sudden impacts to the pit wall can mostly be attributed to underground activity. While pit wall integrity is featured in the bow-tie model for ground control, it does not address the issue with salt build-up: it occurs steadily over time until a piece breaks off. Like deterioration of support elements underground, the build up occurs gradually and is measurable. Having netting in place might prevent incidents from damaging equipment or causing injuries, yet the only way to prevent these incidents is through proper maintenance and scaling of the pit wall above mining portals.

7.3.8.3. Operator Procedure

All three cases in the category of operator procedure concern entry into unsupported ground. In one case, this was due to the fact the person involved was not familiar with the supporting process at SDGM, causing this person to mistake a face with shotcrete yet without bolts for a fully supported entry. The second case concerned an operator moving his shotcreting jumbo under unsupported ground but not himself. In the last instance, an operator worked too close to the face, which caused stope rilling to hit the operator in question.

Within the mine, significant awareness is spread on never going into unsupported ground. None of the incidents mentioned seem to have precipitated out of malice. Rather, unfamiliarity with proper distancing rules might have been the underlying factor in causing an operator to mistake what is considered safe, and what is not. Access through non-supported areas is classified as a pathway in the ground control bow-tie model, which can be seen in Figure 7.32.

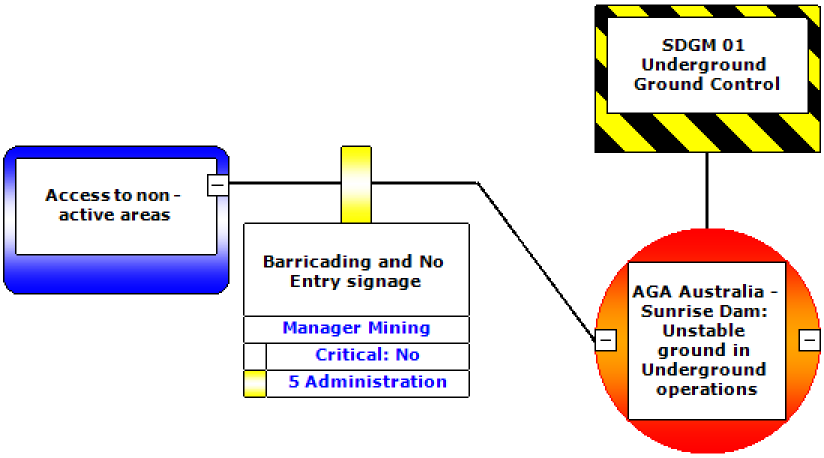


Figure 7.32: Bow-tie pathway for access to non-supported areas out of the ground control model

Although the application of barricading and signage prevents people unfamiliar with the current state of affairs in the mine, it does nothing to prevent the three incidents discussed above from happening. These are better mitigated by the critical control Ground Support Systems discussed in Paragraph 7.3.7. What might be difficult for planners is acknowledging that access to non-supported areas rarely happens in a static environment. That is to say, no activity is currently taking place in a dead end of the mine and someone crosses into unsupported ground in such a location. Rather, moving under unsupported ground takes place when during development, or moving that extra meter to help spot something for a jumbo operator. Taking this dynamic factor into account means that ground support procedures need to be clear for everyone entering active mining areas.

7.3.9. Bow-tie modeled causes and critical controls

An overview of all incidents related to ground control has been given, and underlying patterns have been established in some cases. All of those listed have been discussed throughout the incident categories but for Seismicity. Most of the causes described in the bow-tie model capture ground control incidents at SDGM to a considerable degree. In the case of scaling as an injury category, the causes identified are applicable however the controls in the model do not reflect the nature of scaling activities.

7.4. Summary of Outcomes

Both case studies demonstrate the use of incident data in critical control management. When the aggregated risk score was measured over a prolonged period, relative significance of all Major Hazard Standards within the mine can be established. This can help operations prioritize which controls need attention or even overhaul. As such, it can be used as a lagging indicator for critical control performance. The case studies also demonstrated that if critical controls are monitored, a considerable amount of risk can be reduced with regards to Material Unwanted Events. Although failures of specific critical controls could not implemented into incident registration within scope of this research, the possibility to do so is there. It should be noted that this can only be implemented effectively if incident registration is conducted or verified by an employee knowledgeable about relevant critical controls on-site.

7.4.1. Case 1: Underground Fire

In the first case study, the effectiveness of AFFF as a critical control was measured against the rate of underground fire incidents at SDGM. Applying a 5.5 year period, a moving average risk score was created to reflect the relative significance of fire incidents during 6 month periods with a one-month interval. A steady decline from 2012 to 2015 with a slow rise until 2017 was at first partly attributed to a fleet change-out. Although the decline could be related to change-out, upon closer examination the rise in fire incidents was due to an increasing amount of Light Vehicle (LV) fires. Not only were LV's the major cause of fire incidents since 2015, the nature of LV fires was also a majority of electrical fires.

While the AFFF did help reduce risk in terms of fire on most of the truck fires, the increasing amount of electrical fires reduce its effectiveness as it is not rated to fight those fires. Because the critical control produces an aqueous film forming foam, its effectiveness is reduced as it conducts electricity. This is particularly the case in the underground environment of SDGM, which is hyper-saline.

The conclusion of the first case study is that through the reactive nature of the observed control, its effectiveness can change over time without outside influence on the control itself. However, a reduction of risk of 25% was generated out of AFFF alone. As such, ensuring the control performance when needed supports the prevention of a significant amount of risk exposure, especially when the source of fire is a flammable liquid or solid.

7.4.2. Case 2: Underground Ground Control

Instead of the reactive side of the bow-tie model, the second case study focused on looking at incident cause and proactive prevention. Within SDGM, 8 incident categories were identified. For each of these the validity of the bow-tie model for ground control issues was verified. While none of the causes specified in the model exactly denote the incident cause, controls were assessed to be adequate. For some critical controls, additional verification steps were identified in order to mitigate incident borne out of a lack of understanding such as scaling incidents.

However, the critical control most effective within the studied domain at SDGM was that of remote loading. If this form of extraction is applied exclusively, incidents involving personnel are minimized. The questions that verify the performance of this control are of the same nature as all other controls and can thus be routed through the Critical Control Management System. This demonstrates both the scalability and potential effectiveness of the system.

8

Discussion

8.1. System Design

No validation has been carried out to assess if the Critical Control Management System is the most efficient way of of monitoring control performance and supporting stakeholders in safety decision-making. Although all but one of the critical control data gathering processes can be routed through the bow-tie environment, this could potentially generate issues in the future. If stakeholders have to take extra data entry steps with no clear added value, they might lose faith in the overarching system. The bow-tie environment allows for uncomplicated identification of hazards and controls through its excellent visualization properties. However, the environment currently supports leveraging of critical control data generation in a minimal way. Additionally, analytics have not yet been introduced in that particular software package. To develop a working Critical Control Management System within the scope of research, analytics were run through a data warehouse and OLAP to give stakeholders relevant dashboards for performance review. Furthermore, the bow-tie environment can currently not be adjusted to have questions appear multiple times in a single audit.

In a way, these problems stem from the fact that AngloGold Ashanti is pushing beyond what is expected or required and set the standard instead of following it. When dealing with software development, standardized or not, this may cause problems as going beyond what is standard means redefining systems and therefore the underlying software. Instead of following market products, AngloGold Ashanti could choose to develop an own system with an external party suited directly to its operations. Such a system can utilize a similar approach to Planned Maintenance (PM), that sends requests for audits or maintenance to relevant personnel, and aggregates data based on reaction time, items fixed and close-out time. Because the data in the Performance Standards is a series of closed questions, a binary approach could be applied for data acquisition, simplifying codification of such a system.

This removes the need for reporting every single control based on their inclusion in an inspection. Instead, a form is generated for the relevant employee in which the control questions are pre-coded. If an action request related to a critical control is put in the system, this get denoted as a binary non-compliance in output to the BI environment. As a result the data entry step at the end of workplace inspections is eliminated too. The basis for this project is around using forms that are already sent out daily to fulfil such things as maintenance requests to also include closed questions for critical control integration. It also provides other opportunities such as use of maintenance data, which is described in Section 8.2. Blending automation, BI and resource planning is discussed extensively in literature, as well as doing so in a sustainable manner (Chofreh et al., 2017, Nofal and Yusof, 2013, Sganzerla et al., 2016). Through generating data in such an integrated system, the entire bow-tie environment can be taken out of the equation. Instead, it is used for what it is best used: easy to use visualization of bow-tie models.

Although this systems design will essentially streamline entire critical control management in one system, significant organizational change will be required to allow it to function effectively. In order to create more support for critical control management, a more grass-roots approach as demonstrated in this project can be utilized. As such it is a less-impactful, useful intermediary step to "full" critical control management. Taking the lessons learned through the design, implementation and application of the system developed in this research and using these in other operations will generate the foundation for definitive Critical Control Management at AngloGold Ashanti.

8.2. Expanding Critical Control Management

One of the outcomes of integrating workplace inspections was the fact that complex technical questions were not applicable to that process. In order to get full understanding of the performance of critical controls, maintenance strategy and subsequently generated data could added to give a broader perspective on critical control performance. At AngloGold Ashanti, this is generated through a process called Planned Maintenance (PM), as stated in the previous paragraph. It should be noted however that maintenance data does not cover all critical controls nor all their aspects. This is due to their varying nature: some controls can also be a series of acts, a system or design philosophy which do not adhere to physical maintenance. It can however use technical expertise to ascertain the condition of physical critical controls.

Using the data generated with PM, an accurate picture of critical controls that have technical aspects, such as pressure release valves or storage tanks with hazardous materials can be drawn up. A second benefit of the use of this data is the fact that planned and unplanned work is taken into account. Although uncorroborated by scientific literature, company officials at AGA pointed to this source as potentially much more hazardous for individual performing the task. This is because it is often a rush job, at the end of shift or non-routine work which makes it extra hazardous for the operator.

While incident data can now be integrated on a low level through the addition of relevant Major Hazard Standards to incidents, another data source that could provide significant value is that of incident close-out actions. Instead of treating incidents solely like a lagging indicator, follow-up on reports can be used to indicate at what level the learning organization is operating.

Another use of data on safety incidents could revolve around hot-spotting of high-hazard areas. Already demonstrated in the case studies in Chapter 7, creating a heat-map for similar instances could help establish underlying patterns in incidents. These could be utilized to support decision-making around improving certain areas of plant or underground workings categorized as more hazardous. The potential for this to be used in mining is extensive as ground conditions change through a multitude of factors: distinct geological features, depth, water table and geotechnical properties of the rock.

8.3. Operator Awareness

In Section 6.3 the consideration of operator awareness was discussed. While workplace inspections is valued highly on all other performance indicators, awareness remained lacking. This is in part due to the fact that processes within the current Critical Control Management System focus on assessing the status of controls in place. For a majority of higher order controls this is the only audit required to make sure they are working. A solid steel cage does not rely on operator behaviour to keep personnel safe, it does so by its ongoing integrity.

For the majority of lower order critical controls, this is not the case however. Being administrative, they rely at least in some part on operator behaviour. The perception that operators have of critical controls thus influences their actions, especially in high-stress, demanding working environments. When looking at the data made public by Rio Tinto with regards to their approach to Critical Risk Management, it seems a very comprehensive approach was taken (Rio Tinto, 2017). While generating significant awareness, the changes made to existing processes might bring about negative effects that diminish the overall effectiveness of such a system. Change to production processes often carries risk with itself, and should be controlled through Management-of-Change (MoC) processes (Gerbec, 2017). It also represents a return to the comprehensive framework of applications applied in traditional safety management approaches as noted by Makin and Winder (2008) in Section 1.1. When dealing with a plurality of operations, stakeholders and cultures, these can have significant impact on the end result of such an implementation. A grassroots approach might therefore be more suitable, at the expense of direct impact on the organization.

One way to solve this issue is already being pursued by SDGM in the form of Safety Observations. This process functions as a peer-to-peer review for operators on the ground and helps assess jobs on use of critical controls. When looking at the processes discussed in Section 6.3, potential for slight integration into all of the processes was found. Although in many cases no results may be monitored, performing that integration within all processes could generate significant operator awareness at little cost for disrupting the business.

Central around such an approach should be branding of Critical Control Management. At Rio Tinto, it is called "Critical Risk Management" (Rio Tinto, 2017). At Glencore, it is called "Catastrophic Hazard Management (Glencore, 2016). Generating operator awareness could be done merely through low-impact integration of marking critical controls within the aforementioned processes.

8.4. Tailoring of Business Intelligence

While an adaptable, functional dashboard has been created for stakeholders, more features can still be included to expand leveraging of data generated. In this section two methods to this end are discussed: using maintenance actions and close-out times to identify vulnerabilities in the operation, and developing an overall measure for the performance of an operation with regards to sustainable development.

8.4.1. Maintenance

In addition to the notions set forth in Section 6.7, several other measures could be developed to help leaders business-wide understand their own processes better. The immediate target for integration here is that of maintenance strategy and behaviour. It should be noted that at this stage the BI environment transcends safety and moves into the technical domain of different maintenance strategies. Especially when performing preventative maintenance or Condition Based Maintenance (CBM), an organization can benefit from data-driven processes supporting (high-level) decision making (Cerrada et al., 2018).

8.4.2. Performance in Terms of Sustainability

One of the main goals of the other sustainability disciplines within AngloGold Ashanti is integration into Critical Control management. This opens up another avenue of sustainable production, as BI can be utilized to deliver a real-time sustainability performance index for all included operations. Not only could such a measure indicate performance, it also provides a broad risk profile of the operations and their most pressing concerns. It supports decision-making as it can link previously unseen trends in all disciplines, as demonstrated in Chapter 7, Case Studies.

While integration of Health, Environment, Security and Community are projects onto themselves, the infrastructure for Critical Control Management is already laid down. As discussed in Paragraph 5.1.2, once the data is being generated into the bow-tie environment, it can immediately be adopted for further use. This can help sustainability leaders establish priorities, especially when vying to gain and or maintain the social license to operate.

8.5. Implementation

The first step to take for other operations is implementation of the quarterly, supervisor process on site. As discussed in Section 6.8, it covers a little over 40% of all required company wide Performance Standard validation questions. It has can be measured within a reasonable timeframe after implementation and gives supervisors, who are the conduit between managers and operators, the knowledge and tools to identify and maintain critical controls. Because this process is more abstract than the exact situation on the shop floor, it requires little tailoring in order to suit it to other operations.

For successful implementation to take place, buy-in is required from senior managers on-site. This layer in the organization does not necessarily particate in verification of controls, but is accountable for their performance and their ownership. It is the responsibility of safety personnel on the operational level and especially the corporate level to convince managers of its use. The lessons learned at SDGM could function as a useful platform to establish this. In doing so, one should remain aware of cultural differences across sites as well as continents when duplicating critical control management.

After awareness is created in line management through the supervisor and subsequently manager level questions, workplace inspections can be tailored to the operational level to start monitoring critical controls on a more frequent basis. Any process like safety observations should be considered above and beyond the standard. Implementing such a system should remain last priority. However, integration of critical control branding into operator processes can be run simultaneously, again pointing to the need for an overall corporate managed strategy that focuses on visibility and awareness.

8.6. Predictive Risk

Being able to predict risk is of the goals set out by AngloGold Ashanti for critical control management. However making any useful prediction with regards to the hazards faced in a mine requires many factors to be taken into account. The division between planned and unplanned work is but one of the possibilities for expanding the current system to gain more control over operational safety. Other data that could possibly be used to predict risk exposure in a mine is for example:

- Operator Demographics
- Operator Experience and Education
- Prevailing weather data
- Production data
- Maintenance Scheduling

Combining the factors above could lead to the identification of more-than-average likely tasks resulting in injuries. If an inexperience operator has to perform unplanned maintenance at the end of shift, the likelihood for an injury can be estimated based on previous, similar cases found within the data. As found in Reason's Swiss Cheese Model, it is often a combination of such factors that allow an operator to be put into a situation where the probability of making a mistake is significantly higher. Another example of this could be an inexperienced hauling truck driver that has to make up for decreasing production figures by rushing his task.

Faced with inclement weather, end of shift time and a lack of experience with affected roadways, it is not unlikely for such a situation to translate into a Material Unwanted Event. Combining the data sources mentioned above is not unfeasible using current technology. This could for instance be achieved through methods described by Aidman et al. (2015) combined with hot-spot mapping as described in Section 8.2. Together such an approach could present the next step in building resilient systems for organizations where high reliability is required. Ultimately however, removing employees from the hazards is what will truly prevent fatalities. Companies are already implementing remote hauling trucks, as discussed extensively by Parreira (2013). That may not solve all high-hazard issues, but it will remove some.

8.7. Results and Benefits of Agile Approach

After the framework for design of the CCMS had been set up during the literature study, the scope changed when interviewing the aforementioned officials. At that stage, preliminary plans for the addition of a new process were already in motion. By being able to quickly re-adjust deliverables through Agile, all stages of the project were still finished on time and to the approval of stakeholders.

Another potential issue that was avoided through the use of Agile was invalid verification of critical controls. During systems design, neither the questions to validate critical controls had been set-up nor had the frequency of these assessments been determined. Through re-scoping the project by adding in Performance Standard impmlementation on-site, the verification questions had already been developed for further use during this study. Subsequently, the nature of these questions was assessed to determine their applicable frequency, to the approval of stakeholders at SDGM and elsewhere in the company.

Finally, re-scoping of system validation had to be carried out as the operational processes could not be implemented before departure back to the Netherlands. Due to the very limited amount of data gathered, two other case studies were developed instead. Although these did not measure critical controls directly, a wider time frame was covered with a more representative data set. Additionally, incident data was demonstrated to have significant potential as a lagging indicator for critical control performance.

9

Conclusions

The purpose of this research was to support decision-making on operational safety through management of critical controls with the creation of an simple, robust, and scalable system. The main research question focused on identifying in what way such a system could be successfully implemented in an AngloGold Ashanti operation, while remaining scalable to other operations. A system was designed that allows the integration of multiple data acquisition processes for critical control monitoring. Patterns in the data generated are made comprehensible in a Business Intelligence (BI) environment for support of stakeholder decision-making. One of the data acquisition processes feeding into the management system was created through non-invasive process optimization to assess critical control performance at the operational level. Case studies on underground fire and ground control demonstrate the viability for integration of incident data into the larger system. Together, critical control management was demonstrated to support decision-making on operational safety at every level in the company hierarchy.

An extensive assessment of the entire organizational hierarchy was conducted to identify company-wide requirements for critical controls. By interviewing a range of employees from senior management officials to process plant operators as described in Chapter 4, a comprehensive view was gathered on the organizational requirements for successful adaptation by stakeholders in the company. As a secondary objective the interviews were utilized to re-familiarize company personnel with critical control thinking and gain broad-based support for implementation. Main outcomes of the requirements centred on keeping the system simple ("KISS"), weaving critical controls into the business, observing cultural differences, assuring data integrity and minimizing impact on business. By adhering to these requirements, key elements for successful implementation were both identified and applied, thus answering the first research sub-question.

A design for Critical Control Management System was developed that considers multiple critical control monitoring processes. Combining elements of safety science, risk management and IT, a modular platform was created that allows integration of multiple different sources for data analytics. It considers the inclusion of data feeds that were out-of-scope such as maintenance and production data. The system is able to extract data in real time, potentially enabling decision-making during work shifts. The design adheres to the organizational requirements set forth and can be scaled to other AngloGold Ashanti operations. Combining these two elements means solving the issue posed by the second research sub-question as to how scalability can be included into systems design.

Integration of critical controls was carried out to demonstrate their inclusion into operator processes. Before integration, a strategy was developed in order to minimize interruption to business and maximize operational support. In order to aid further implementation, adoption of unpublished company Performance Standards was carried out. Because the addition of a new process was considered deviation of scope, all operator processes were assessed on their potential suitability for critical control integration. The process of monthly workplace inspections was selected and mapped to prepare it for data acquisition. A solution was formulated that uses an intermediary data entry step to reduce licensing cost and provide opportunity for assessment of data integrity. The workplace inspections were assessed for potential inclusion of critical control validation elements, which was subsequently carried out. After integration of critical control elements, process optimization was carried out through removal and adjustment of all other inspection items. This resulted in an overall reduction of workload and thus widespread operational support. Through assessment of operator processes for suitability to critical control integration, no single process was identified. Instead, the criteria for integration of critical controls into operational processes was defined. This provided company stakeholders with a tool to identify what use is desired out of integration, and to select an operational process accordingly. As such, the third research sub-question is answered.

Through assessment of two case studies on underground fire and ground control, the bow-tie models of these hazards has been validated. The case study on underground fire is built around a single, reactive critical control and shows that the cost-effectiveness of such a control changes over time without influence on the system itself. This demonstrates inherent vulnerability of reactive mitigation in a high-pressure, dynamic environment such as an underground mine. The second case study assesses ground control as a hazard and the potential sources that could lead to a loss of control event. Using incident categories generated out of a five year time span, dominant pathways to loss of control events are validated. Controls on these pathways are generally correct but miss a human component, both in incident causation as well as prevention. The same is true for the case study on underground fire. The fourth research sub-question posed the issue of measuring critical control performance. As both case studies demonstrate, small changes can be made to include incident data into critical control management to increase effectiveness of the system.

With the results generated during this study, the research questions listed in the Introduction could be answered. The main research question was:

How can an effective Critical Control Management System be implemented in AngloGold Ashanti operations to mitigate fatal incidents?

Through the steps taken in this study, an effective Critical Control Management System was implemented in an AngloGold Ashanti operation. This was accomplished by using a flexible method for development of the system, while ensuring output was tailored to the organization in a least-invasive manner.

10

Recommendations

Develop BI suite
The dashboards available for stakeholders are currently still in development. To tailor these dashboards requires sole input of a business intelligence developer or person versed in the OLAP environment of PowerBI. In order to streamline development of these dashboards, corporate requirements should be developed first. When these are available, data presentation needs be adapted to support stakeholder reporting, insight and decision-making.

Start branding of critical controls
Improving the visibility of critical controls organization-wide needs to be a priority for the global safety team. Non-invasive techniques to generate awareness will work best and require integration into current processes. Many operator level procedures have the potential for adapting critical controls and will generate awareness amongst front-line personnel. Criteria for selection should be based on pro-active, institutionalized processes like JHA's.

Integrate incident data
Viability for the inclusion of incident data in critical control management has been demonstrated. Adoption of data into the system requires simple management-of-change processes. Assuring data integrity should be based on developing the understanding of safety personnel as these assess both Major Hazard Standards and controls. Comprehension should focus on hazards first and controls second.

Prepare other operations
Implementation of critical control management at SDGM rested on the adaptive capacities of an experienced safety department with good understanding. Other operations will likely neither have the adaptive capacity nor the required level of understanding. Additionally, line management is ultimately accountable for critical controls and their drive in the operation, while the safety department merely facilitates this process. Implementation should therefore not be left to the operations themselves. Before additional capacity is made available, the general manager and safety department head should be made stakeholders of the project. Secondly, implementation plans need to be prepared behorehand in collaboration with site officials and with approval of the general manager. Finally, a specialist with knowledge on critical controls should support roll-out of operational processes and develop understanding among employees on-site.

Add other sustainability disciplines
Environment, health, security and community are currently following safety closely in development of bow-tie models to mitigate Material Unwanted Events. Critical controls within these disciplines should be included one discipline at a time, preferably environment and health first. Both of these disciplines have potential for current operations and their possible incidents. In specific cases where a mine-site suffers from excessive intrusions of illegal miners, security should be prioritized.

Collaborate with software developer

In the current situation, not all processes are functioning as designed due to limitations in the software packages used. Imperfections in systems integrity will certainly hamper introduction of critical controls in other sites. Goals for collaboration should centre on translating needs to a simple set of requirements and establishing a short-term time horizon for further updating of processes. These can established through the development of use-cases that demonstrate which functional needs are necessary to create a fully functioning system.

Assess integration of maintenance data

After incident data, the next frontier for a complete critical control management system lies in adapting maintenance data of these controls into the overarching system. Data on maintenance sits within one application, so integration should focus on extracting data and subsequently building from there. Once it can be integrated in the BI environment, utilization solely rests on definition of useful parameters for end users.

Determine feasibility of using a dedicated infrastructure

While asset integrity data is already generated through Planned Maintenance, there is significant technical and economical potential for critical control data to be routed through the same platform. Not only would this simplify the system in use, it would also cut down on associated licensing costs of secondary systems. Feasibility of use should focus on determining what development would cost for extensive action management of a diverse suite of audits, as well applicability to handheld devices. As this process would have to be replicated at each operation for both the current and potential systems infrastructure, early adaption can potentially reduce costs extensively.

Bibliography

Abdo, H., Flaus, J.-M., and Masse, F. (2017). Uncertainty quantification in risk assessment - representation, propagation and treatment approaches: Application to atmospheric dispersion modeling. *Journal of Loss Prevention in the Process Industries*, 49:551–571. doi: 10.1016/j.jlp.2017.05.015.

Aidman, E., Chadunow, C., Johnson, K., and Reece, J. (2015). Real-time driver drowsiness feedback improves driver alertness and self-reported driving performance. *Accident Analysis & Prevention*, 81:8–13. doi: 10.1016/j.aap.2015.03.041.

Al-Aqrabi, H., Liu, L., Hill, R., and Antonopoulos, N. (2015). Cloud BI: Future of business intelligence in the cloud. *Journal of Computer and System Sciences*, 81(1):85–96. doi: 10.1016/j.jcss.2014.06.013.

AMCA Inter-consult LTD (2012). Study of migration of youth in mining areas in tanzania. [online] Terre des hommes Schweiz. Retrieved from: https://assets.terredeshommesschweiz.ch/downloads/migration_study_of_youth_in_mining_areas_in_tanzania_by_terre_des_hommes.pdf. Accessed on 13-11-2017.

AngloGold Ashanti (2014). Material issues: Safety and health. In *Sustainable Development Report 2014*. Retrieved from: http://www.anglogoldashanti.com/sustainability/reports/#2014. Accessed on 10-10-2017.

AngloGold Ashanti (2015). Material issues: Employee safety. In *Sustainability Report 2015*, pages 26–31. Retrieved from: http://www.anglogoldashanti.com/sustainability/reports/#2015. Accessed on 10-10-2017.

AngloGold Ashanti (2016). Mineral resource and ore reserve report 2016. Retrieved from: http://www.aga-reports.com/16/. Accessed on 16-11-2017.

Australian Bureau of Statistics (2007). Regional wage and salary earner statistics, australia - data cubes, 2003-04. Retrieved from: http://www.abs.gov.au/ausstats/abs@.nsf/mediareleasesbytopic/ACBB277878352202CA25729800182199?OpenDocument. Accessed on 15-11-2017.

Aven, T. (2009). Perspectives on risk in a decision-making context – review and discussion. *Safety Science*, 47(6):798–806. doi: 10.1016/j.ssci.2008.10.008.

Aven, T. (2012). The risk concept—historical and recent development trends. *Reliability Engineering & System Safety*, 99:33–44. doi: 10.1016/j.ress.2011.11.006.

Aven, T. (2014). *Risk, Surprises and Black Swans*. Taylor & Francis Ltd.

Aven, T. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, 253(1):1–13. doi: 10.1016/j.ejor.2015.12.023.

Bakolas, E. and Saleh, J. H. (2011). Augmenting defense-in-depth with the concepts of observability and diagnosability from control theory and discrete event systems. *Reliability Engineering & System Safety*, 96(1):184–193. doi: 10.1016/j.ress.2010.09.002.

Baybutt, P. (2014). Competency requirements for process safety auditors. *Process Safety Progress*, 34(2):179–182. doi: 10.1002/prs.11684.

Berner, C. L. and Flage, R. (2017). Creating risk management strategies based on uncertain assumptions and aspects from assumption-based planning. *Reliability Engineering & System Safety*, 167:10–19. doi: 10.1016/j.ress.2017.05.009.

BHP (2016). Safety: our requirements. Retrieved from: http://www.bhp.com//media/bhp/documents/aboutus/ourcompany/governance/160404_gld_safety.$pdf.Accessedon26-10-2017$.

Borys, D., Else, D., and Leggett, S. (2009). The fifth age of safety: the adaptive age. *Journal of health and safety research and practice*, 1(1):19–27.

British Standards Institute (2017). OHSAS 18001. In *Occupational Health and Safety Management Systems*. Accessed on 10-10-2017.

Brown, S. M., Groves, D. I., and Newton, P. G. (2002). Geological setting and mineralization model for the cleo gold deposit, eastern goldfields province, western australia. *Mineralium Deposita*, 37(8):704–721. doi: 10.1007/s00126-002-0255-x.

Cerrada, M., Sánchez, R.-V., Li, C., Pacheco, F., Cabrera, D., de Oliveira, J. V., and Vásquez, R. E. (2018). A review on data-driven fault severity assessment in rolling bearings. *Mechanical Systems and Signal Processing*, 99:169–196. doi: 10.1016/j.ymssp.2017.06.012.

Chofreh, A. G., Goni, F. A., and Klemeš, J. J. (2017). Development of a roadmap for sustainable enterprise resource planning systems implementation (part II). *Journal of Cleaner Production*, 166:425–437. doi: 10.1016/j.jclepro.2017.08.037.

Costella, M. F., Saurin, T. A., and de Macedo Guimarães, L. B. (2009). A method for assessing health and safety management systems from the resilience engineering perspective. *Safety Science*, 47(8):1056–1067. doi: 10.1016/j.ssci.2008.11.006.

de Rosa, M. (2004). Analyses of mobile equipment fires for all u.s. surface and underground coal and metal/nonmetal mining categories, 1990-1999. In *C 9467 - Information Circular/2004*, volume 2004-105. U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health.

de Ruijter, A. and Guldenmund, F. (2016). The bowtie method: A review. *Safety Science*, 88:211–218. doi: 10.1016/j.ssci.2016.03.001.

Department of Minerals and Petroleum (1994). Mines Safety and Inspection Act 1994. Retrieved from: https://www.slp.wa.gov.au/pco/prod/filestore.nsf/FileURL/mrdoc_28463.pdf/$FILE/Mines%20Safety%20And%20Inspection%20Act%201994%20-%20%5B06-a0-01%5D.pdf?OpenElement. Accessed on 26-10-2017.

Department of Minerals and Petroleum (1997). Foam fire suppression systems on mine vehicles - guidelines. Retrieved from: http://www.dmp.wa.gov.au/Documents/Safety/MSH_G_FoamFireSupressionSystems.pdf. Accessed on 12-11-2017.

DiCicco-Bloom, B. and Crabtree, B. F. (2006). The qualitative research interview. *Medical Education*, 40(4):314–321. doi: 10.1111/j.1365-2929.2006.02418.x.

Dixon, N. (2011). Work health & safety act 2011 (qld). [online] Queensland Parliament Library. Retrieved from: www.parliament.qld.gov.au/documents/explore/researchpublications/researchbriefs/2011/rbr201117.pdf. Accessed on 16-11-2017.

Domingues, M. S., Baptista, A. L., and Diogo, M. T. (2017). Engineering complex systems applied to risk management in the mining industry. *International Journal of Mining Science and Technology*, 27(4):611–616. doi: 10.1016/j.ijmst.2017.05.007.

Ericson, C. A. (1999). Fault tree analysis. In *System Safety Conference, Orlando, Florida*, pages 1–9.

Floyd, H. L. and Floyd, A. H. (2017). Residual risk and the psychology of lower order controls. *IEEE Transactions on Industry Applications*, pages 1–1. doi: 10.1109/tia.2017.2748919.

Galvin, J. (2016). *Ground Engineering - Principles and Practices for Underground Coal Mining*. Springer International Publishing. doi: 10.1007/978-3-319-25005-2.

Galvin, J. (2017). Critical role of risk management in ground engineering and opportunities for improvement. *International Journal of Mining Science and Technology*, 27(5):725–731. doi: 10.1016/j.ijmst.2017.07.005.

Gandomi, A. and Haider, M. (2015). Beyond the hype: Big data concepts, methods, and analytics. *International Journal of Information Management*, 35(2):137–144. doi: 10.1016/j.ijinfomgt.2014.10.007.

Gerbec, M. (2017). Safety change management – a new method for integrated management of organizational and technical changes. *Safety Science*, 100:225–234. doi: 10.1016/j.ssci.2016.07.006.

Glencore (2016). Glencore Sustainability Report 2016. Retrieved from: http://www.glencore.com/assets/sustainability/doc/sd_reports/2016-Glencore-Sustainabilty-Report.pd. Accessed on 02-11-2017.

Haddon, W. (1963). A note concerning accident theory and research with special reference to motor vehicle accidents. *Annals of the New York Academy of Sciences*, 107(2):635–646. doi: 10.1111/j.1749-6632.1963.tb13307.x.

Haddon, W. (1968). The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based. *American Journal of Public Health and the Nations Health*, 58(8):1431–1438. doi: 10.2105/ajph.58.8.1431.

Hajkowicz, S. A., Heyenga, S., and Moffat, K. (2011). The relationship between mining and socio-economic well being in australia's regions. *Resources Policy*, 36(1):30–38. doi: 10.1016/j.resourpol.2010.08.007.

Hale, A. R. and Hovden, J. (1998). Management and culture: the third age of safety. a review of approaches to organizational aspects of safety, health and environment. *Occupational injury: Risk, prevention and intervention*, pages 129–165.

Hansen, R. (2017). Fire behavior of mining vehicles in underground hard rock mines. *International Journal of Mining Science and Technology*, 27(4):627–634. doi: 10.1016/j.ijmst.2017.05.010.

Hansen, R. and Ingason, H. (2013). Heat release rate measurements of burning mining vehicles in an underground mine. *Fire Safety Journal*, 61:12–25. doi: 10.1016/j.firesaf.2013.08.009.

Heinrich, H. and Petersen, D. (1980). *Industrial Accident Prevention.* McGraw-Hill Companies.

Hetzer, R., Kümmerlen, F. K., Wirz, K., and Blunk, D. (2014). Fire testing a new fluorine-free AFFF based on a novel class of environmentally sound high performance siloxane surfactants. *Fire Safety Science*, 11:1261–1270. doi: 10.3801/iafss.fss.11-1261.

Hill, E. J., Oliver, N. H., Cleverley, J. S., Nugus, M. J., Carswell, J., and Clark, F. (2014). Characterisation and 3d modelling of a nuggety, vein-hosted gold ore body, Sunrise Dam, Western Australia. *Journal of Structural Geology*, 67:222–234. doi: 10.1016/j.jsg.2013.10.013.

Hochleitner, M. and Roche, E. (2017). Auditing management systems for safety controls, alarms, and interlocks: How effective are your instrumented protective systems? *Process Safety Progress*, 36(3):301–306. doi: 10.1002/prs.11875.

Hoda, R., Salleh, N., Grundy, J., and Tee, H. M. (2017). Systematic literature reviews in agile software development: A tertiary study. *Information and Software Technology*, 85:60–70. doi: 10.1016/j.infsof.2017.01.007.

Hyndman, R. J. (2011). Moving averages. In *International Encyclopedia of Statistical Science*, pages 866–869. Springer Berlin Heidelberg. doi: 10.1007/978-3-642-04898-2_380.

ICMM (2015). Benchmarking 2015 safety data: progress of ICMM members. Retrieved from: https://www.icmm.com /safety-data-2015. Acccessed on 11-11-2017.

ICMM (2015a). Critical control management: Implementation guide. Retrieved from: https://www.icmm.com/website/publications/pdfs/9722.pdf. Accessed on 06-10-2017.

ICMM (2015b). Minerals and metals management 2020: Status report 2015. Retrieved from: https://www.icmm.com /website/publications/pdfs/9427.pdf. Accessed on 05-09-2017.

ICMM (2016). Benchmarking 2016 safety data: progress of ICMM members. Retrieved from: https://www.icmm.com /safety-data-2016. Acccessed on 08-11-2017.

International Organization for Standardization (2009). ISO 31000. Retrieved from: https://www.iso.org/iso-31000-risk-management.html Accessed on 13-11-2017.

Kitula, A. (2006). The environmental and socio-economic impacts of mining on local livelihoods in tanzania: A case study of geita district. *Journal of Cleaner Production*, 14(3-4):405–414. doi: 10.1016/j.jclepro.2004.01.012.

Lane, A., Guzek, J., and van Antwerpen, W. (2015). Tough choices facing the South African mining industry. *Journal of the Southern African Institute of Mining and Metallurgy*, 115:471 – 479. http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532015000600006&nrm=iso.

Lekka, C. and Sugden, C. (2011). The successes and challenges of implementing high reliability principles: A case study of a UK oil refinery. *Process Safety and Environmental Protection*, 89(6):443–451. doi: 10.1016/j.psep.2011.07.003.

Machado, C. G., de Lima, E. P., da Costa, S. E. G., Angelis, J. J., and Mattioda, R. A. (2017). Framing maturity based on sustainable operations management principles. *International Journal of Production Economics*, 190:3–21. doi: 10.1016/j.ijpe.2017.01.020.

Mair, J. L., Ojala, V. J., Salier, B. P., Groves, D. I., and Brown, S. M. (2000). Application of stress mapping in cross-section to understanding ore geometry, predicting ore zones and development of drilling strategies. *Australian Journal of Earth Sciences*, 47(5):895–912. doi: 10.1046/j.1440-0952.2000.00814.x.

Makin, A. and Winder, C. (2008). A new conceptual framework to improve the application of occupational health and safety management systems. *Safety Science*, 46(6):935–948. doi: 10.1016/j.ssci.2007.11.011.

Maphosa, F. and Morojele, R. (2013). Changing the culture of migration? attitudes towards education among former basotho labour migrants to south african mines. *Africa Development*, 38(1-2):151–170.

Mishra, R., Janiszewski, M., Uotinen, L., Szydlowska, M., Siren, T., and Rinne, M. (2017). Geotechnical risk management concept for intelligent deep mines. *Procedia Engineering*, 191:361–368. doi: 10.1016/j.proeng.2017.05.192.

Mittermayr, F., Bauer, C., Klammer, D., Böttcher, M. E., Leis, A., Escher, P., and Dietzel, M. (2012). Concrete under sulphate attack: an isotope study on sulphur sources. *Isotopes in Environmental and Health Studies*, 48(1):105–117. doi: 10.1080/10256016.2012.641964.

Morad, A. M., Pourgol-Mohammad, M., and Sattarvand, J. (2014). Application of reliability-centered maintenance for productivity improvement of open pit mining equipment: Case study of sungun copper mine. *Journal of Central South University*, 21(6):2372–2382. doi: 10.1007/s11771-014-2190-2.

Nofal, M. I. and Yusof, Z. M. (2013). Integration of business intelligence and enterprise resource planning within organizations. *Procedia Technology*, 11:658–665. doi: 10.1016/j.protcy.2013.12.242.

Parreira, J. (2013). *An interactive simulation model to compare an autonomous haulage truck system with a manually-operated system.* PhD thesis, University of British Columbia.

Pasman, H. and Rogers, W. (2013). Bayesian networks make LOPA more effective, QRA more transparent and flexible, and thus safety more definable! *Journal of Loss Prevention in the Process Industries*, 26(3):434–442. doi: 10.1016/j.jlp.2012.07.016.

Pillay, M. (2015). Accident causation, prevention and safety management: A review of the state-of-the-art. *Procedia Manufacturing*, 3:1838–1845. doi: 10.1016/j.promfg.2015.07.224.

Pillay, M., Borys, D., Else, D., and Tuck, M. (2010). Safety culture and resilience engineering–exploring theory and application in improving gold mining safety. In *Gravity Gold Conference*, volume 21, pages 129–140.

Pillay, M. and Tuck, M. (2017). Permit-to-work systems as a health and safety risk control strategy in mining: A prospective study in resilience engineering. In *Advances in Human Error, Reliability, Resilience, and Performance*, pages 145–154. Springer International Publishing. doi: 10.1007/978-3-319-60645-3_14.

Porte, T. L. and Consolini, P. (1998). Theoretical and operational challenges of "high-reliability organizations": air-traffic control and aircraft carriers. *International Journal of Public Administration*, 21(6-8):847–852. doi: 10.1080/01900699808525320.

Prior, T., Giurco, D., Mudd, G., Mason, L., and Behrisch, J. (2012). Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change*, 22(3):577–587. doi: 10.1016/j.gloenvcha.2011.08.009.

Reason, J. (2000). Human error: models and management. *BMJ*, 320(7237):768–770. doi: 10.1136/bmj.320.7237.768.

Rio Tinto (2017). Critical Risk Management. Retrieved from: http://www.riotinto.com/ourcommitment/spotlight-18130_21440.aspx. Accessed on 10-10-17.

Robbins, S. (2010). *Organisational Behaviour: Global and Southern African Perspective*. Pearson Education South Africa.

Roberts, K. H. (1990). Some characteristics of one type of high reliability organization. *Organization Science*, 1(2):160–176. doi: 10.1287/orsc.1.2.160.

Robinson, R. and Francis, G. (2014). Sfairp vs alarp. In *Core 2014: Conference on Railway Excellence*. Extracted from: http://www.r2a.com.au/wp-content/uploads/2015/02/CORE-2014-paper-SFAIRP-vs-ALARP.pdf. Accessed on 09-10-2017.

Satish, C. and Crow, D. R. (2014). External audits to evaluate and enhance electrical safety and maintenance. In *2014 IEEE IAS Electrical Safety Workshop*. IEEE. doi: 10.1109/esw.2014.6766915.

Saunders, F. C. (2015). Toward high reliability project organizing in safety-critical projects. *Project Management Journal*, 46(3):25–35. doi: 10.1002/pmj.21498.

Schulz, K.-P., Geithner, S., and Mistele, P. (2017). Learning how to cope with uncertainty. *Journal of Organizational Change Management*, 30(2):199–216. doi: 10.1108/jocm-08-2015-0142.

Sganzerla, C., Seixas, C., and Conti, A. (2016). Disruptive innovation in digital mining. *Procedia Engineering*, 138:64–71. doi: 10.1016/j.proeng.2016.02.057.

Sklet, S. (2006). Safety barriers: Definition, classification, and performance. *Journal of Loss Prevention in the Process Industries*, 19(5):494–506. doi: 10.1016/j.jlp.2005.12.004.

Sung, Y.-H., Brugger, J., Ciobanu, C. L., Pring, A., Skinner, W., and Nugus, M. (2009). Invisible gold in arsenian pyrite and arsenopyrite from a multistage archaean gold deposit: Sunrise dam, eastern goldfields province, western australia. *Mineralium Deposita*, 44(7):765–791. doi: 10.1007/s00126-009-0244-4.

Swuste, P., van Gulijk, C., Zwaard, W., Lemkowitz, S., Oostendorp, Y., and Groeneweg, J. (2016). Developments in the safety science domain, in the fields of general and safety management between 1970 and 1979, the year of the near disaster on three mile island, a literature review. *Safety Science*, 86:10–26. doi: 10.1016/j.ssci.2016.01.022.

Swuste, P., van Gulijk, C., Zwaard, W., and Oostendorp, Y. (2014). Occupational safety theories, models and metaphors in the three decades since world war II, in the united states, britain and the netherlands: A literature review. *Safety Science*, 62:16–27. doi: 10.1016/j.ssci.2013.07.015.

Usman, M. and Galler, R. (2013). Long-term deterioration of lining in tunnels. *International Journal of Rock Mechanics and Mining Sciences*, 64:84–89. doi: 10.1016/j.ijrmms.2013.08.028.

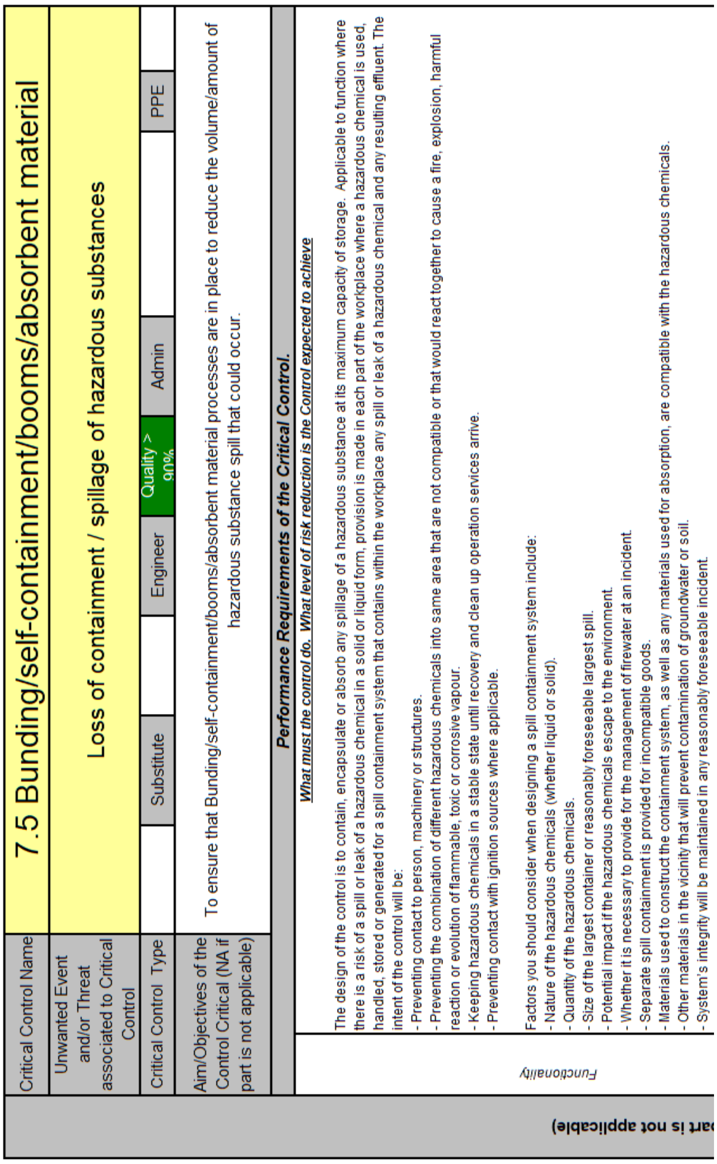
Wadnerkar, D., Tade, M. O., Pareek, V. K., and Utikar, R. P. (2015). Modeling and optimization of carbon in leach (CIL) circuit for gold recovery. *Minerals Engineering*, 83:136–148. doi: 10.1016/j.mineng.2015.09.001.

Weick, K. E. and Sutcliffe, K. (2007). *Managing the Unexpected*. Jossey Bass Wiley, Second edition.

Xia, X., Li, H., Li, J., Liu, B., and Yu, C. (2013). A case study on rock damage prediction and control method for underground tunnels subjected to adjacent excavation blasting. *Tunnelling and Underground Space Technology*, 35:1–7. doi: 10.1016/j.tust.2012.11.010.

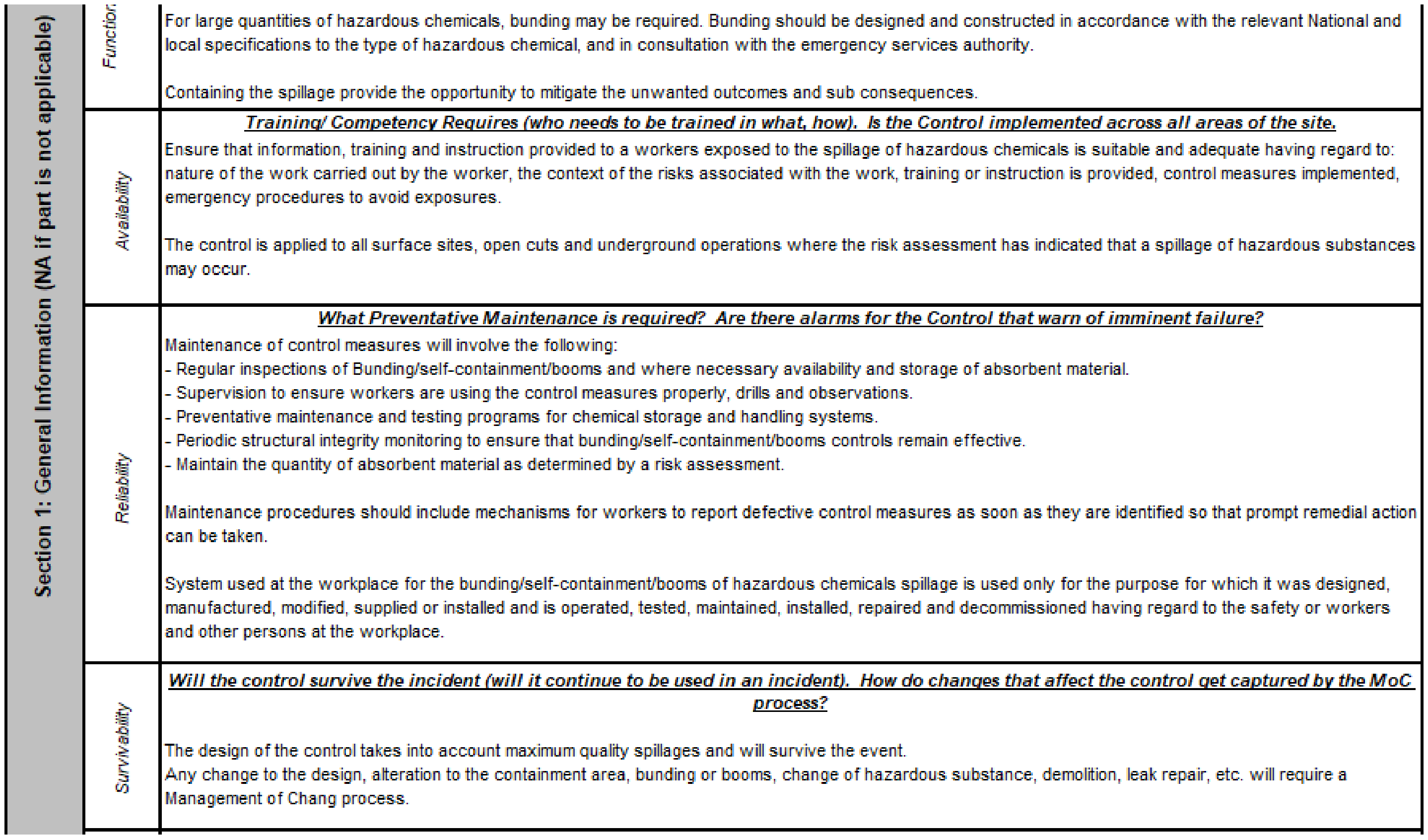
A

Sample Performance Standard



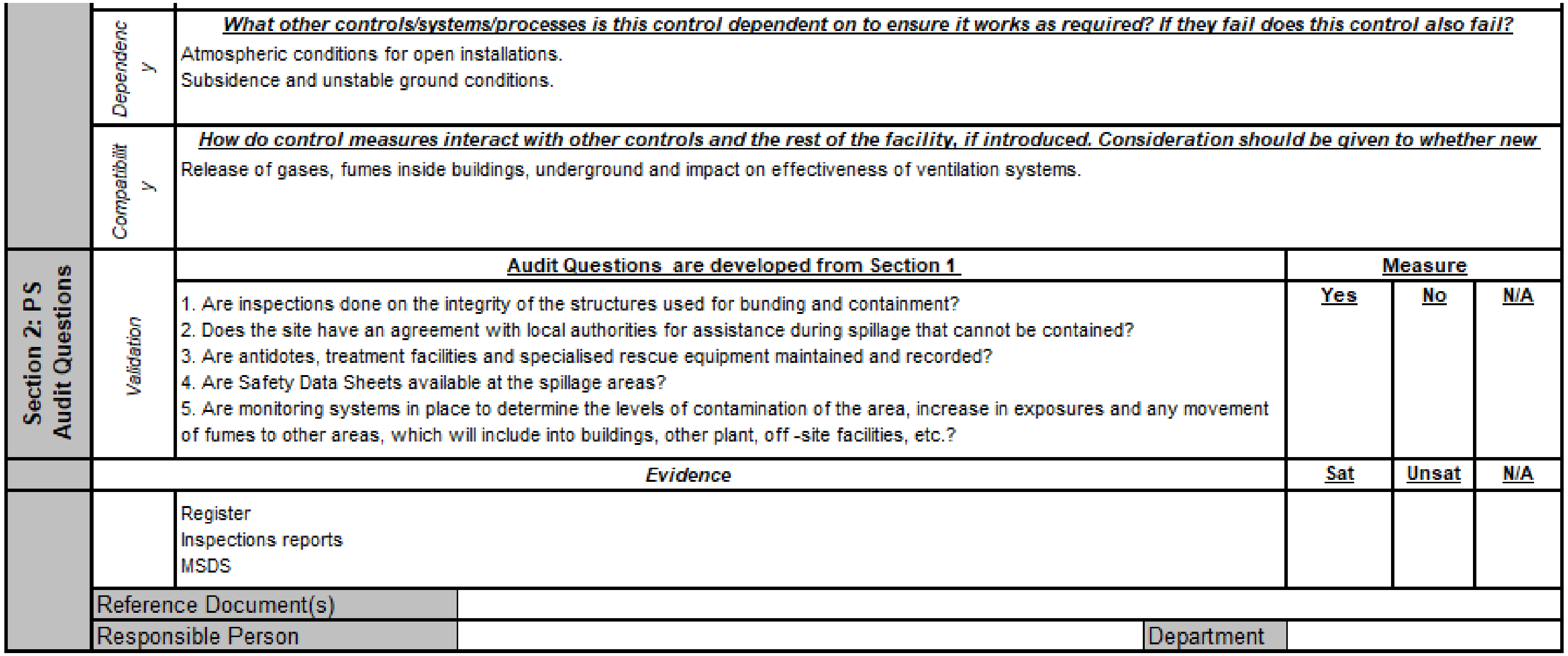
Critical Control Name	7.5 Bunding/self-containment/booms/absorbent material
Unwanted Event and/or Threat associated to Critical Control	Loss of containment / spillage of hazardous substances
Critical Control Type	Substitute Engineer Quality > 90% Admin PPE
Aim/Objectives of the Control Critical (NA if part is not applicable)	To ensure that Bunding/self-containment/booms/absorbent material processes are in place to reduce the volume/amount of hazardous substance spill that could occur.
	Performance Requirements of the Critical Control.
	What must the control do. What level of risk reduction is the Control expected to achieve
Functionality	The design of the control is to contain, encapsulate or absorb any spillage of a hazardous substance at its maximum capacity of storage. Applicable to function where there is a risk of a spill or leak of a hazardous chemical in a solid or liquid form, provision is made in each part of the workplace where a hazardous chemical is used, handled, stored or generated for a spill containment system that contains within the workplace any spill or leak of a hazardous chemical and any resulting effluent. The intent of the control will be: - Preventing contact to person, machinery or structures. - Preventing the combination of different hazardous chemicals into same area that are not compatible or that would react together to cause a fire, explosion, harmful reaction or evolution of flammable, toxic or corrosive vapour. - Keeping hazardous chemicals in a stable state until recovery and clean up operation services arrive. - Preventing contact with ignition sources where applicable. Factors you should consider when designing a spill containment system include: - Nature of the hazardous chemicals (whether liquid or solid). - Quantity of the hazardous chemicals. - Size of the largest container or reasonably foreseeable largest spill. - Potential impact if the hazardous chemicals escape to the environment. - Whether it is necessary to provide for the management of firewater at an incident. - Separate spill containment is provided for incompatible goods. - Materials used to construct the containment system, as well as any materials used for absorption, are compatible with the hazardous chemicals. - Other materials in the vicinity that will prevent contamination of groundwater or soil. - System's integrity will be maintained in any reasonably foreseeable incident.
	art is not applicable)

Figure A.1: First section of Peformance Standard on Bunding/Self-Adsorbment of Hazardous Materials



Section 1: General Information (NA if part is not applicable)	*Functio*	For large quantities of hazardous chemicals, bunding may be required. Bunding should be designed and constructed in accordance with the relevant National and local specifications to the type of hazardous chemical, and in consultation with the emergency services authority. Containing the spillage provide the opportunity to mitigate the unwanted outcomes and sub consequences.
	Availability	***Training/ Competency Requires (who needs to be trained in what, how). Is the Control implemented across all areas of the site.*** Ensure that information, training and instruction provided to a workers exposed to the spillage of hazardous chemicals is suitable and adequate having regard to: nature of the work carried out by the worker, the context of the risks associated with the work, training or instruction is provided, control measures implemented, emergency procedures to avoid exposures. The control is applied to all surface sites, open cuts and underground operations where the risk assessment has indicated that a spillage of hazardous substances may occur.
	Reliability	***What Preventative Maintenance is required? Are there alarms for the Control that warn of imminent failure?*** Maintenance of control measures will involve the following: - Regular inspections of Bunding/self-containment/booms and where necessary availability and storage of absorbent material. - Supervision to ensure workers are using the control measures properly, drills and observations. - Preventative maintenance and testing programs for chemical storage and handling systems. - Periodic structural integrity monitoring to ensure that bunding/self-containment/booms controls remain effective. - Maintain the quantity of absorbent material as determined by a risk assessment. Maintenance procedures should include mechanisms for workers to report defective control measures as soon as they are identified so that prompt remedial action can be taken. System used at the workplace for the bunding/self-containment/booms of hazardous chemicals spillage is used only for the purpose for which it was designed, manufactured, modified, supplied or installed and is operated, tested, maintained, installed, repaired and decommissioned having regard to the safety or workers and other persons at the workplace.
	Survivability	***Will the control survive the incident (will it continue to be used in an incident). How do changes that affect the control get captured by the MoC process?*** The design of the control takes into account maximum quality spillages and will survive the event. Any change to the design, alteration to the containment area, bunding or booms, change of hazardous substance, demolition, leak repair, etc. will require a Management of Chang process.

Figure A.2: Second section of Peformance Standard on Bunding/Self-Adsorbment of Hazardous Materials



Section 2: PS Audit Questions	*Dependency*	***What other controls/systems/processes is this control dependent on to ensure it works as required? If they fail does this control also fail?*** Atmospheric conditions for open installations. Subsidence and unstable ground conditions.			
	Compatibility	***How do control measures interact with other controls and the rest of the facility, if introduced. Consideration should be given to whether new*** Release of gases, fumes inside buildings, underground and impact on effectiveness of ventilation systems.			
	Validation	**Audit Questions are developed from Section 1**	**Measure**		
		1. Are inspections done on the integrity of the structures used for bunding and containment? 2. Does the site have an agreement with local authorities for assistance during spillage that cannot be contained? 3. Are antidotes, treatment facilities and specialised rescue equipment maintained and recorded? 4. Are Safety Data Sheets available at the spillage areas? 5. Are monitoring systems in place to determine the levels of contamination of the area, increase in exposures and any movement of fumes to other areas, which will include into buildings, other plant, off -site facilities, etc.?	**Yes**	**No**	**N/A**
	Evidence		**Sat**	**Unsat**	**N/A**
		Register Inspections reports MSDS			
	Reference Document(s)				
	Responsible Person		Department		

Figure A.3: Third section of Peformance Standard on Bunding/Self-Adsorbment of Hazardous Materials

B

Critical Control Elements

Non-applicable Elements

As will become clear when examining the mapping tool applied to the workplace inspections, some technical level questions could not be fitted or were simply not appropriate. In this section, a short outline will be given around these elements and the reason why they were not applicable. These elements are:

- CSE-M.02 - Multi-Gas Measurements system
- ELE-M.01 - Isolation, lock out and tag process
- ESG-M.03 - Emergency stop button and/or lanyard
- ESG-M.05 - Emergency stop button and/or lanyard
- PRE-M.01 - Pressure release valves
- PRE-M.02 - Blow-down valves

The multi-gas measurement systems audit is conducted through a bump test. This goes beyond the skill of a standard safety representative, as well as sitting within the strategy of the maintenance department. Essentially, this performance standard element is already answered, but not within the scope of the systems applied.

Although several significant pieces of electrical equipment are utilized, the applicable signage is already installed. While there is sense in checking that the signage remains in place, this is already covered by yearly audits specified through statutory requirements.

The two elements applicable to emergency stop buttons and/or lanyard were included in an early stage before validation of the critical control elements was conducted. In the first instance, by auditing the systems in place the question is intrinsically answered. However, as stated in section 5.2.2, this is a systems question designed for higher level assessment. As such, this element will be slated when reviewed. In the second instance, all lanyards are designed and required to cover the entire length of the applicable machinery, thus making the question an arduous yet ultimately irrelevant process.

The final two elements of pressure release and blow-down valves are checked within the strategy of the maintenance department, again demonstrating the need for inclusion of this strategy within the overarching Critical Control Management System.

		Coding	CSE-M.01	CSE-M.02	ELE-M.01	ELE-M.02	ESG-M.01	ESG-M.02	ESG-M.03	ESG-M.04	ESG-M.05	ESG-M.06	EXP-M.01	EXP-M.02	EXP-M.03	EXP-M.04	EXP-M.05	FIR-M.01	FIR-M.02	FIR-M.03
		Crit. Control	CSR	MMM	ISO	LOC	BAR	DEM	EMS	EMS	EMS	GOM	SEP	EAB	TRA	RIT	MIS	FDS	RES	RES
		PS nr.	4	6	3	5	7	1	1	4	5	3	1	2	2	5	1	1	2	3
		Sum per CC	28	0	0	2	1	19	0	11	0	80	5	2	4	2	1	12	1	5
Inspection name	**Sum CC Questions**																			
E - Core Shed	9		0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
G - Admin Area	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0
G - ERT Areas (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - Warehouse (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P - Crusher	70		19	0	0	0	0	3	0	8	0	31	0	0	0	0	0	0	0	0
P - Gold Room	8		0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
P - Grinding	29		5	0	0	0	0	1	0	0	0	18	0	0	0	0	0	0	0	0
P - Laboratory	9		0	0	0	0	0	1	0	0	0	4	0	0	0	0	0	0	0	0
P - Paste Plant (REMOVED)	16		0	0	0	1	0	2	0	0	0	5	0	0	0	0	0	0	0	0
P - Projects	6		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
P - Reagents	20		0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0
P - Thick. CIL	37		4	0	0	0	0	3	0	0	0	16	0	0	0	0	0	0	0	0
M - Layd. Dies. Sto.	10		0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
M - LV Workshop	5		0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
M - Crib/Training Room	2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
M - Workshops	6		0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
U - Explosives Storage	17		0	0	0	0	0	3	0	0	0	0	5	1	4	0	0	0	0	0
U - Refuge Chambers	14		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
U- Surface Areas	10		0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0
U - UG Works	26		0	0	0	0	1	3	1	0	0	0	0	0	0	2	1	0	0	2
U- Workshop	10		0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
U - Bindah (REMOVED)	4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U - SDGM TMP	24		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	317		9%	0%	0%	1%	0%	6%	0%	3%		25%	2%	1%	1%	1%	0%	4%	0%	2%

Table B.1: First section of the mapping tool used to identify and categorize critical control elements in workplace inspections

		Coding	FIR-M.04	FIR-M.05	FIR-M.06	FIR-M.07	HAZ-M.01	HAZ-M.02	HAZ-M.03	HAZ-M.04	HAZ-M.05	HAZ-M.06	HAZ-M.07	HME-M.01	ISO-M.01	ISO-M.02	LIF-M.01	LIF-M.02	LIF-M.03	LIF-M.04
		Crit. Control	RES	RES	RES	AFS	BUN	BUN	BUN	GUA	GUA	SIM	LAI	TMP	LAB	MLD	CMT	CMT	CMT	DRO
		PS nr.	4	6	7	4	1	3	4	2	4	6?	1	2	1	?	1	2	3	5
		Sum per CC	2	2	6	3	14	1	7	1	3	7	1	2	1	1	5	10	4	2
Inspection name	**Sum CC Questions**																			
E - Core Shed	9		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - Admin Area	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - ERT Areas (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - Warehouse (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P - Crusher	70		0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
P - Gold Room	8		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0
P - Grinding	29		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
P - Laboratory	9		0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
P - Paste Plant (REMOVED)	16		0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
P - Projects	6		0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P - Reagents	20		0	0	0	0	6	0	1	0	2	4	1	0	0	0	0	0	0	0
P - Thick. CIL	37		0	0	0	0	4	0	1	0	0	2	0	0	0	0	1	1	0	1
M - Layd. Dies. Sto.	10		0	0	0	1	2	0	1	1	1	1	0	0	0	0	0	0	0	0
M - LV Workshop	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0
M - Crib/Training Room	2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M - Workshops	6		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
U - Explosives Storage	17		0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U - Refuge Chambers	14		2	2	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U- Surface Areas	10		0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
U - UG Works	26		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
U- Workshop	10		0	0	0	0	0	0	1	0	0	0	0	0	0	1	2	1	1	0
U - Bindah (REMOVED)	4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U - SDGM TMP	24		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	317		1%	1%	2%	1%	4%	0%	2%	0%	1%	2%	0%	1%	0%	0%	2%	3%	1%	1%

Table B.2: Second section of the mapping tool used to identify and categorize critical control elements in workplace inspections

		Coding	LVE-M.01	LVE-M.02	LVE-M.03	LVE-M.04	PRE-M.01	PRE-M.02	PRE-M.03	PRE-M.04	PRE-M.05	UGV-M.01	UGV-M.02	UGV-M.03	UGV-M.04	UGC-M.01	UGC-M.02	WAH-M.01	WAH-M.02	WAH-M.03
		Crit. Control	TMP	TMP	TMP	PSC	PRV	BDV	FLO	SIM	SIM	FHS	EME	MCV	PSC	GSS	HZC	GAB	GAB	QUA
		PS nr.	1	2	6	1	4	4	2	5	6	1	3	8	2	1	3	3	4	4
		Sum per CC	23	19	3	2	0	0	14	2	2	2	1	2	2	7	1	3	7	1
Inspection name	**Sum CC Questions**																			
E - Core Shed	9		0	3	1	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0
G - Admin Area	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - ERT Areas (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G - Warehouse (REQUIRE RE-ASSESSMENT	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P - Crusher	70		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	0
P - Gold Room	8		0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
P - Grinding	29		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
P - Laboratory	9		0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
P - Paste Plant (REMOVED)	16		1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	1	0
P - Projects	6		1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P - Reagents	20		0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0
P - Thick. CIL	37		0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
M - Layd. Dies. Sto.	10		0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M - LV Workshop	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M - Crib/Training Room	2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M - Workshops	6		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U - Explosives Storage	17		0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
U - Refuge Chambers	14		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U- Surface Areas	10		3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U - UG Works	26		0	2	0	0	0	0	0	0	0	2	1	2	2	5	1	0	0	0
U- Workshop	10		1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
U - Bindah (REMOVED)	4		3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U - SDGM TMP	24		13	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	317		7%	6%	1%	1%	0%	0%	4%	1%	1%	1%	0%	1%	1%	2%	0%	1%	2%	0%

Table B.3: Third section of the mapping tool used to identify and categorize critical control elements in workplace inspections

Type of Entity	Frequency	Code	Name	Major Hazard Standard	Critical Control
Question	Monthly	CSE-M.01	Are all confined spaces on the register identified and labelled?	Confined Space Entry	Confined Space Register
Question	Monthly	CSE-M.02	Has the bump test been conducted and gasses expected in the space being set in the multimeter?	Confined Space Entry	Multi gas measuring instrum
Question	Monthly	ELE-M.01	Are effective warning signage, including electric flash signage and rated voltage posted as per statutory/local requirements?	Electrical Installations	Isolation, lock and tag out p
Question	Monthly	ELE-M.02	Are locks fitted and locked for all Electrical installations with low or higher voltage?	Electrical Installations	Electrical installations with
Question	Monthly	ESG-M.01	Do the procedures provide for different types and construction of barricades, and is a system in place to inspect and record findings of the condition and effectiveness of barricades?	Equipment Safeguarding	Barricades
Question	Monthly	ESG-M.02	Is a system in place to inspect and record finding of the condition and effectiveness of the demarcation of areas where there is temporary restricted access or limited space?	Equipment Safeguarding	Demarcation to restricted ac
Question	Monthly	ESG-M.03	Is a system in place to inspect, maintain and record all emergency stop and/or emergency trip switches/pull wires in use on site?	Equipment Safeguarding	Emergency lanyard / stop bu
Question	Monthly	ESG-M.04	Are emergency stop and/or emergency trip switches/pull wires positioned conspicuously and within immediate reach of operators?	Equipment Safeguarding	Emergency lanyard / stop bu
Question	Monthly	ESG-M.05	Does the emergency stop and/or emergency trip switches/pull wires cover the full length of exposed moving part including the sections behind guards or fences, tail ends and drive pulleys?	Equipment Safeguarding	Emergency lanyard / stop bu
Question	Monthly	ESG-M.06	Are all guarding interlocked with the operation of the equipment or machinery?	Equipment Safeguarding	Guarding of moving or rotati
Question	Monthly	EXP-M.01	Have the monthly magazine inspections verified that explosives are correctly stored and segregated?	Explosives Handling and Storage	Separation of explosives an
Question	Monthly	EXP-M.02	Does the earthing and bonding programme include the risk of atmospheric electricity?	Explosives Handling and Storage	Earthing and bonding
Question	Monthly	EXP-M.03	Are precautions measure and procedures been developed to prevent access to explosives by people not authorised or lawfully entitled to have access?	Explosives Handling and Storage	Competent and authorised S
Question	Monthly	EXP-M.04	Is a system or protection devices in place to ensure the blasting imitators, instrumentation and wires are not exposed to other sources that may render an electrical pulse, which can initiate a blast?	Explosives Handling and Storage	Electronic, remote initiation
Question	Monthly	EXP-M.05	Does the mine have documented procedures in place defining precautionary measures to be taken prior, during and after treatment of the misfires?	Explosives Handling and Storage	Treatment of misfires
Question	Monthly	FIR-M.01	Does the detection system cover all working areas of the mine and air velocity taken into account to determine location of detection systems?	Fire	Fire detection system
Question	Monthly	FIR-M.02	Does the refuge bays/chambers provide for adequate number of persons, including visitors, at the workplace they cater for?	Fire	Refuge bays/chambers
Question	Monthly	FIR-M.03	Are escape route demarcated, illuminated, accessible and known to employees?	Fire	Refuge bays/chambers
Question	Monthly	FIR-M.04	Has records been kept up to dates with the statutory inspections and findings?	Fire	Refuge bays/chambers
Question	Monthly	FIR-M.05	Does the Refuge chamber has a positive pressure to ensure clean breathable air for occupants?	Fire	Refuge bays/chambers
Question	Monthly	FIR-M.06	Does the Refuge chamber meet the statutory requirements?	Fire	Refuge bays/chambers
Question	Monthly	FIR-M.07	Are competent and authorised personnel conducted inspections and tests of automatic fire suppression systems?	Fire	Automatic fire suppression s
Question	Monthly	UGC-M.01	Have the scheduled visual inspections and quantitative tests of ground support elements been completed?	Underground Ground Control	Ground support systems
Question	Monthly	UGC-M.02	Are competent persons obliged to conduct hazard assessments, inspections, demarcation and communication of geological structures?	Underground Ground Control	Hazard control
Question	Monthly	HME-M.01	Does the traffic management plan sets out the design requirements for segregation of traffic, direction of traffic and signage in/near mining operation areas?	Heavy Mobile Equipment	Traffic management plan
Question	Monthly	HAZ-M.01	Are inspections done on the integrity of the structures used for bunding and containment?	Hazardous Materials	Bunding/self-containment/b
Question	Monthly	HAZ-M.02	Are antidotes, treatment facilities and specialised rescue equipment maintained and recorded?	Hazardous Materials	Bunding/self-containment/b

Table B.4: First section of Monthly workplace inspection questions on critical controls

Type of Entity	Frequency	Code	Name	Major Hazard Standard	Critical Control
Question	Monthly	HAZ-M.03	Are Safety Data Sheets available at the spillage areas?	Hazardous Materials	Bunding/self-containment/b
Question	Monthly	HAZ-M.04	Has there been a risk assessment to identify all areas that require guarding and barricading to protect the asset?	Hazardous Materials	Guarding/Barricading
Question	Monthly	HAZ-M.05	Are guard or barricades inspected as per the monthly inspection routine or as per the statutory	Hazardous Materials	Guarding/Barricading
Question	Monthly	HAZ-M.06	Does the site include structural integrity monitoring into the maintenance system and is it scheduled and planned?	Hazardous Materials	Structural Integrity Monitori
Question	Monthly	HAZ-M.07	Are isolation procedures documented and accessible to workers in the workplace?	Hazardous Materials	Lock out and isolation
Question	Monthly	ISO-M.01	Are isolation points on critical plant and equipment labelled and lockable for accurate reference of the equipment in the field against those on the isolations list?	Energy Isolation	Isolation points labelled an
Question	Monthly	ISO-M.02	Is a register kept of the range of mechanical locking devices, including purpose built isolation devices, available for selection to suit the specific application?	Energy Isolation	Mechanical locking devices
Question	Monthly	LIF-M.01	Does all lifting equipment have a visible tag that is attached and colour coded to that specific quarter?	Lifting Operations	Clearly marked and Tagged L
Question	Monthly	LIF-M.02	Are safe working loads (SWL) marked in a conspicuous place in a legible and durable manner?	Lifting Operations	Clearly marked and Tagged L
Question	Monthly	LIF-M.03	Have the quarterly inspection, test and tag of rigging equipment been completed with records maintained?	Lifting Operations	Clearly marked and Tagged L
Question	Monthly	LIF-M.04	Are lifting and drop zones clear of unnecessary people, material, machinery and equipment?	Lifting Operations	Lifting and drop zones
Question	Monthly	LVE-M.01	Does the traffic management plan specify the site standards for road design, traffic control and light vehicle operation?	Light Vehicles	Traffic management plan
Question	Monthly	LVE-M.02	Are there scheduled inspections and maintenance of roadways, carparks and traffic signage?	Light Vehicles	Traffic management plan
Question	Monthly	LVE-M.03	Is there positive control of access to active mining areas (puck/barrier)?	Light Vehicles	Traffic management plan
Question	Monthly	LVE-M.04	Are all light vehicles checked against set criteria to ensure they are safe to drive prior to operation each shift with records maintained?	Light Vehicles	Pre-start chedks
Question	Monthly	PRE-M.01	Are pressure release valves directed in a safe direction should discharging take place?	Pressurized Equipment	Pressure release valves
Question	Monthly	PRE-M.02	Are blowdown valves directed in a safe direction should discharging take place?	Pressurized Equipment	Blowdown valve
Question	Monthly	PRE-M.03	Are all flow rate devices positively identified and flow direction indicated?	Pressurized Equipment	Flow control
Question	Monthly	PRE-M.04	Was equipment found to be out of specification or where defects were detected reported to the responsible person?	Pressurized Equipment	Structural Integrity measure
Question	Monthly	PRE-M.05	Is the equipment that is utilise to perform testing and measurement activities calibrated as per	Pressurized Equipment	Structural Integrity measure
Question	Monthly	UGV-M.01	Is the storage of hazardous materials and equipment at intake airways prohibited?	Underground Ventilation	Fire Hazard Standard
Question	Monthly	UGV-M.02	Do the mines ventilation plan show; the direction, course and volume of air currents, and the position of all air doors, stoppings, fans regulators and other ventilating plant and structures, and a copy available for inspection?	Underground Ventilation	Emergency response
Question	Monthly	UGV-M.03	Are daily ventilation measurements completed by the underground shift bosses / responsible persons with records maintained?	Underground Ventilation	Monitoring of critical ventila
Question	Monthly	UGV-M.04	Are over inspections conducted by supervisors?	Underground Ventilation	Pre-start checks
Question	Monthly	WAH-M.01	Is all signage posted and barricades installed inspected by a competent person and recorded on a register or checklist?	Working at Heights	Signage and barricades
Question	Monthly	WAH-M.02	Are all permanent and temporary barricading on an inspection and maintenance program?	Working at Heights	Signage and barricades
Question	Monthly	WAH-M.03	Does the inspection programme include periodic inspections of fall arrest equipment in storage?	Working at Heights	Quarterly inspections

Table B.5: Second section of Monthly workplace inspection questions on critical controls

C

Case Study bow-tie models

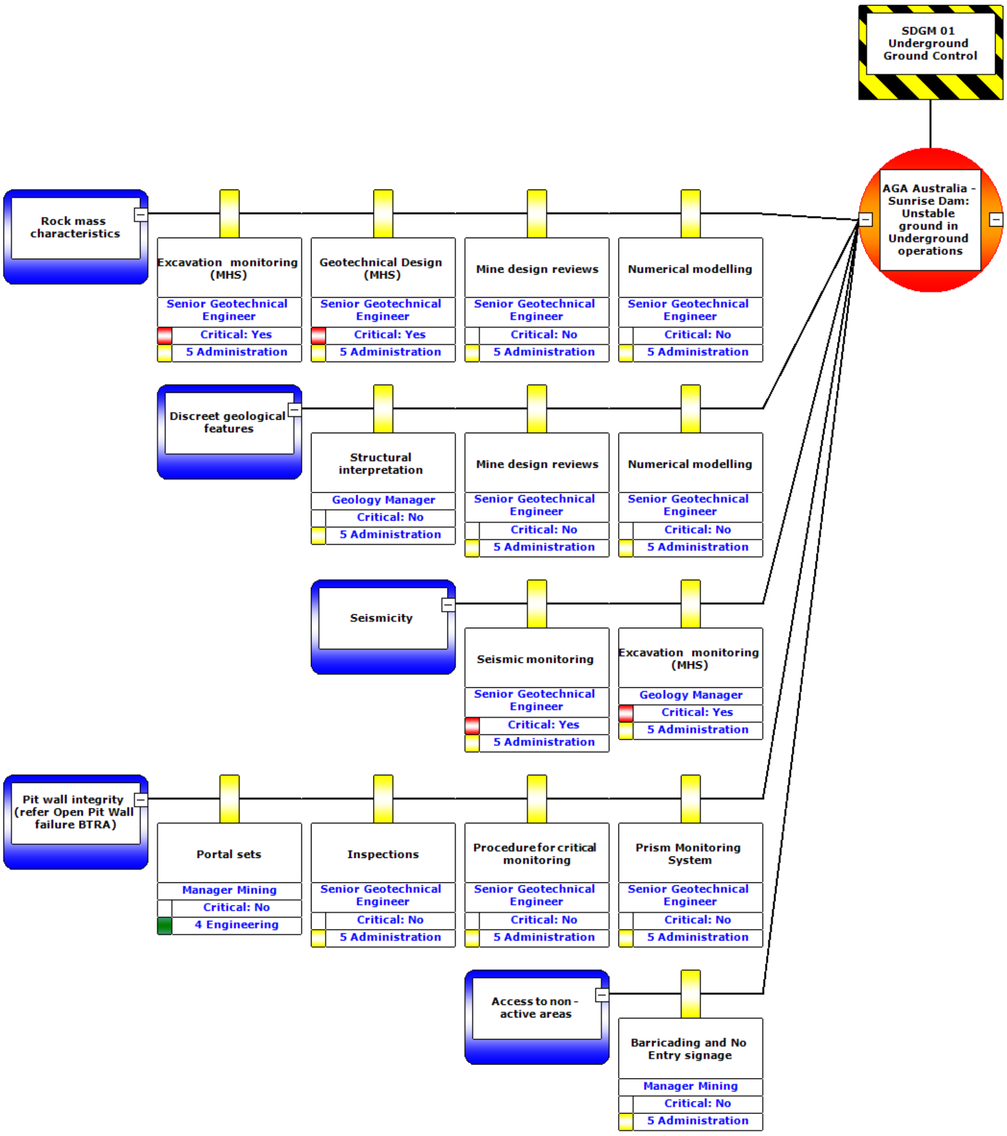


Figure C.1: First section of the pro-active side of the SDGM bow-tie model for Ground Control

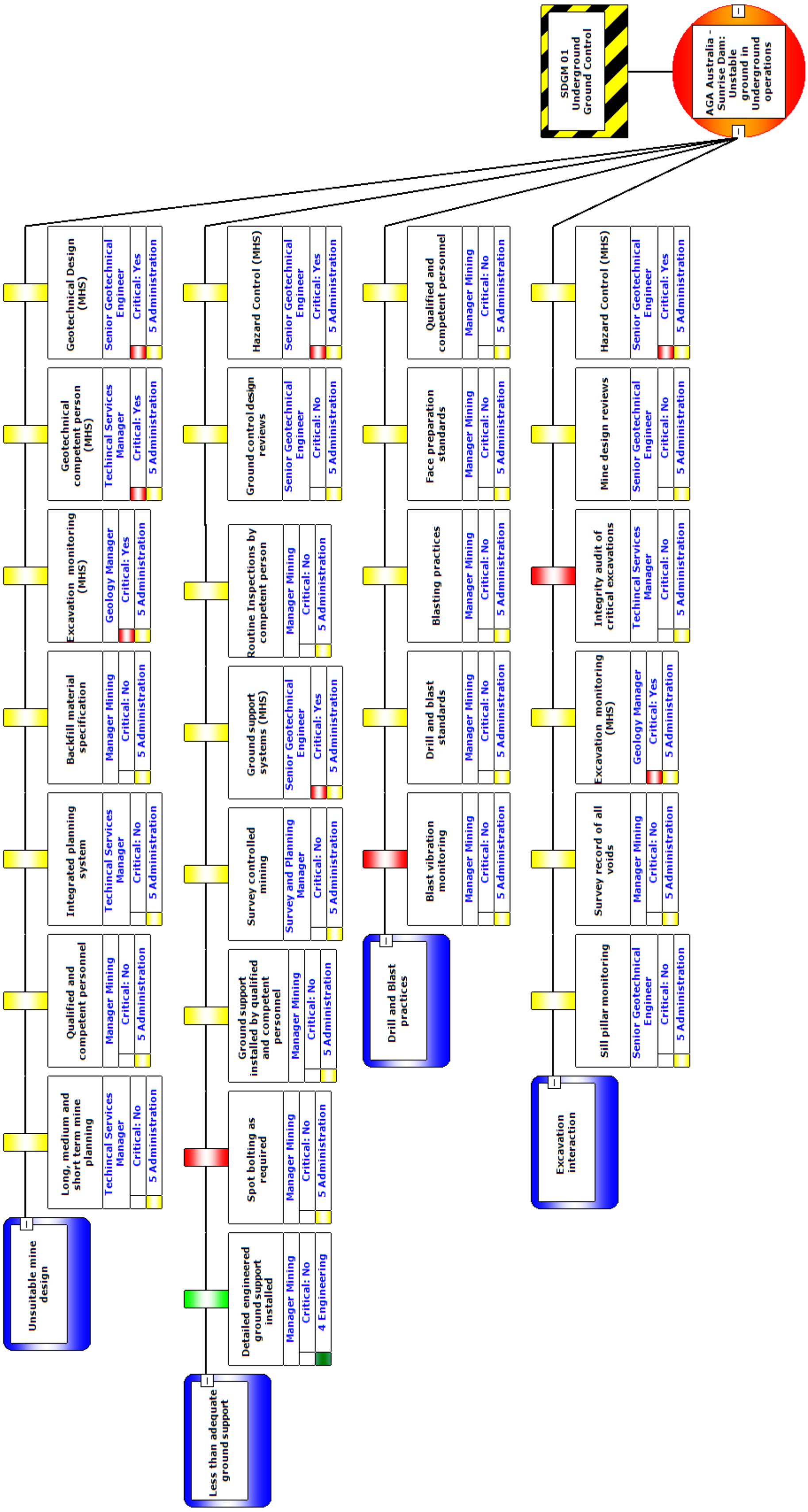


Figure C.2: Second section of the pro-active side of the SDGM bow-tie model for Ground Control

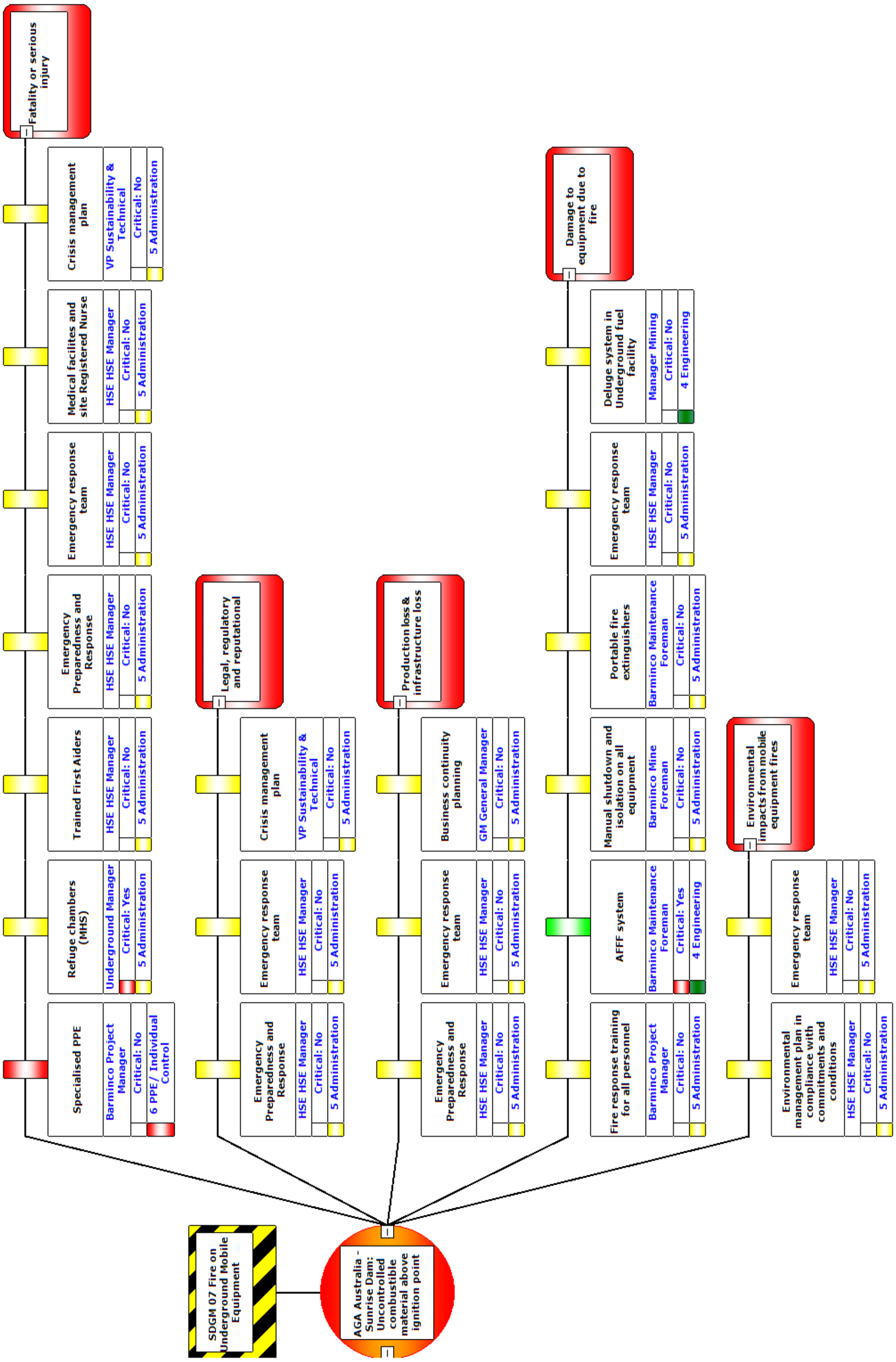
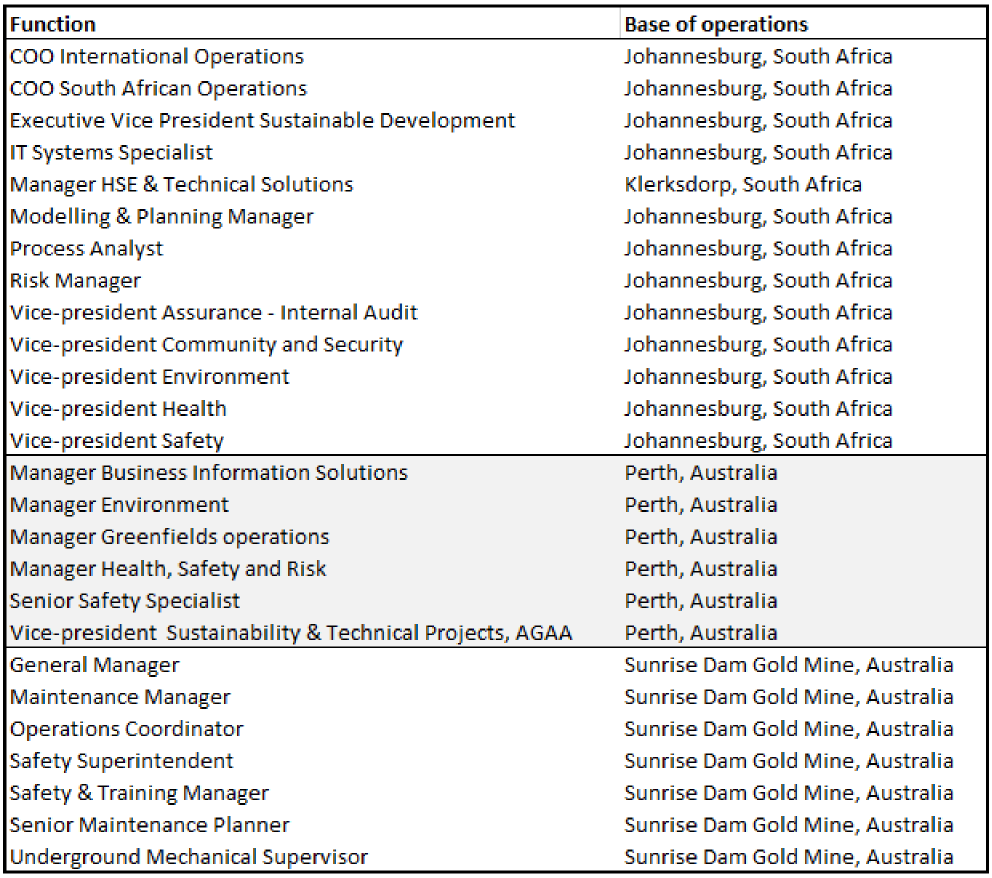


Figure C.3: Complete section of the reactive side of the SDGM bow-tie model for Underground Fire

D

Interview data

In this Appendix, the function titles of AngloGold Ashanti officials interviewed as well as their base of operations can be examined for reference to the creation of organizational requirements. In Table D.1, the functions and base of operations of the employees interviewed can be viewed in alphabetical order.



Function	Base of operations
COO International Operations	Johannesburg, South Africa
COO South African Operations	Johannesburg, South Africa
Executive Vice President Sustainable Development	Johannesburg, South Africa
IT Systems Specialist	Johannesburg, South Africa
Manager HSE & Technical Solutions	Klerksdorp, South Africa
Modelling & Planning Manager	Johannesburg, South Africa
Process Analyst	Johannesburg, South Africa
Risk Manager	Johannesburg, South Africa
Vice-president Assurance - Internal Audit	Johannesburg, South Africa
Vice-president Community and Security	Johannesburg, South Africa
Vice-president Environment	Johannesburg, South Africa
Vice-president Health	Johannesburg, South Africa
Vice-president Safety	Johannesburg, South Africa
Manager Business Information Solutions	Perth, Australia
Manager Environment	Perth, Australia
Manager Greenfields operations	Perth, Australia
Manager Health, Safety and Risk	Perth, Australia
Senior Safety Specialist	Perth, Australia
Vice-president Sustainability & Technical Projects, AGAA	Perth, Australia
General Manager	Sunrise Dam Gold Mine, Australia
Maintenance Manager	Sunrise Dam Gold Mine, Australia
Operations Coordinator	Sunrise Dam Gold Mine, Australia
Safety Superintendent	Sunrise Dam Gold Mine, Australia
Safety & Training Manager	Sunrise Dam Gold Mine, Australia
Senior Maintenance Planner	Sunrise Dam Gold Mine, Australia
Underground Mechanical Supervisor	Sunrise Dam Gold Mine, Australia

Table D.1: List of function titles and base of operations of employees interviewed