

**A methodology for risk-based management of the remaining life  
of structures in vertical mine shafts through integrated structural  
inspection and maintenance**

by

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## ABSTRACT

Mine shaft structures play a crucial role in mining operations, and their structural integrity is essential for ensuring operational safety. However, these structures deteriorate over time because of various factors such as corrosion, cracking, structural damage and structural ageing. The structural deterioration impacts on production, safety, and the environment. Estimating their remaining life is critical for preventive maintenance planning and ensuring continued operation. Corrosion significantly affects steel structures, leading to accelerated deterioration and potential catastrophic failures. Regular Structural Inspection and Maintenance Management (SIMM) programmes are essential to detect and address wear, preventing failures, and extending shaft lifespan.

Challenges persist in managing corrective measures for mine shaft maintenance, hampering data reliability and informed decision-making. The disconnect between structural inspection results and maintenance systems leads to unaddressed defects and inadequate tracking of critical maintenance in Computerised Maintenance Management Systems (CMMS). This gap hampers informed decision-making regarding life cycle cost (LCC) and life of mine (LoM) estimation. This dissertation aims to bridge the gap by integrating structural inspection and maintenance data with CMMS, proposing the Integrated Structural Inspection and Maintenance Management System (iSIMM) and prognostic and risk/economics-based maintenance decision-making model for improved structural maintenance in the mining industry.

The research journey starts by exploring mine shaft intricacies and the SIMM, followed by an extensive literature review on structural health and monitoring, covering corrosion, ageing, maintenance, and regulatory requirements. It progresses to developing an iSIMM and a maintenance decision-making model. Validation through a case study at Harmony Gold Mine confirms the practical application of these models in real mining environments.

The research findings underscore the potential extension of mine shaft structures' lifespan by timely replacement of degraded parts, ensuring continuous operations without significant disruptions. Investors have the opportunity to assess risks and returns for possible mine life extension. The implementation of an integrated inspection system enhances visibility into required maintenance for the mine shaft structures, facilitating effective monitoring of maintenance progress and structural condition changes affected by proper upkeep. Proactive monitoring and management practices contribute to

reducing LCCs by employing risk-based inspection and condition-based maintenance strategies for optimal maintenance.

Moreover, the prognostic and risk/economics-based maintenance decision-making model aids in estimating mine life and supports resource planning. Predictive modelling plays a vital role in determining replacement costs, contributing to future budget planning efforts.

The credibility and dependability of the findings are based on the analysis of reports from third-party structural engineering inspections conducted over the past decade. These findings have been verified through physical inspections, in-depth discussions with both mine engineers and contracted structural engineers, and consultations with the engineering teams responsible for performing regular shaft examinations.

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## ABBREVIATIONS

<b>Abbreviation</b>	<b>Definition</b>
CBDA	Corrosion-Based Design Approach
CBM	Condition Base Maintenance
CM	Corrective Maintenance
CMMS	Computerised Maintenance Management Systems
DMRE	Department of Mineral Resources and Energy
EPCM	Engineering, Procurement and Construction Management
FAT	Failure Analysis Test
FEA	Finite Element Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
iSIMM	Integrated Structural Inspection and Maintenance Management
LCC	Life Cycle Cost
LoM	Life of Mine
MHSA	Mine Health and Safety Act
NDE	Non-Destructive Evaluation
PRA	Probabilistic Risk Assessment
PM	Preventive Maintenance
RBI	Risk-based Inspection
RUL	Remaining Useful Life
SHM	Structural Health Monitoring
SIMM	Structural Inspection and Maintenance Management
SPR	Statistical Pattern Recognition
SSM	Systemic Structural Modelling

## TERMS AND DEFINITIONS

<b>Term</b>	<b>Definition</b>
Headgear	The superstructure above the shaft bank used for normal winding including overrun space.
Major repairs	Any work which due to time required or complexity is noted during shaft examination and then carried out at a convenient time.
Nominal guide gauge	Design dimensions between guides or set of shaft guides as specified on the relevant shaft drawings.
Routine repairs	Minor repairs that can be performed during shaft examination (while not impeding the purpose of the normal shaft examination).
Safety devices	As used in the shaft examination shall mean:  Handrails, a roof or cover as per the Mine Health and Safety Act, regulation 16.13 and 16.14, and full safety harnesses or any other device used during the examination to provide for the safety and health of the persons carrying out the examination, or as prescribed by the responsible engineer.
Shaft	The portion of the total system below the bank, including overrun space at shaft bottom and any contiguous system for the hoisting of spillage from the shaft bottom.
Shaft equipment	Any structure that would support the pathway of the conveyance and any structure that would be required inside the shaft to support ancillary equipment in the shaft, namely pipe columns, electrical cables, etc.
Shaft station	Any landing or place used for stopping, loading or offloading men or material in the shaft.
Sidewall	Any vertical/inclined rock face or concrete lined face, which forms the lining of the shaft, against which the support structures are mounted throughout the entire shaft.
Station safety device	An approved device installed for preventing inadvertent entry of any persons, rail bound equipment and trackless mobile machinery into unauthorised areas at the station and shaft.

## CHAPTER 1: INTRODUCTION

This section provides an introduction to the main topic, focusing on the intricacies of mine shafts. It explains the core concept of a mine shaft, detailing its typical characteristics and different subsystems. It also discusses the structural elements within a mine shaft and their crucial role in ensuring safety during operations. Furthermore, it explores the SIMM used in the mining industry, highlighting its methodologies and current implementation. In addition, it investigates the common structural failures observed in mine shafts, offering valuable insights into their implications. Finally, the chapter outlines the selected research methodology, detailing the approach used to thoroughly analyse and address key aspects of mine shaft structures and their maintenance.

### 1.1 BACKGROUND

South Africa is renowned for its abundant mineral resources, with mining playing a pivotal role in the country's economy. The mining sector encompasses various significant contributors such as gold, platinum, diamond, iron ore, and coal mines. However, it is important to note that these are not the only contributors (Fedderke and Pirouz, 2002).

In every country, the extraction, processing, and sale of minerals necessitate obtaining a permit from the government. Acquiring such a permit entails a substantial amount of work to ensure compliance with a set of Acts and regulations throughout the entire lifespan of the mine and its operations. Once the permit is obtained, maintaining it primarily revolves around adhering to legislation that prioritises environmental care, safety, health, and the well-being of both mine workers and the surrounding community.

For the past 150 years, the mining industry has exerted a profound influence on the South African economy (Davenport, 2013). Since the discovery of diamonds in 1867 and subsequent gold findings, the mineral sector's contributions have propelled South Africa into becoming the most advanced economy in Africa. Despite ongoing economic challenges, South Africa remains firmly established as a prominent global participant, both owing to the substantial value of its mineral resources and its robust industrial and supplier sectors (Korinek and Ramdoo, 2017). Currently, South Africa holds its position as the world's largest producer of platinum, vanadium, manganese, vermiculite, and chrome. In addition, it ranks as the second largest producer of ilmenite, palladium, zirconium, and rutile. Notably, South Africa stands as the third-largest coal supplier and a significant producer of iron ore and gold, as reported by the United States Geological Service (Davenport, 2013).

### 1.1.1 Typical vertical mine shaft

A mine shaft is a vertical entry hole with a considerable diameter that extends deep into the earth, reaching the lowest point where valuable minerals are located (refer to Figure 1.1 below). It serves as the primary access point for mining operations, providing a workspace for miners, equipment, and machinery (Annels, 2012). Vital utilities such as water, ventilation, and electricity are conveyed through the mine shaft to the working areas where ore is extracted. To transport the ore to the surface, hoists move up and down the mine shaft.

Mine cages are structures constructed from steel and aluminium, designed to transport miners and other personnel working within the shaft. Operating similarly to elevators in tall buildings, these cages travel up and down the shaft while adhering to mandatory manufacturing standards to ensure safe and efficient operations (Cortie, McEwan and Enright, 1996).

Figure 1.1 presents a cross-sectional view of a typical mine shaft, showcasing the structural components characteristics of underground shaft and slope mines. Within the shaft mine, there are dedicated compartments for a skip hoist or elevator, cages and essential service amenities like ventilation ducts. Similarly, in a slope mine, miners operate across various levels, and the transportation of ore to the surface is executed using bucket hoists (Giraud and Galy, 2018; Jones, 2012).

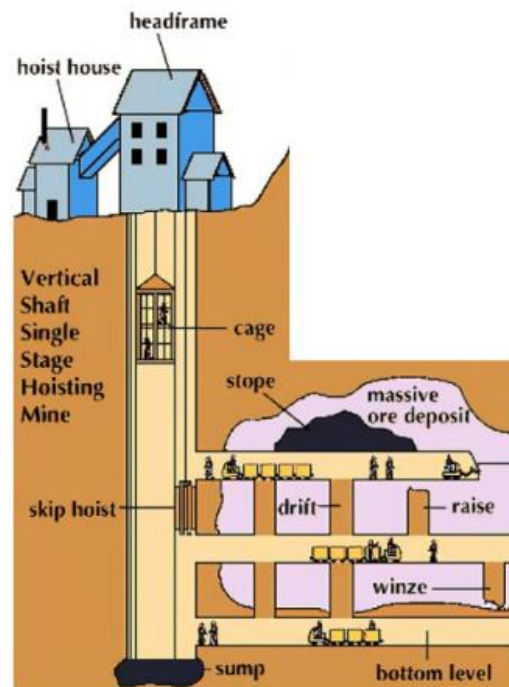


Figure 1.1: Vertical mine cross-section (Encyclopedia Britannica, Inc.)

### 1.1.2 The function of the mine shaft system

Deep mining is a method commonly used to extract mineral deposits, and mine shafts play a vital role in such operations. These shafts serve as crucial infrastructure by enabling access for mining activities, transporting personnel, and delivering necessary equipment. In addition, they facilitate the conveyance of essential resources like ventilation, compressed air, electricity, and water to support the functioning of the mine. Given their critical role, it is of utmost importance to regularly monitor mine shafts to mitigate the risk of potential damage or safety incidents.

In a typical mining setup, there are both underground operations and multiple surface treatment processes. The gold mine employs a design featuring paired vertical and sub-vertical shaft systems, applying conventional mining techniques in a grid layout. The deepest shaft descends beyond 4 kilometres and serves as the primary vertical access point to reach valuable mineral deposits. It functions as a conduit to the mining site, accommodating miners, equipment, and machinery. Crucial resources like water, ventilation, and electricity are routed through the shaft to the extraction zones. Hoists, facilitating vertical movement within the mine shaft, transport extracted ore to the surface.

As mine shaft structures age, the degradation becomes an anticipated challenge that can have detrimental effects on production performance, safety, and long-term environmental sustainability. Hence, estimating the remaining useful life of these structures becomes crucial in determining the necessary preventive maintenance measures to prevent degradation from reaching a point where the mine would need to be shut down. In addition, understanding the remaining useful life aids in formulating strategies that extend the lifespan through investments in time, financial resources, and suitable maintenance approaches (Cui, Huo, Xie, Xu, Kuang and Dong, 2022).

It is widely acknowledged that the integrity and lifespan of steel structures are adversely affected by corrosion, primarily due to the steel being exposed to atmospheric conditions (Peng, Jones, Berto and Razavi, 2018). In the case of mine shaft environments, wet conditions caused by groundwater and the presence of chemicals in the air often contribute to the deterioration process. The purpose of conducting inspections on structures and buildings is to identify various types of structural defects, signs of distress and deformation, and any indications of material deterioration. These inspections also aim to assess the loading arrangement on a structure or building and detect any deviations from its intended use, as well as instances of misuse or abuse that can lead to overloading.

Staffing the organisational structure includes individuals assigned to manage mining, processing, and final product sales permits, ensuring adherence to permit regulations. The engineering department within the organisation assumes a pivotal role. Maintenance engineers are responsible for machinery

safety, supervising operations, prioritising personnel safety while using machinery, and ensuring asset reliability.

Maintenance engineers have distinct roles dedicated to preserving the safety and integrity of the engineering infrastructure within the mine. There is limited knowledge regarding the strength and behaviour of the material or structural form (Rankine, Krige, Teshome, Grobler and Glauber, 1995). Hence, it is expected that the structural engineer will diligently conduct visual inspections of buildings, structures, and constructions, exercising reasonable care to assess their condition.

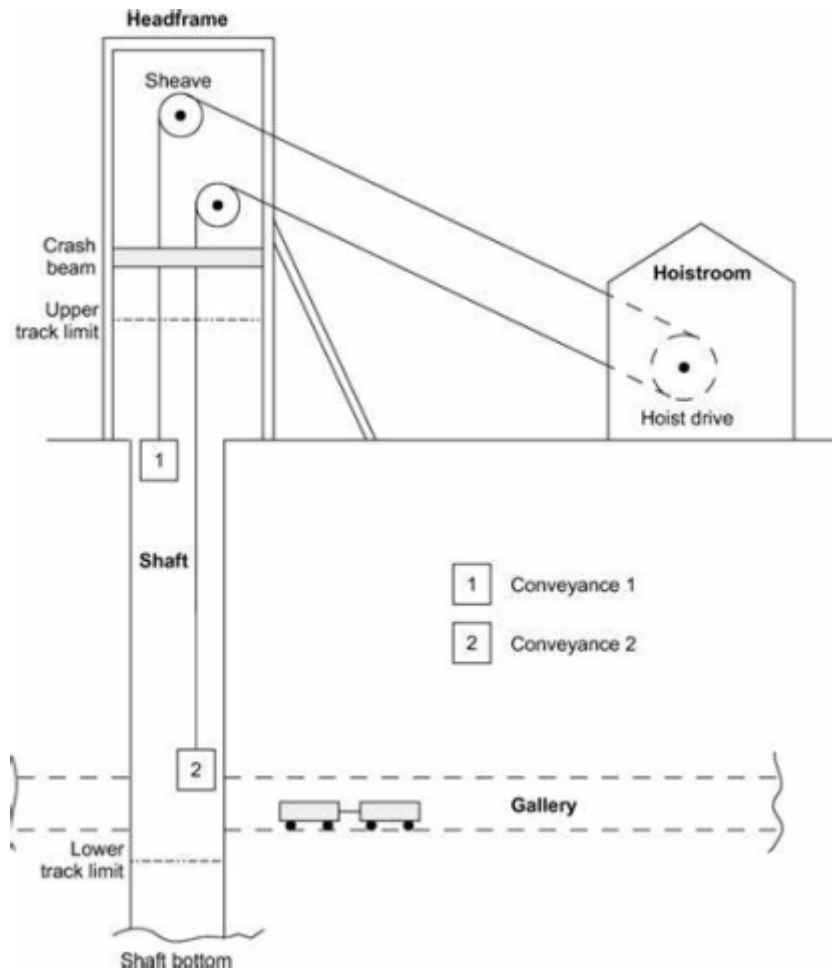
The addition or modification of any elements that affect the structure can lead to overloading or negative impacts on its integrity. Unless a structural engineer advises otherwise, a visual inspection is generally sufficient if there are no indications of structural deterioration or defects. However, if noticeable signs of significant structural deterioration or defects are detected, it is necessary for a structural engineer to assess the situation professionally and provide recommendations for appropriate actions.

The gold mine considered in this study is subject to an extremely corrosive setting. This heightened corrosiveness is primarily attributed to the substantial influx of water, stemming from the seepage of a nearby water dam. When comparing corrosion rates, mine shafts typically exhibit notably higher levels of corrosion compared to residential areas. This discrepancy can be attributed to the elevated presence of moisture and air pollutants within mine shafts. These actions may include repairs or a comprehensive investigation of specific components or the entire structure.

Refer to Figure 1.2, depicting the main components of a mine shaft (Giraud and Galy, 2018).

A typical mine shaft consists of:

- the shaft barrels
- shaft steelwork
- headgear/headframe
- sheave wheels
- safety devices
- tip storage bins
- bulk air cooler columns
- pipes for service water and chilled water
- electrical cables
- mud columns



**Figure 1.2: Mine shaft main component (Giraud and Galy, 2018)**

The integrity of mine shafts, related systems, and shaft operations is crucial because of the significant energies and forces involved. When these structures are compromised, there are heightened risks involved. Over the past few years, there have been numerous instances of structural failures occurring during project construction and mine operation in various mining companies. These structural failures are considered high-risk incidents. Insufficient performance of structures can have severe consequences on safety and production, and result in costly repair work. Therefore, it is imperative to prevent structural failures. To address this issue, recent amendments to the Occupational Health and Safety Act 85 of 1993 (Republic of South Africa, 1993) have made regular structural inspections a legal requirement. Furthermore, the South African National Standard guideline (SANS 10160: Basis for structural design and actions for buildings and industrial structures) has been introduced to assist in preventing subpar designs.

The longevity of vertical mine shafts relies on the state of their structures. The integrity of mine shaft conveyance systems and their subsystems is crucial for ensuring the safe transportation of materials and personnel to and from underground work areas. Therefore, maintaining the condition of the vertical mine shaft structure is vital for supporting the productivity of mining operations. It is crucial to prioritise

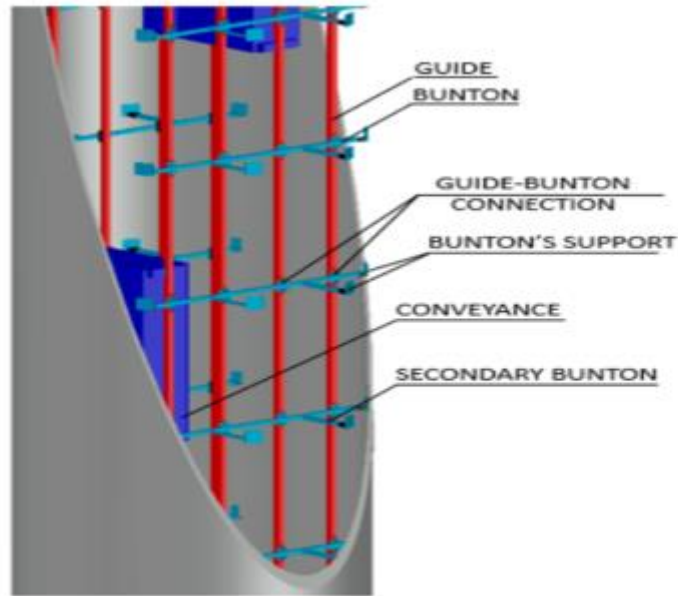
the estimation of the remaining useful life (RUL) of equipment, as this knowledge plays a vital role in the development of condition-based and predictive maintenance strategies (Yang and Frangopol, 2021).

### 1.1.3 Mine shaft steelwork

Figure 1.3 below highlights a significant characteristic of vertical mines shaft steelwork. This steelwork plays a crucial role in guiding the linear motion of mine conveyances within the vertical shaft. The cages and skips, with a combined mass ranging from 20 to 80 tonnes, smoothly traverse along the guides at speeds of 20 to 60 km/h. In a typical mine in South Africa, the main shaft steelwork consists of horizontally mounted main and secondary buntons, complemented by vertically mounted guides attached to the buntons. Proper alignment of guides is essential for the dynamic performance of conveyances in mineshafts. Misalignment can introduce significant dynamic loads and movements, negatively impacting the safety and operational efficiency of the conveyance system. As noted by Krige (1983), the primary cause of such dynamic behaviour is likely guide misalignment. While complete elimination of misalignment is not feasible, it is typically maintained within specified limits of approximately  $\pm 6$  mm from a vertical reference line. This misalignment can lead to horizontal accelerations reaching two or three times the force of gravity, resulting in fatigue damage and potential plastic deformation of the conveyance or guides, especially when dynamic excitation coincides with natural frequencies.

Furthermore, the effective position of the guides is influenced by factors such as wheel preload and guide stiffness, which together establish the baseline guide position necessary for accurately modelling the conveyance's behaviour (Krige, 1983). Consequently, ensuring proper guide alignment is critical for minimising dynamic loads and maintaining the safe operation of mining conveyances. Excessive guide displacement can lead to dangerous conditions, such as a conveyance becoming wedged between guides, which may result in slack rope scenarios. These slack conditions are especially hazardous, as they can cause uncontrolled descents of the conveyance (Beus, Hatzikiriakidis and van der Merwe, 2023). Misalignment of the rope guides can have a substantial impact on rope tension; for instance, when the guides are displaced, the tension in the rope may drop to around 60% of the conveyance's weight, creating the risk of a sudden drop when the slack is taken up (Beus, et al., 2023). In South African mining operations, visual inspections of the guides are mandated as part of standard procedures, and when misalignment is detected, appropriate remedial actions are implemented.

Figure 1.3 provides a simplified visual representation of this essential shaft steelwork (Jakubowski and Fiołek, 2021).



**Figure 1.3: Rough depiction of the steelwork within a shaft (Jakubowski and Fiolek, 2021)**

#### 1.1.4 SIMM

Regulation 16 of the South African Mine Safety and Health Act of 1996 mandates regular inspections of mine shaft structures to identify any defects or weaknesses. The SIMM tool facilitates these required inspections, tracks findings, and assists in resolving issues such as structural wear and tear. (Erling, 2012; Republic of South Africa, 1996).

The inspection system involves regularly examining the condition of a mine shaft and rating the condition. Inspecting structures is essential to assess their physical condition. Well-executed inspection programmes are pivotal in reducing structural failures, concentrating on maintenance, taking corrective actions, and prolonging the structure's lifespan. Regular inspections hold particular importance for industrial structures (Go, Morgan and Gatto, 2021). The mine shaft's environment and mechanical stress contribute to the deterioration of concrete and steel structures.

By taking action based on inspection findings and effectively managing them, uncertainties and risks can be reduced. Implementing an inspection system for mine shafts enhances decision-making processes, maintenance quality, safety, and reliability at an optimal cost. Proactive monitoring and management of the mine shaft's condition, as indicated by the inspection system, are crucial for minimising LCC. This approach offers the opportunity to utilise risk-based inspection (RBI) and condition-based maintenance (CBM) methods, depending on the value of information obtained from inspections (Chen and Bai, 2019).

SIMM are primarily visual inspections, and there is a full description of what must be inspected during a visual inspection and in how much detail. This allows maintenance and structural engineers to understand the specific expectations for each inspection. Subsequent to every inspection, it is crucial to report the condition of the structures to mine management, enabling informed decisions about the mine's future and its structural maintenance.

Various defects in both the lining and reinforcement within these shafts are scrutinised, ranging from micro cracks, wear out, inrush, crusting, openings and weakening of attachments, to mechanical damages (Pleshko, Kulikova and Nasonov, 2018). This survey process involves meticulous analysis of design documentation, visual and instrumental inspections, determination of actual parameters of the lining and reinforcement, and assessment of material strength. For data analysis, the five-point scale protocol is employed to categorise the findings of shaft inspections, assessing the technical condition of vertical shafts in Russia. This protocol aids in the examination and identification of defects in the lining and reinforcement by detecting deviations from design criteria, regulatory requirements, and damage sustained during operation. It generates conclusions and recommendations for the continued use of shafts (Pleshko, et al., 2018). Rating scales provide structured conclusions and recommendations for continued operations, emphasising the importance of rating inspection findings and guiding remedial actions.

During the inspection, the structural engineer identifies any structural elements in the shaft that might compromise safety and must document these as safety-critical findings in a formal report. Collaboration between the mine maintenance engineer and an external structural engineer is essential to promptly address these safety concerns.

Mining companies have introduced SIMM protocols to adhere to regulatory requirements, typically involving periodic assessments conducted by an external structural engineer. The SIMM report encompasses overall observations covering safety issues, structural defects, and maintenance-related matters that might contribute to accelerated structural degradation.

Anglo American is a multinational mining company with its headquarters in London, United Kingdom. It is one of the world's largest and most diversified mining companies, operating in various regions globally. Anglo American developed the condition rating of the structures which is now adopted widely in the mining industry. The 1 to 5 scale condition rating system used by Engineers Australia in the Infrastructure Report Card helps identify defects and assess the condition of industrial structural components, aiding in determining their remaining lifespan. Defects rated 4 or higher typically necessitate intervention, such as repairs or monitoring. This system provides guidelines for inspections, facilitating defect identification and overall condition assessment. After inspections, condition ratings

can be aggregated to offer a comprehensive overview of structures (Go, Morgan and Gatto, 2021), emphasising the critical role of a rating system in categorising findings and guiding remedial actions.

The scope of inspection necessary for deteriorating structures can be notably extensive, rendering the process arduous and demanding. However, the SIMM method has introduced a systematic framework by standardising the assessment of deterioration levels attributed to various causes. This systematic approach facilitates the prompt identification of critical issues, enabling swift implementation of remedial measures. Despite streamlining the process, it does not diminish the essential effort required for this crucial task. Instead, it eradicates uncertainties and sweeping generalisations that have historically led to complications (Erling, 2012).

The SIMM condition rating system is designed to identify potential failures and assess the extent of early-stage deterioration, primarily attributed to factors like corrosion and falling debris (Anglo American, 2011c).

The primary focus of the structural framework's functional requirements is on safety, stability, and achieving optimal functionality. Measures such as secure flooring aim to prevent hazards, while adherence to strength and stiffness standards aim to prevent structural failure and reduce deflections (Erling, 2012).

## **1.2 PROBLEM STATEMENT**

In the mining industry, the occurrence of structural failures in vertical mine shafts poses a significant threat to both worker safety and the ongoing viability of operations. The ageing infrastructure of gold mines, particularly the vertical and sub-vertical shaft systems, necessitates a proactive stance towards preserving structural integrity. Presently, the implementation and integration of SIMM practices within this sector are inadequate, resulting in insufficient maintenance and potential risks.

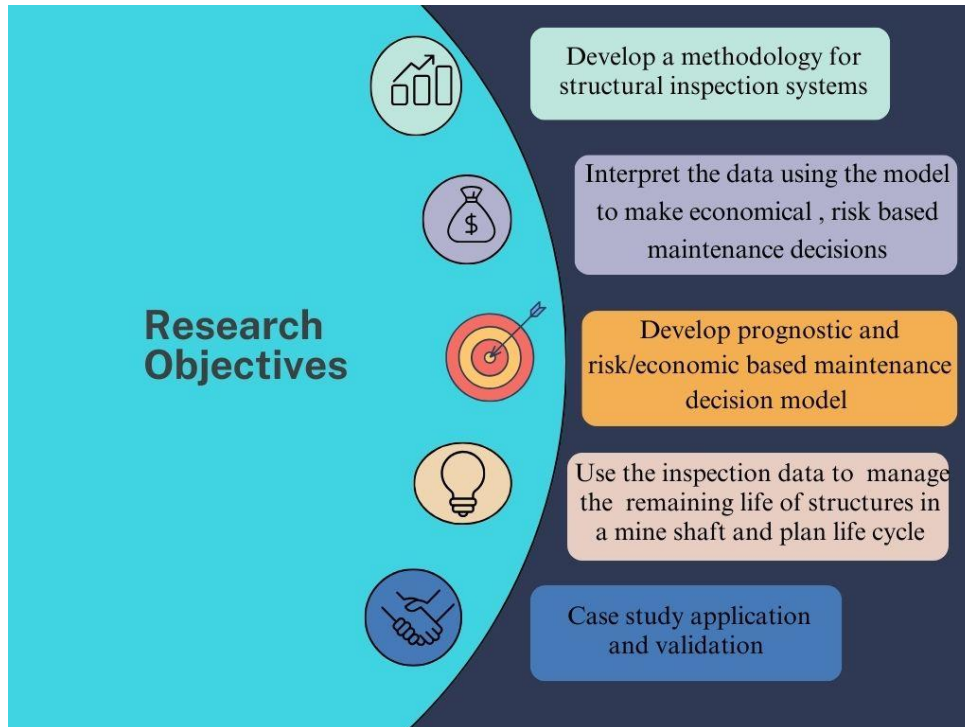
This dissertation seeks to propose remedies by introducing two significant methodologies:

- the development of an iSIMM
- the development of a prognostic and risk/economics-based maintenance decision-making model

These innovative systems and approaches aim to completely transform the existing paradigm of structural inspection and maintenance in the mining industry. The principal goal is to address prevalent deficiencies in implementation strategies, facilitate seamless integration of inspection data, and elevate the monitoring process. Ultimately, these proposed solutions strive to chart a course towards a safer and more sustainable future for mining operations.

### 1.2.1 The objectives for research

The illustration in Figure 1.4 below provides a visual representation of the primary goal that this dissertation seeks to achieve. In this graphical depiction, we can observe and understand the overarching objective that guides the content and focus of the dissertation.



**Figure 1.4: Research objectives**

### 1.2.2 Benefits

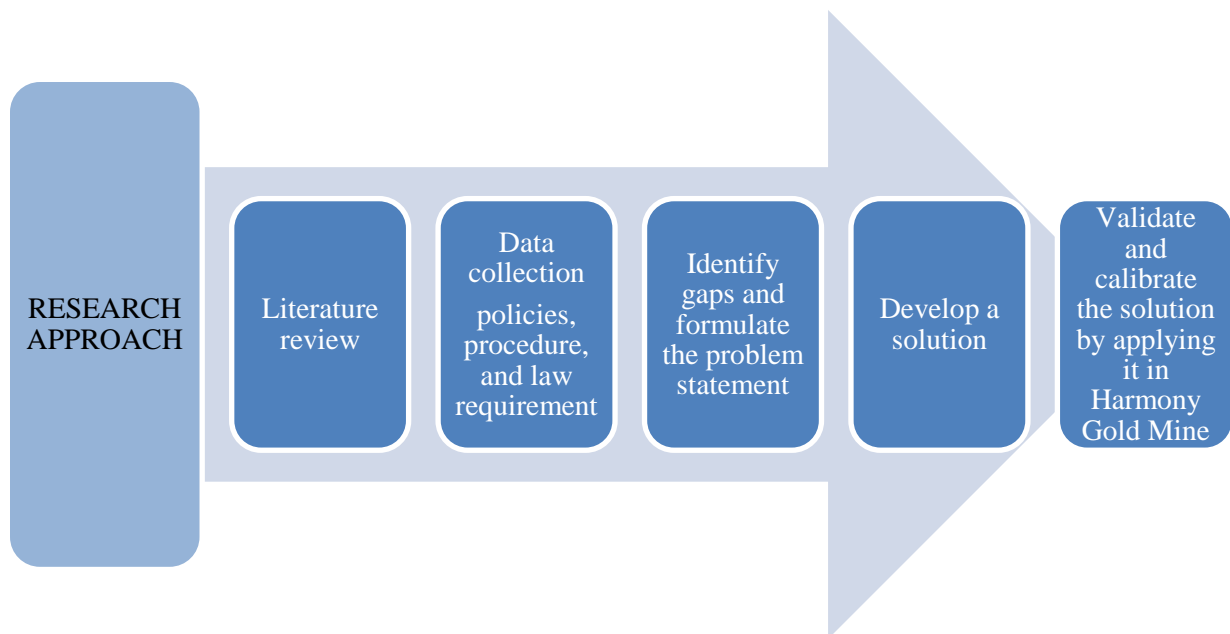
The main benefits of employing these methodologies and approaches in the mining industry are:

- **Enhanced safety measures:** By introducing the iSIMM and the prognostic and risk/economics-based maintenance decision-making model, the mining industry significantly improves its ability to assess and manage the remaining life of structures in mine shafts. This proactive stance contributes to a safer working environment, minimising the potential hazards posed by structural failures and prioritising worker safety.
- **Cost-efficient operations:** The utilisation of structural health monitoring (SHM) techniques and the integration of diverse sensors offer a data-driven approach to predicting the RUL of structures. This knowledge empowers the industry to implement more cost-effective condition-based maintenance (CBM) strategies, optimising maintenance efforts, and reducing unnecessary operational costs arising from inefficient, time-based maintenance practices.

- Optimised planning and budgeting: The incorporation of LCC analysis, excluding initial design and construction expenses, allows for effective planning and budgeting across the entire service life of mining structures. This approach aids in estimating net present value and offers a comprehensive view of costs, facilitating informed decisions concerning maintenance strategies and resource allocation.
- Improved decision-making: The shift from traditional time-based maintenance to predictive and condition-based strategies revolutionises decision-making within the industry. It enables more informed, reliable, and cost-effective decisions based on accurate insights derived from historical failures, repairs, and maintenance activities, excluding the initial design and construction costs.
- Sustainability and longevity: Implementing these innovative methodologies signifies a move towards a more sustainable future for mining operations. By assessing LCCs, predicting remaining useful life, and implementing condition-based maintenance, the mining industry aims to extend the life of structures in mine shafts responsibly, ensuring the longevity and sustainability of mining operations.

### 1.2.3 Research approach

Figure 1.5 delineates the comprehensive research approach undertaken in this study.



**Figure 1.5: Research approach**

In this work, conducting a literature review was pivotal, facilitating an in-depth exploration and understanding of previous scholarly works. These reviews allowed the author to identify advancements in the field, providing a comprehensive view of the existing knowledge landscape. The understanding

of this played a pivotal role in identifying gaps and steering subsequent investigations. This elaborate process entailed delving into a myriad of sources to extract valuable insights into methodologies, discoveries, and conclusions put forth by others, thereby shaping and establishing the framework for the current research trajectory.

The objective of data collection was to acquire a comprehensive record of structural inspection and maintenance activities over the past decade. To achieve this, maintenance activity data was logged within a CMMS software application. This software facilitated the retrieval of data for analysis purposes. An intriguing observation made during this process revealed that a substantial portion of mine shaft operations lack the necessary rigour in capturing remedial actions stipulated by structural engineers.

In instances where data has not been documented within the CMMS, alternative sources were sought. The data collection process entailed visiting eight mine shaft operations.

Where information was not accessible through the CMMS software, it was likely to be available within files or emails maintained by mine engineers. These on-site visits served a dual purpose: apart from data collection, they also provided an avenue for conducting interviews with mine engineers, supervisors, artisans, timbermen and planners. These interactions delved into matters concerning the management of structural inspection and maintenance processes.

#### **1.2.4 Significance of research**

The structural integrity of a mine shaft is deteriorating over time due to ageing. Given the significant energies and forces involved in mine shafts, their related systems, and operations, there are heightened risks if the integrity of these structures becomes compromised. In preceding years, several instances of catastrophic incidents involving mine shafts were reported by mining companies. Despite the gold mine's aspiration to continue mining operations for another seven decades, this objective will remain unattainable unless rigorous monitoring and maintenance of the mine shaft's structural integrity are upheld.

To address this challenge, the researcher developed a monitoring system that focuses on anticipated preventive remedial measures to effectively manage the life span of the mine shaft. By implementing an integrated monitoring system tailored for the mine shaft, it is believed that greater visibility, efficient monitoring, and enhanced execution of remedial actions identified during structural inspections will be achieved.

It is anticipated that the establishment of an integrated platform for recording, managing, and monitoring the inspection and maintenance of structures will empower mine managers and executives to contemplate the future ramifications of their current decisions.

### **1.3 DOCUMENT OVERVIEW**

The dissertation commences with Chapter 1, the background. This section serves as an introduction to the overarching topic, delving into the intricacies of mine shafts. It elucidates the fundamental concept of a mine shaft, explaining its typical characteristics and various subsystems. Furthermore, it expounds upon the structural components within a mine shaft and their criticality in ensuring operational safety. The chapter also explores the SIMM within the mining industry, shedding light on its methodologies and how it is currently executed. In addition, it examines the primary structural failures commonly observed in mine shafts, providing valuable insights into their implications. Finally, the chapter delineates the chosen research methodology, outlining the approach undertaken to comprehensively analyse and address the pertinent aspects of mine shaft structures and their maintenance.

Chapter 2 of the dissertation delves into a comprehensive literature review encompassing structural health monitoring. This section meticulously examines a range of factors that affect the structural integrity of mine shafts. It covers diverse elements such as the influence of falling objects in shafts, susceptibility to corrosion, and how age probabilistically affects structural components. Furthermore, it scrutinises human errors, insufficient designs, and their subsequent effects on structural integrity.

The chapter delves into the potential threat posed by fatigue cracks and thoroughly explores decision-making in maintenance practices, utilising tools like failure modes, effects and criticality analysis (FMECA) and employing risk-based maintenance strategies. Moreover, it scrutinises the regulatory requirements within the mining industry while identifying gaps in existing literature. This lays a strong foundation for defining the problem statement and research objectives, aiming to bridge these gaps and elevate the understanding and management of structural health in mine shafts.

Chapter 3 focuses on the development of an iSIMM. This pivotal chapter delves into creating the structural inspection system itself, outlining its design and development intricacies. It explores the integrated system's functionality, elucidating how various components work together for effective management. Moreover, it outlines the overall logic governing the system's operations, providing insights into its comprehensive functioning. In addition, the chapter delves into the critical aspect of shaft baseline inspection, elucidating the foundational process and its significance within the broader context of the iSIMM.

Chapter 4 focus on developing a prognostic and risk/economics-based maintenance decision-making model, a crucial endeavour. This chapter extensively covers the methodology of iSIMM, delving into

the intricacies of this innovative system, which integrates prognostic and risk-based models for maintenance decision-making. It examines the profound effects of corrosion rates and corrosion probability on structural health, shedding light on their implications within mine shafts. Furthermore, it explores the impact damage and immerses into numerical experience using finite element analysis (FEA) experiments, studying the combination of failure mechanisms and predicting the number of failures. Moreover, it assesses the condition of structural members within mine shafts and analyses LCC based on the failure analysis test (FAT) results, aiming to optimise maintenance decisions from an economic perspective. This comprehensive chapter forms a pivotal aspect of the dissertation, emphasising a forward-thinking approach to mine shaft structural management.

Chapter 5, focuses on the application and validation through a case study conducted at Harmony Gold Mine. This chapter serves to introduce Harmony as the selected site for the case study application, providing context to the mining environment and its relevance. It delves into an analysis of Harmony's current reporting system, showcasing the existing framework and its limitations. Moreover, the chapter presents the solution application, detailing how the developed iSIMM is implemented within the Harmony context. In addition, it emphasises the calibration process, highlighting the necessary adjustments and fine-tuning required for the successful integration and alignment of iSIMM within Harmony's operational framework. This chapter acts as a critical validation step, ensuring the practicality and effectiveness of the developed model within a real-world mining environment.

In Chapter 6, the research ends with a comprehensive conclusion. This segment encapsulates the key insights gathered through the research, significant learnings, and an outline of recommended avenues for future research endeavours.

Figure 1.6 provided below shows the document overview.

## DOCUMENT OVERVIEW

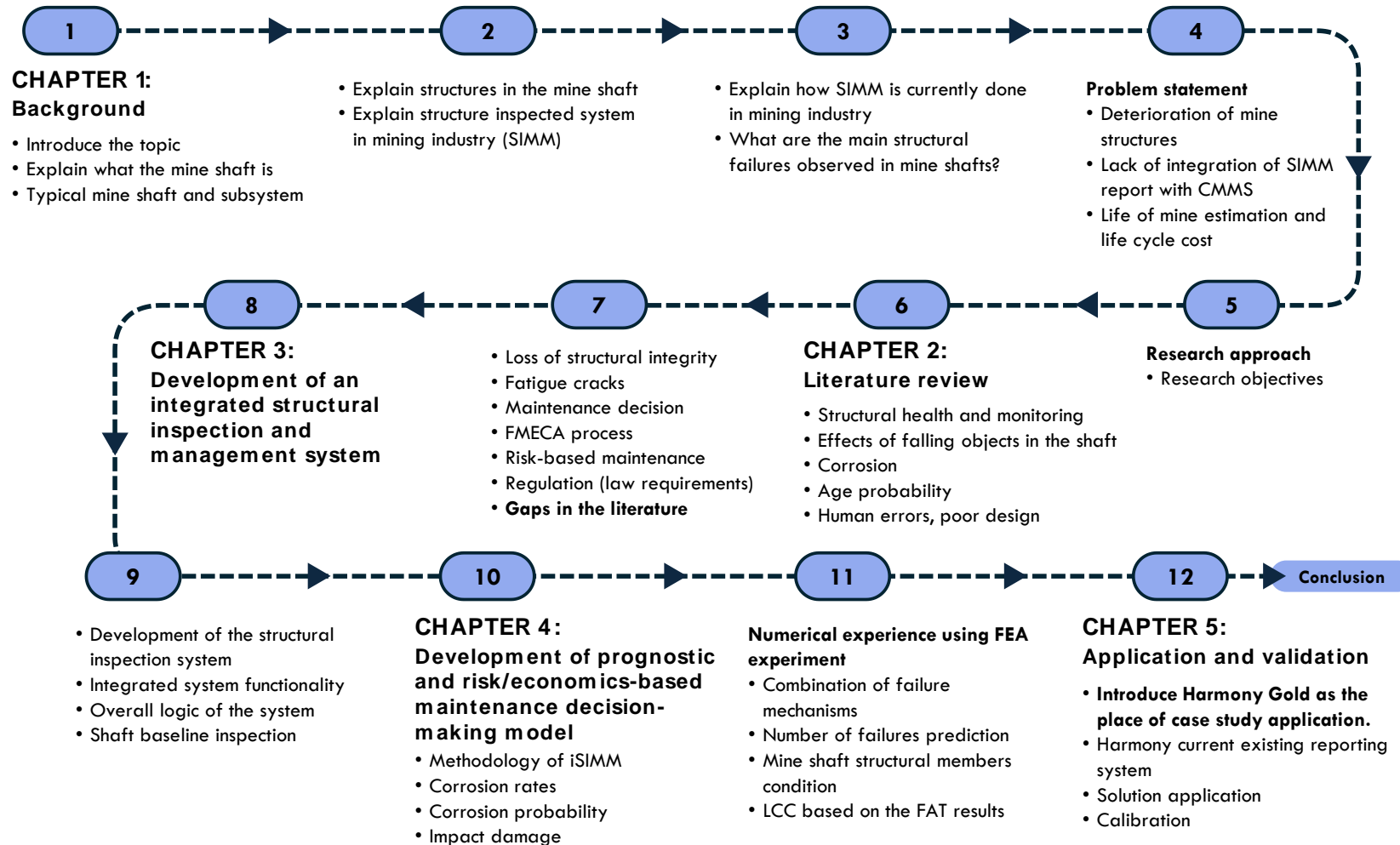


Figure 1.6: Signpost for the research process flow

## CHAPTER 2: LITERATURE REVIEW

### 2.1 INTRODUCTION

This section conducts an in-depth literature review focused on structural health and monitoring, examining various aspects that influence the structural integrity of mine shafts. It thoroughly investigates multiple factors including the impact of falling objects within shafts, susceptibility to corrosion, and the probabilistic effects of age on structural components. In addition, it analyses human errors, inadequate designs, and their subsequent implications on structural stability.

Furthermore, the chapter delves into the potential risks posed by fatigue cracks and extensively explores decision-making in maintenance practices. It utilises tools such as FMECA and risk-based maintenance strategies. Moreover, it scrutinises the regulatory requirements within the mining industry, pinpointing gaps in the existing literature. This forms a robust basis for defining the problem statement and research objectives, aiming to bridge these gaps and enhance the comprehension and management of structural health in mine shafts.

### 2.2 MAIN CONDITIONS THAT LEAD TO STRUCTURAL DETERIORATION

Understanding the conditions that lead to structural deterioration is pivotal in developing comprehensive maintenance strategies. Several factors contribute to the degradation of structural elements, each posing distinct challenges and implications for the integrity of the construction.

- **Corrosion:** One significant cause involves the corrosion of steel and reinforcing elements. This deterioration phenomenon can range from minor degradation (Condition 0) to severe deterioration (Condition 5), as showcased by visual examples illustrating rusting steel within concrete. This rusting leads to expansion, exerting pressure that causes concrete spalling, as supported by photographic evidence (Erling, 2012; Rao, Lepech, Kiremidjian and Sun, 2018).
- **Cracking:** Extensive examples were presented to delineate different types of cracking. These encompass fatigue-induced cracking, concrete shrinkage during curing (also applicable to timber), bursting due to expansion, and impact-related damage. These visual representations serve to underline the diverse nature of structural cracking (Erling, 2012).
- **Structural Damage:** Various forms of structural damage arise from falling objects, vehicle impacts, and pressure resulting from ground or foundation movements. The visual documentation aids in highlighting the potential sources and impacts of such damage on structural integrity (Erling, 2012).

A comprehensive understanding of these conditions offers invaluable insights into the multifaceted nature of structural deterioration and informs effective maintenance and mitigation strategies.

### **2.3 STRUCTURAL HEALTH MONITORING (SHM)**

Mechanical structures undergo continuous deterioration owing to operating conditions and ambient environmental factors. These degradation processes manifest in various forms such as corrosion, fatigue cracks, erosion, and strength reduction (Animah and Shafiee, 2018). The severity of these mechanisms hinges on factors like applied static/dynamic loads, operational settings, and material properties encompassing corrosion resistance, microstructural characteristics, crystallographic orientation, and grain-boundary structure.

Historically, the inspection and maintenance of mechanical structures primarily adhered to a preventive (time-based) approach. However, recent years have seen a heightened recognition of SHM techniques in evaluating structural health, predicting RUL, and executing CBM for degrading structures (Animah and Shafiee, 2018). The SHM approach involves gathering data from diverse sensors installed on structures and analysing these findings to make dependable and cost-effective decisions regarding CBM under varied operational conditions.

Various health assessment methods like bulk wave ultrasonic, X-rays, infrared thermography, and eddy current techniques effectively facilitate non-destructive evaluation (NDE) of structures. Nonetheless, many of these techniques, particularly in the case of large structures (such as pipelines, marine vessels, ships, and aerospace applications), tend to be sluggish and unwieldy.

Integrated SHM systems have enhanced the oversight, administration, and decision-making concerning bridges through ongoing surveillance and assessment of operational conditions (He, Li, Salehi, Zhang, Zhou and Jiao, 2022).

### **2.4 RISK MANAGEMENT AND PRIORITISATION**

Risk assessment plays a crucial role in pinpointing critical areas for the initiation of SHM implementation, emphasising urgent actions or high-priority tasks during the prioritisation phase. Specifically, regions presenting heightened risks are accorded precedence for the incorporation of SHM methodologies. The risk matrix depicted in Figure 2.1 operates as a tool for evaluating risk magnitude and streamlines the identification of essential measures intended to mitigate or minimise these risks.

The utilisation of a risk matrix aids in evaluating zones of risk exposure and delineating their boundaries. Typically, a risk matrix divides into three exposure zones: high, medium, and low. Dealing with risks in the high-exposure zone necessitates specific measures by an organisation, while those in the medium-exposure zone might warrant mitigation if the benefits outweigh the costs. The

establishment of boundaries within these exposure zones reflects the decision-makers' risk inclination, and standardised frameworks are available for this purpose.

Subsequently, decision-makers must set the risk appetite across these zones and devise an action plan aligned with the risk management strategy. The risk appetite is significantly lower for the high-exposure zone compared to the medium-exposure zone. Once the decision-makers establish this risk appetite, risks can be prioritised across the zones using proposed risk metrics, allocating resources based on their normalised risk indices. Figure 2.1 below illustrates the application of the proposed process.

CONSEQUENCE / SEVERITY	<b>C5</b>	High Risk	High Risk	High Risk	High Risk	High Risk
	<b>Catastrophe</b>	Stop Fix	Stop Fix	Stop Fix	Stop Fix	Stop Fix
		A	A	A	A	A
		H15	H19	H22	H24	H25
	<b>C4</b>	Medium Risk	High Risk	High Risk	High Risk	High Risk
	<b>Major</b>	Immediate Action Plan	Stop Fix	Stop Fix	Stop Fix	Stop Fix
		B	A	A	A	A
		M12	H14	H18	H21	H23
	<b>C3</b>	Medium Risk	Medium Risk	Medium Risk	High Risk	High Risk
	<b>Moderate</b>	Immediate Action Plan	Immediate Action Plan	Immediate Action Plan	Stop Fix	Stop Fix
	B	B	B	A	A	
	M9	M11	M13	H17	H20	
<b>C2</b>	Low Risk	Low Risk	Medium Risk	Medium Risk	High Risk	
<b>Minor</b>	Action Later	Action Later	Immediate Action Plan	Immediate Action Plan	Stop Fix	
	C	C	B	B	A	
	L3	L5	M8	M10	H16	
<b>C1</b>	Low Risk	Low Risk	Low Risk	Low Risk	Medium Risk	
<b>Insignificant</b>	Action Later	Action Later	Action Later	Action Later	Immediate Action Plan	
	C	C	C	C	B	
	L1	L2	L4	L6	M7	
LIKELIHOOD / FREQUENCY/ PROBABILITY						

**Figure 2.1: Risk matrix for structures (Anglo American internal document, Harmony Gold internal document)**

## 2.5 THE MINE SHAFT FAILURE MECHANISMS

The failure mechanisms of mine shafts can encompass a range of factors, including human errors such as inadequate monitoring, insufficient routine maintenance, or improper responses following the detection of potential defects (Erling, 2012). Various factors have the potential to compromise the structural integrity of a mine shaft and its associated infrastructure. Among these factors, damage to the

shaft lining is notable, with common underlying causes stemming from incorrect utilisation and insufficient maintenance of the mine shaft.

Excessive water pressure exerted on the shaft lining has the potential to lead to ruptures. Subsurface water can also contribute to chemical or mechanical stain; further inducing strains within the shaft lining that could result in ruptures (Xue, Yao, Jing and Song, 2020).

Another potential hazard arises from inadequate geological structures. Numerous techniques exist for identifying risks to a shaft and its associated subsystems. These methods assess the condition of the shaft's concrete lining, the potential horizontal or vertical dislodgment of shaft elements, and the integrity of steel infrastructure. However, no single method is capable of detecting all occurrences and identifying their root causes. Geophysical methods are commonly used for detecting shallow rock formations (Wohlfeil, Spreckels, Strackenbrock, Choinowski and Schlienkamp, 2015).

Furthermore, various distortions can result from the failure of utility infrastructure, including ventilation, water supply, electricity, telecommunications, and more. Consequently, while geoelectrical methods yield promising outcomes in undeveloped areas, their effectiveness is limited when dealing with extensive rock masses surrounding the shaft, especially when accompanied by complex infrastructure. SIMM specifically focuses on fully developed mine shaft structural infrastructure. During routine SIMM procedures, instances of damage to mine shaft steel structures caused by falling objects within the shaft are noted.

### **2.5.1 Probability of falling objects**

Objects that fall down a mine shaft can consist of various items, such as debris, tools, and maintenance materials, encompassing pipe columns and steel plates, with weights spanning from 1 kg to 5 000 kg. The impact of these falling objects is often linked to multiple occurrences of bunton damage. Despite the mine's efforts to lessen the risk of falling objects, complete elimination of this probability remains challenging due to factors like human errors, shaft design issues, and equipment malfunctions.

Anglo American, headquartered in London, United Kingdom, stands as a multinational mining corporation. Renowned as one of the most extensive and diversified mining enterprises globally, it operates across multiple regions worldwide.

Some years ago, Anglo American Technical Services collected the input of skilled engineers from mining companies, and a questionnaire was deployed to gather data concerning falling objects. This data covered aspects such as size, mass, type, and frequency of falling objects, along with the consequential impact damage effects. Examination of this data revealed a spectrum of falling objects, comprising small, medium, and large rocks, dolly wheels, guide wheels, bolts and nuts, chute liners,

skip liners, pipes, cable brackets, shaft screens, shaft steel, cable wedges, valves, pipe straps or brackets, miscellaneous steel, and more (Anglo American Technical, 2007).

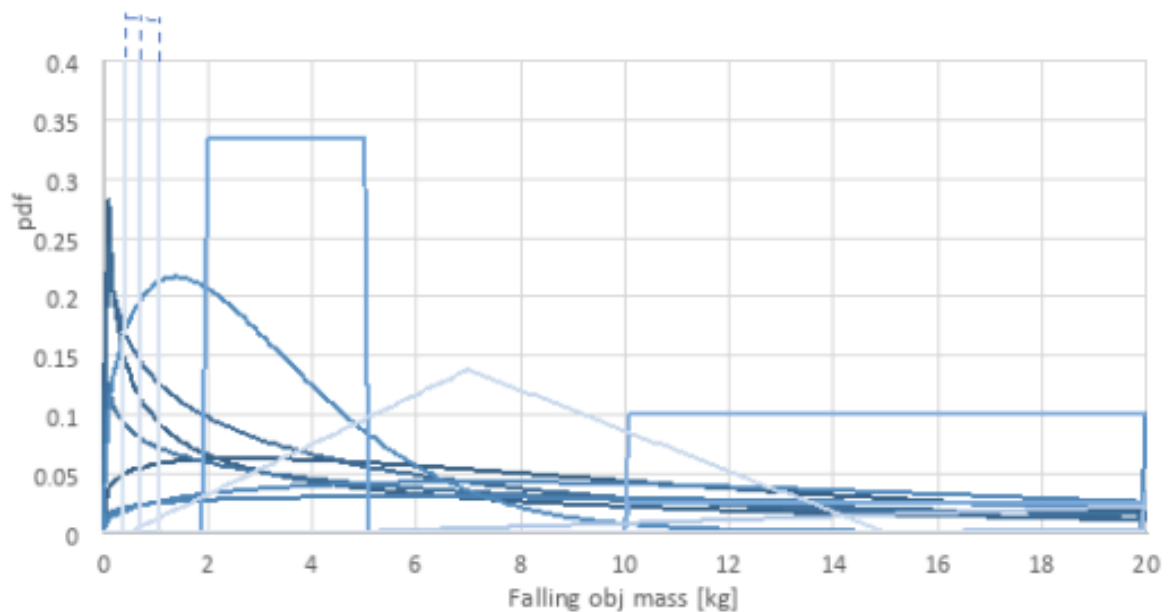
Table 2.1 presents the analysed data results on the frequency of occurrence for various mass categories, as provided by the shaft engineers.

**Table 2.1: Falling object questionnaire results (Wannenburg, 2023)**

Object type	Material	Dist type	Parameter 1	Parameter 2	Parameter 3
small rocks	rock	Weibull	1.4	3.4	
medium rocks	rock	Weibull	0.6	15.3	
large rocks	rock	Weibull	1.2	12.1	
small rocks	rock	Weibull	1.4	3.4	
medium rocks	rock	Weibull	0.8	7.6	
large rocks	rock	Weibull	0.8	17.6	
dolley wheel	steel	Uniform	20	30	
guide wheel	steel	Uniform	10	15	
bolts&nuts	steel	Histogram			{0.1,0.15,0.3,0.45}
headgear					
chute liners	steel	Uniform	25	50	
skip liners	steel	Uniform	25	50	
bolts&nuts	steel	Histogram			{0.1,0.15,0.3,0.45}
small pipes, pieces of pipes	steel	Trian	5	800	80
cable bracket	steel	Uniform	10	20	
shaft screens	steel	Uniform	20	50	
shaft steel	steel	Weibull	1.2	25.4	
cable wedges	steel	Uniform	2	5	
valves	steel	Weibull	1.4	3.4	
pipe straps or brackets	steel	Weibull	1.4	3.4	
bolts&nuts	steel	Histogram			{0.067,0.13,0.267,0.53}
miscellaneous steel	steel	Weibull	1.2	25.4	
shaft screens	steel	Uniform	10	50	
light objects	steel	Trian	0.5	15	7
medium objects	steel	Trian	5	60	30
heavy objects	steel	Trian	25	300	80
ultra-heavy objects	steel	Trian	1500	2500	300
slinging	steel	Trian	400	5000	1000
light objects	steel	Trian	0.5	15	7
medium objects	steel	Uniform	10	20	
heavy objects	steel	Weibull	1.4	17.4	
rolling stock	steel	-	5000		
welding machines	steel	-	100		
gas bottles, compressor	steel	Uniform	150	200	
mechanical machinery, material car	steel	-	125		

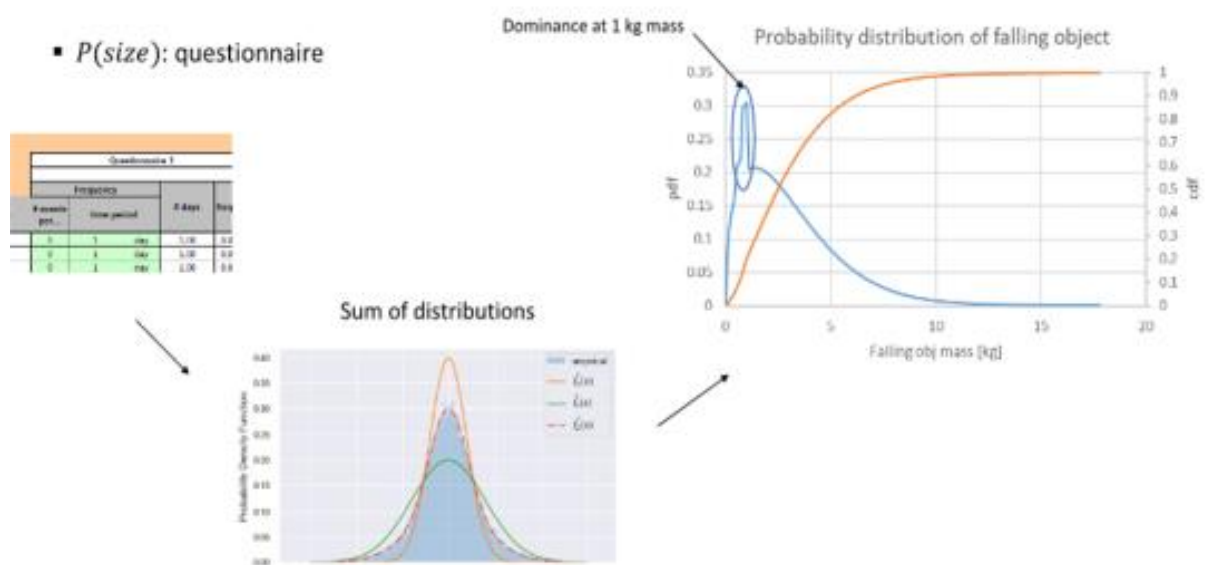
Figure 2.2 displays the mass distributions of different object types, along with their associated probability density and probability distributions as outlined in Wannenburg (2022). These separate

distributions were consolidated into a combined distribution by adding all distributions multiplied by their respective frequencies of occurrence.



**Figure 2.2: Distribution of mass for each object type (Wannenburg, 2023)**

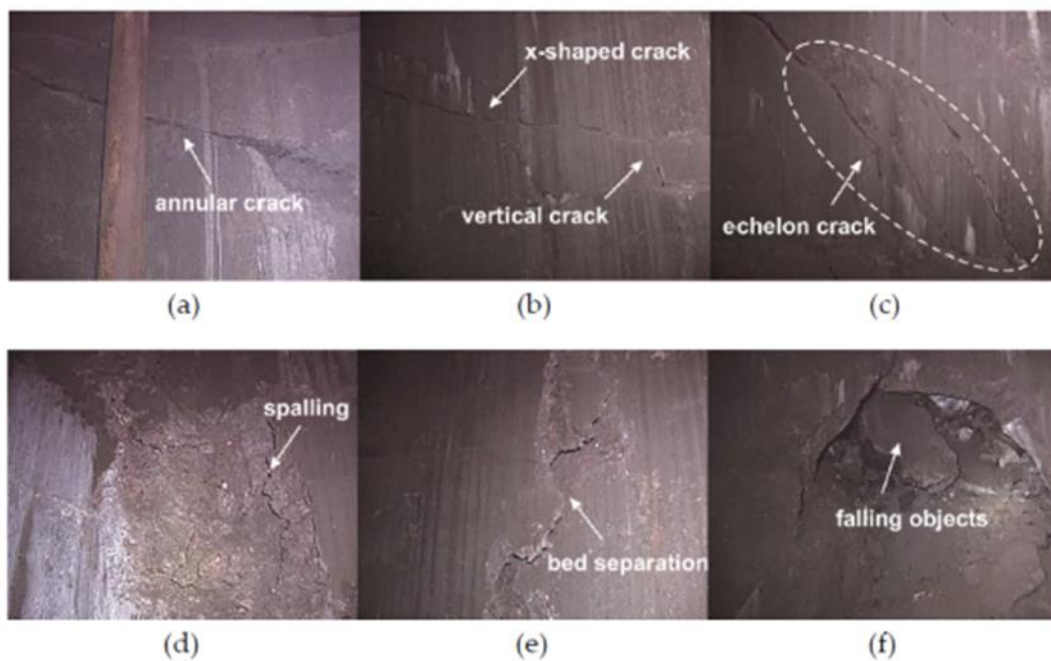
Figure 2.3 presents the analysed data points, along with the probability density function and cumulative distribution function plotted in correlation with the descending object’s mass. The choice of the object’s mass for experimentation was supported by insights derived from the probability distribution. It is crucial to highlight that the assumption regarding the object’s height aligns with typical mining shaft depths and operational levels.



**Figure 2.3: Probability density function and the cumulative distribution function against the mass of the falling object (Wannenburg, 2023)**

## 2.5.2 Impact of falling objects on shaft lining

Figure 2.4 illustrates instances of dislocation cracks resulting from the impact of falling objects on the concrete lining of the shaft. In panels (a), (b) and (c), there are clear manifestations of roadway connections deformation and failure adjacent to the vertical shaft lining. Roadway is the horizontal or nearly horizontal passageway within the mine that connects different areas or levels. These deformations take on various shapes, such as annular, vertical, x-shaped intersections, or echelon patterns. Spalling, as depicted in panel (d), is a prevalent occurrence, primarily driven by either tension or shearing effects.



**Figure 2.4: Falling object damages on shaft concrete lining (Sun, Ma, Guo, Li and Feng, 2020)**

Longitudinal cracks that penetrate the sidewall are also observable, accompanied by a limited occurrence of rock falls. These factors collectively contribute to the fracturing of the concrete lining and subsequently exacerbate the growth of spalling, as illustrated in panel (e). Furthermore, there is a concurrent development of voids between the lining and the surrounding rock due to these processes. The damage to the shaft lining originates from the surrounding rock mass and fractures rather than the steel structure and affects the overall integrity of the shaft system. The concrete lining serves as a crucial structural component, providing essential support to maintain the shaft's shape and prevent potential collapse. When the concrete lining experiences damage, such as cracking or spalling, it compromises this structural integrity, which can lead to destabilisation of the shaft. Furthermore, such damage can disrupt the alignment of the guides, resulting in increased wear and tear on hoisting equipment and compromising the safety of the conveyance system. Furthermore, compromised linings may allow for the release of rock and debris from the surrounding strata, creating safety hazards for personnel and

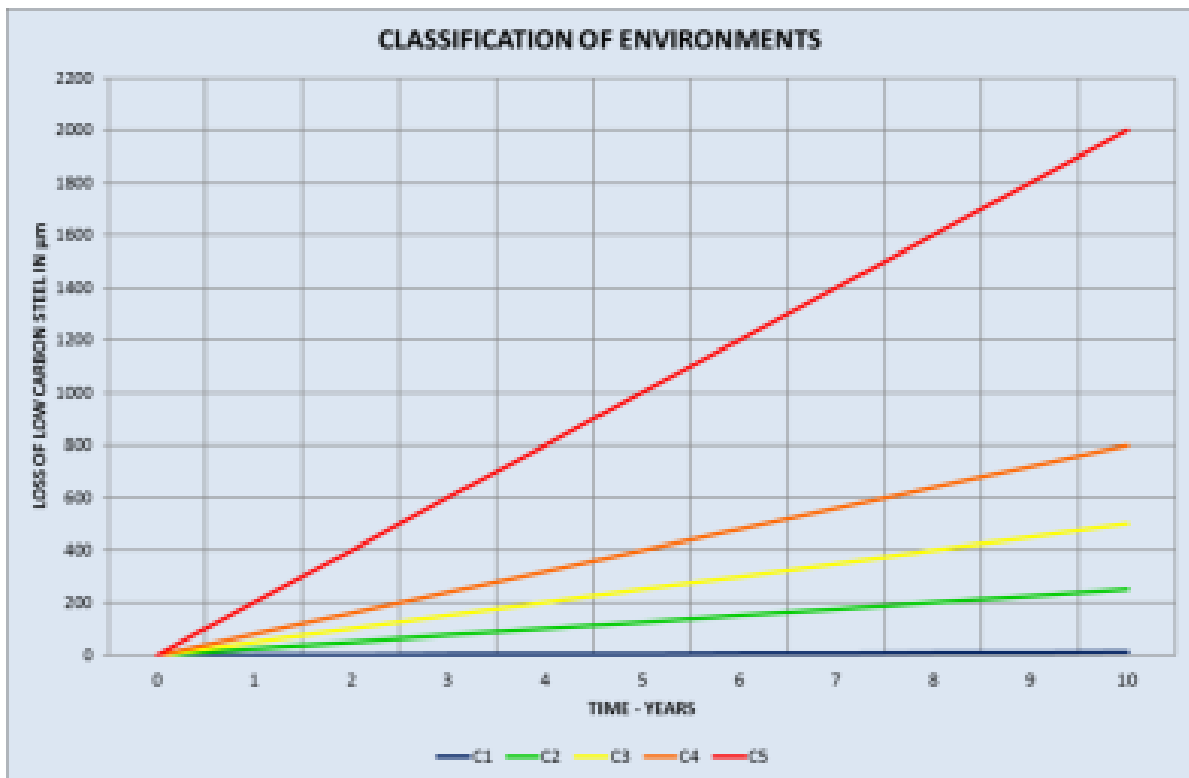
increasing the risk of structural damage from falling rocks. Therefore, the condition of the concrete lining is vital not only for the shaft’s stability but also for the safety and efficiency of mining operations.

The impact of falling rocks is vividly demonstrated in the formation of a cavity, depicted as a hole in panel (f), within the mine shaft wall (Sun, Ma, Guo, Li and Feng, 2020).

### 2.5.3 Steel Corrosion Mechanism

Gong and Frangopol (2020) highlighted that steel degradation results from the corrosion process, particularly in the context of the reliability of steel girder bridges affected by dependent corrosion growth. However, an increasing trend of deterioration is evident, particularly in regions where maintaining a dry shaft atmosphere poses challenges. This issue affects both concrete and steel structures that suffer from neglect.

Corrosion involves a chemical or electrochemical interaction between a material and its environment, leading to material deterioration and a decline in its inherent properties. The corrosion rate for both steel and protective coatings typically follow a theoretically linear progression, as illustrated by the theoretical steel corrosion curves in different environmental conditions, presented in Figure 2.5 below.



**Figure 2.5: Theoretical corrosion rate of exposed steel in varying corrosively environments (Di Sarno, Majidian and Karagiannakis, 2021)**

Steel has a natural tendency to corrode and to return to its natural state as iron ore, typically ferric oxide,  $Fe_2O_3$ . Corrosion rate on structures is dependent on the atmospheric condition. Water, PH, oxygen, properties of steel, and temperature forms part of the environment at which corrosion is formed (Fu, Li, Luo, Du and Li, 2021). Shaft steelwork, involves horizontal buntons and vertical guides, and is vulnerable to corrosion and mechanical impairment.

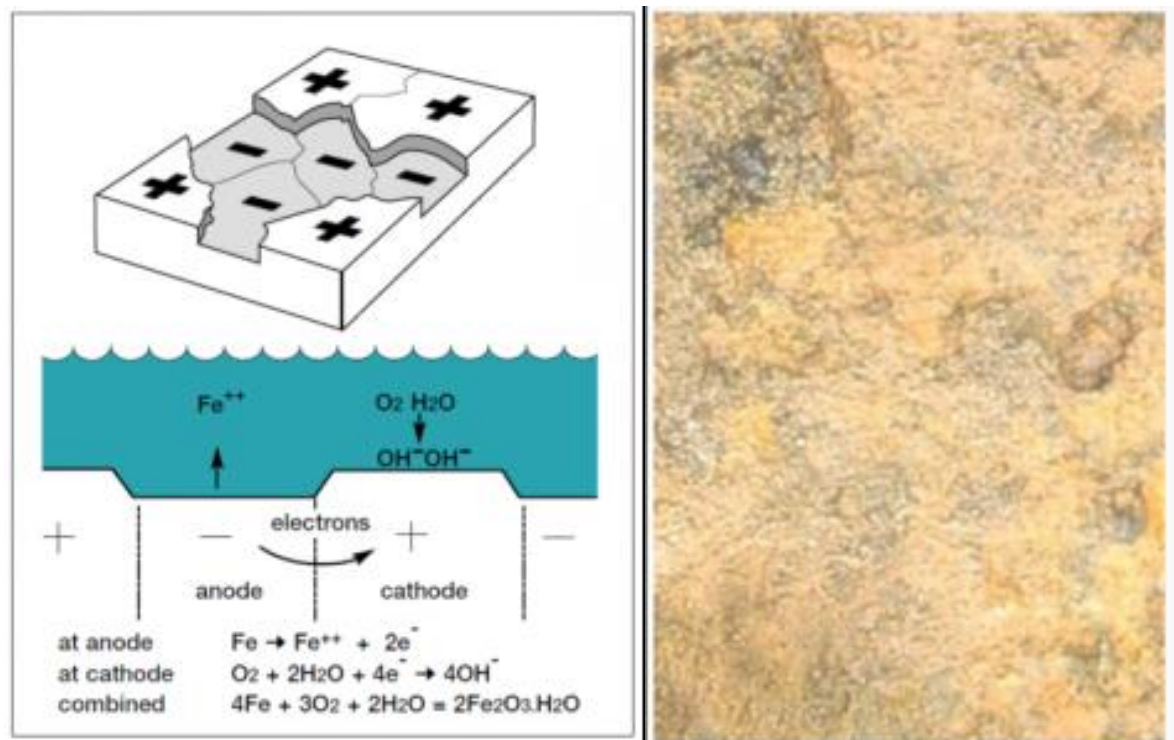
When steel undergoes corrosion, its stiffness decreases owing to the loss of material integrity and the formation of corrosion products, which disrupt the uniformity of the steel's microstructure. As the stiffness of the steel diminishes, its ability to resist deformation under load is compromised, resulting in a decline in the effective load-bearing capacity of the cross-section. This decline occurs because stiffness is a function of both material properties and geometric characteristics of the cross-section; therefore, any reduction in material because of corrosion directly impacts the load that can be safely applied.

The effects of corrosion lead to a reduction in the thickness of steel members as the corrosion process consumes the base metal, effectively reducing the cross-sectional area available for load support. Material loss can be attributed to both uniform corrosion, which affects the surface evenly, and localised corrosion, such as pitting, which can cause significant reductions in thickness in specific areas. As thickness decreases, the load-bearing capacity of the member is further diminished, leading to increased stresses in the remaining material.

These stresses primarily arise from local buckling stress and guide deflections. Local buckling stress occurs in thin-walled steel members where compressive stresses exceed the material's critical buckling strength. As the thickness is reduced owing to corrosion, the structural member becomes more susceptible to local buckling, which can lead to failure if applied loads exceed the buckling capacity of the compromised section. In addition, as the cross-section degrades, guide deflections, which are deviations from the original alignment of the structure caused by lateral loads, can increase due to the loss of stiffness, resulting in misalignment and further degradation of structural integrity (Jakubowski and Fiolek, 2021).

An oxide layer, known as passive film, helps in slowing down the corrosion rate by preventing water and air to get in contact with reinforced steel. If water or oxygen is not present, corrosion will not happen. The high pH of approximately 13 on the concrete pore creates a passive layer. Dissolved chloride ions are a big contributor to corrosion in concrete because they impair the passivity of the reinforcement and increase the active corrosion rate of steel (Kepler, Darwin and Locke, 2000). Oxidation is enhanced through the formation of an iron chloride complex, which is subsequently converted to iron oxide and chloride ions, which are then available to again combine with iron in the reinforcement (Li, Zhang, Xu, Cai and Yan, 2022; Locke, 2000; Yan, Kang, Xu and Li, 2021).

Figure 2.6 indicates the electrochemical process in the formation of corrosion of steel. Reaction of anode and cathodes results in electrons (Loto, Loto and Popoola, 2019). When the electrons combine with oxygen and water, the formation of hydroxyl iron occurs. This reacts with the ferrous ions from the anode to produce ferrous hydroxide, which itself is further oxidised in air to produce hydrated ferric oxide (i.e. red rust). The equation below illustrates the formation of corrosion (Steel) + (Oxygen) + (Water) = Hydrated ferric oxide (Rust).



**Figure 2.6: Electrochemical process (Loto, Loto and Popoola, 2019)**

Corrosion begins with the formation of rust. When these reaction processes occur repeatedly, corrosion develops after a prolonged period. Anodes are prone to corrosion processes (Fonna, Ibrahim, Huzni, Ikhsan and Thalib, 2021).

The corrosion rate is intricately linked to the extent of moisture and the presence of airborne contaminants, such as acids, chlorides, chlorine and dust. An example of this relationship can be seen in the table provided below, which outlines various categories of atmospheric corrosiveness and their associated processes. Table 2.2 illustrates both the environmental implications of corrosion categories and the corresponding reduction in carbon steel thickness owing to this corrosion process.

**Table 2.2: Atmospheric corrosivity**

ISO 12944 Classification	Typical Environments
C1 C2	Rural areas, low pollution. Heated buildings/neutral atmosphere.
C3	Urban and industrial atmospheres. Moderate sulphur dioxide levels. Production areas with high humidity.
C4	Industrial and coastal. Chemical processing plants.
C5I	Industrial areas with high humidity and aggressive atmospheres.
C5M	Marine, offshore*, estuaries, coastal areas with high salinity.

#### 2.5.4 Loading

The accumulation of ore material on vertical mine shaft structures is a common occurrence. The loading station lacks control during the loading of ore into the ore skip for hoisting, resulting in frequent overflow and spillage during the hoisting process. This gradual build-up of material places additional strain on the structures, leading to eventual cracks.

The design specifications are established based on the maximum load the structure should withstand. Overloading the structure induces deformation, stress, fractures, and displacement, ultimately culminating in catastrophic failure. Loads imposed on structures must adhere to design assumptions to prevent overloading, and regular removal of spillage is necessary. Loads are typically classified as dead loads (DL) or live loads (LL). Dead load pertains to the weight of the structure itself, remaining constant throughout its lifespan. Calculating the dead load involves considering the weight of the materials used, with a factor of safety incorporated to minimise underestimation errors and facilitate future modifications.

Point loads are concentrated loads applied over a small surface area of a structure. Surface loads, also known as distributed loads, are distributed across the surface area of the structure. Live loads, dynamic and temporary in nature, are also referred to as imposed loads. They can be either distributed or concentrated, often involving dynamic factors like vibration and impact.

Wind load (WL) poses a significant risk to tall and lightweight structures, as well as specific structural shapes. Wind speed and movement are critical considerations in designing structures to ensure stability against wind-induced stress.

Snow load (SL) encompasses the weight imposed by snow accumulation and heavy rainfall. In regions with frequent and heavy snowfall, the impact of accumulated snow on the structure's load-bearing capacity must be carefully evaluated. The snow load can negatively affect structures in South Africa in geographical areas where snow is experienced occasionally. Structural designs must also account for earthquake loads, tailoring the analysis to the geographical area's seismic activity.

Thermal loads result from temperature fluctuations, exerting substantial stress on structures. Expansion joints serve to accommodate contractions and expansions during temperature changes without inducing failures. Settlement loads involve striking a balance between structural stiffness and flexibility. Designers must meticulously weigh all relevant factors to make informed decisions in this regard. Mechanical damage arises from external factors such as environmental elements or physical contact with the structure (Laurence, 2021). Instances like tools or rocks falling down a shaft can cause significant structural damage.

### **2.5.5 Age probability**

Over the duration of the structure life cycle, various structures experience continuous ageing and accelerated deterioration, rendering them increasingly susceptible to catastrophic failures following natural or human-induced hazards. Among the factors contributing to this degradation, corrosion of steel reinforcement stands out as a significant cause, notably affecting the deterioration of reinforced concrete structures.

Multiple factors contribute to the ageing and degradation of structures, thereby affecting their overall integrity and safety. Firstly, the absence or loosening of bolts significantly reduces the structural strength. Corrosion emerges as another critical factor in the deterioration process, notably weakening structural integrity over time.

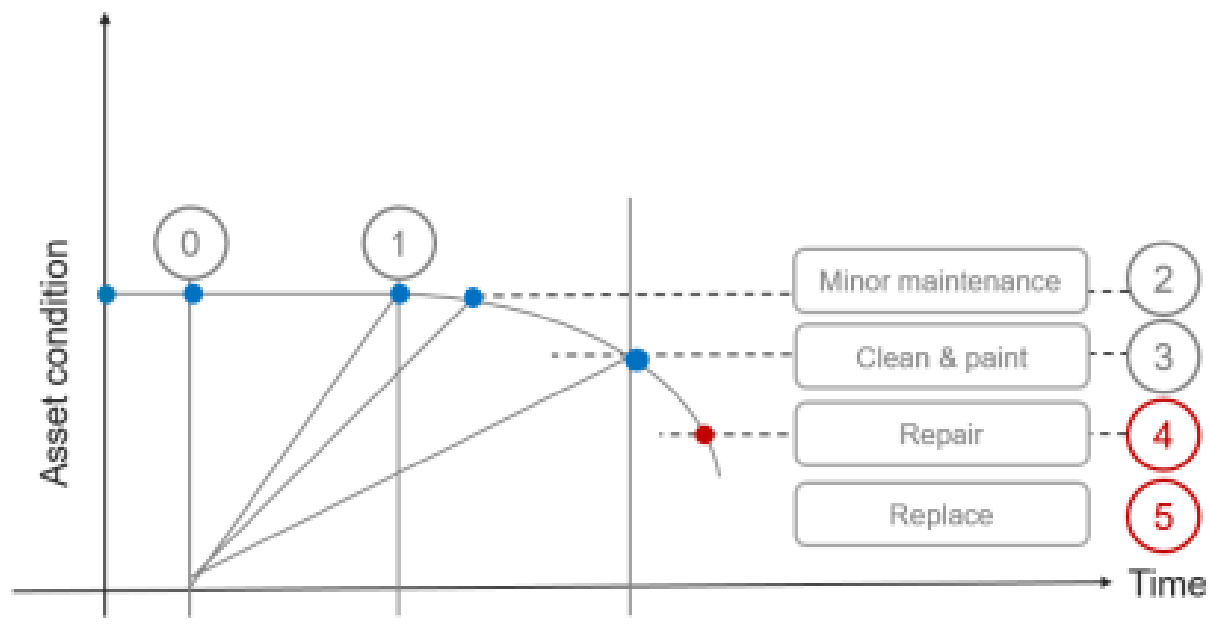
Deferred maintenance and delayed repairs not only pose immediate safety risks but also amplify future repair expenses. Furthermore, corrosion contributes to the depreciation of asset value, affecting the long-term sustainability of structures. Mechanical damage or other forms of harm further diminish structural strength, necessitating prompt reporting and repairs to avert potential hazards.

Chemical attacks on concrete, whether originating internally or externally, initiate a gradual deterioration process that compromises structural stability. Monitoring crack patterns, including map cracking and those aligned with the reinforcement's position, becomes crucial in identifying potential weaknesses and structural vulnerabilities. Ultimately, concrete deterioration severely undermines structural integrity, potentially culminating in structural failure.

The curve depicting potential failure and associated activities serves as a fundamental tool in assessing structural vulnerabilities and risk mitigation strategies. It outlines the progression of potential failure scenarios within structural systems, enabling the identification of critical points requiring intervention and preventive measures. Activities linked to this curve encompass an array of diagnostic assessments, maintenance schedules, and reinforcement strategies aimed at prolonging structural integrity. By closely aligning with this curve, organisations can implement targeted measures to mitigate risks, reduce vulnerabilities, and ensure the long-term sustainability of structures.

The Performance Failure (PF) curve serves as a visual depiction of an asset's behaviour or state prior to reaching a point of failure, offering insight into the asset's trajectory towards failure (Clark, 2019).

Figure 2.7 demonstrates how ageing affects the level of effort required for corrective actions to maintain the structure in a safe and operational condition.



**Figure 2.7: Potential failure curve and activities (Clark, 2019)**

### 2.5.6 Human errors

Observations underscore the significant role of human error as a catalyst in structural failures across various phases, spanning design, fabrication, erection, and modifications throughout the structure's life cycle. These errors often intertwine, evident in incidents such as silo collapses, with a notable concentration occurring during the construction phase, ultimately compromising structural stability.

Another notable instance of human error involves overloading, leading to fatigue cracking within structures. This oversight may result from insufficient knowledge, underestimation of overload

consequences, or inadequate workmanship during repairs (Johnson and Brown, 2020). Cases of fatigue cracking owing to subpar welding also contribute to structural concerns.

The overarching aim of maintenance and repair endeavours is to uphold the structure's capacity to meet its initial design requisites. However, challenges arise because of human error, particularly in data management and application. Often, primary and secondary structural elements remain unrepaired or are replaced inadequately, failing to reinstate the original design strength. Furthermore, neglecting construction drawings jeopardises structural integrity.

Contamination significantly accelerates the corrosion rate within structures. Human involvement in introducing corrosive substances, coupled with delays in cleaning, expedites corrosion. Spillage and staining impose additional loads on structures, fostering an environment conducive to accelerated corrosion, which may be concealed by these spills.

Addressing human error could involve a simple yet effective approach: fostering information sharing through informal and formal training for engineering and production staff. Equipping them with fundamental principles of structural integrity can mitigate errors. Data gathered during inspections and incident investigations is crucial, documented in comprehensive reports to analyse moderate structural failures and address root causes. Competency, in the realm of structural engineering, necessitates possessing theoretical and practical training alongside relevant experience. Professional registration, in compliance with local legislation, is fundamental for demonstrating competency in design. A robust structural maintenance mechanism requires meticulous structuring, facilitating audits and encompassing multiple facets. This includes assigning a designated individual to address inspection findings, and to compile comprehensive documentation of costs and downtime resulting from maintenance and repair activities.

### **2.5.7 Uncontrolled design change**

The absence of adherence to an established change management process stands as a pivotal factor contributing to structural collapses, potentially escalating structural incidents into fatal occurrences. Often, the true significance of preserving structural integrity is underestimated, especially when substantial modifications in design are contemplated. Implementing such changes without subjecting them to meticulous change management processes, risks introducing new vulnerabilities that can compromise structural stability. Within the mining sector, the utilisation of hazard and operability (HAZOP) studies remains prevalent, ensuring that proposed alterations align with the original design's intent, incorporating necessary corrective measures before structural modifications are executed.

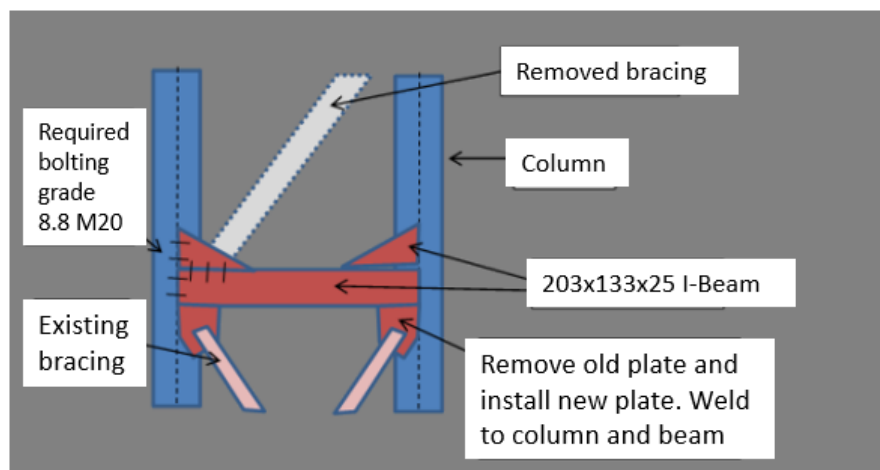
The pivotal requirement of approval by a qualified structural engineer for any design changes is occasionally disregarded, leading to modifications being made without due consideration for the

original design, consequently resulting in structural failures. Such modifications, whether temporary or permanent, bypassing proper engineering assessment and a comprehensive change management process, often result in a loss of critical information essential for informed decisions regarding structural integrity.

A modification is deemed significant when it meets specific criteria: potential for moderate structural failure indicated by risk assessment, necessitating structural element cutting, welding on elements bearing variable loads, exceeding load thresholds at specific points or distributed along lengths, or requiring replacement of structural sections or materials no longer available.

For substantial structural work or modifications, the appointment of a competent structural engineer is mandatory, encompassing responsibilities from design to oversight of construction progress, inspection, certification of completed structures, and assuming legal responsibility for the design. Following construction completion, newly constructed, repaired, or modified structures are subject to inspection and certification by a structural engineer. Upon decommissioning or demolition, the certification of related tasks falls under the purview of the company site engineer.

Figure 2.8 below serves as an illustration of a typical change made to a structure without adhering to the change management process. The findings reveal that bracing was removed to accommodate large piping, yet these alterations were not duly documented.



**Figure 2.8: Uncontrolled change illustration (Anglo American internal document)**

### 2.5.8 Fatigue cracks

Structural overloading stands out as the primary source of cracks, while additional factors encompass subpar welding or impaired weld joints (Pershin, Kopytov, Yuriy and Ahmed, 2018). Impaired welds can manifest even during the initial fabrication stage, before the structure is put into service. In some cases, accidental overloading might result in latent cracks that remain imperceptible. Gradually, these

cracks extend in length. These fractures may come to light during visual inspections or Non-Destructive Testing (NDT) assessments. Monitoring the expansion of these cracks typically becomes necessary when immediate repair is not feasible and there is no immediate danger.

This monitoring strategy is deemed acceptable when there is a comprehension of the critical condition, signified by the minimum crack length, that necessitates halting the structure's operation to avert harm. The PF (Potential Failure) curve proves invaluable in executing this approach, offering insights into the rate of crack growth.

The Paris law, also referred to as the Paris-Erdogan equation, serves as a crack growth equation that predicts the pace at which a fatigue crack advances (Paris and Erdogan, 1963, p. 528). As mining shafts become deeper, the strength of vertical shafts takes on heightened significance for mine safety within intricate geological contexts. Deformation in mine shafts is fundamentally influenced not only by the shaft excavation but also by mining undertakings.

Structural overloading serves as the primary source of cracks, with contributing factors including subpar welds or weld joints that have been compromised. Occasionally, these defects might emerge during the initial fabrication phase, even before the structure is operational.

In certain instances, accidental overloading can lead to hidden, imperceptible cracks. Over time, these cracks extend in length. Visual inspections or NDT assessments might reveal these cracks. Monitoring crack expansion typically becomes necessary when immediate repair is not feasible, and when the cracks do not pose an immediate threat. This monitoring approach gains acceptance when there is an understanding of the critical condition (indicated by the minimum crack length) that mandates halting the structure's operation to avert harm. The PF curve proves instrumental in executing this strategy, offering insights into the pace of crack growth.

In most cases, steel structures rest upon concrete foundations or platforms. The deterioration of reinforced structures imposes economic burdens in terms of repair or replacement costs. This deterioration takes the form of cracking, spalling, delamination, and corrosion in the reinforcing bars.

### **2.5.9 Deformation failure modes**

The contributing factors of deformation failure encompass an unpredictable rock stress environment, coupled with an array of influences on shaft stability, such as mining activities or the collapse of supporting structures. The intricacy of stress in deep vertical shafts surpasses that in shallower counterparts. The complexity of ground stress shifts with changes in structural stope. The variability of ground stress alters with changes in structural stope, resulting in a significantly diverse environment within the vertical shaft, exhibiting substantial differences between its upper and lower regions.

Deeper shaft levels commonly experience higher temperatures, increased humidity, and a higher potential for gas accumulation, conditions less conducive to the durability of structures. The overall stability of the rock mass within a mine shaft is determined by its weakest structural elements, ultimately impacting the shaft's robustness and integrity as a whole.

Mining-induced stress stems from ongoing mining operations, the vibrations caused by blasting, the movement of machinery, and other dynamic loads. Over time, fragile structural components progressively weaken, hastening the distortion and ultimate failure of the mine shaft (Guan, Xiang, Bao and Li, 2022). Dislocation cracking arises within the shaft lining, manifesting distinctive patterns. This phenomenon is often triggered by the concentration of horizontal stress, which prompts adjacent expansion and uniform shear fractures when the extrusion stress from horizontal forces surpasses the strength of the surrounding rock.

Drilling and blasting during mining can lead to movement in the surrounding rock. Consequently, portions of the rock mass may detach from the shaft wall owing to the mining effects, resulting in fractures. Consequently, observable damage affects the structural integrity of the mine shaft.

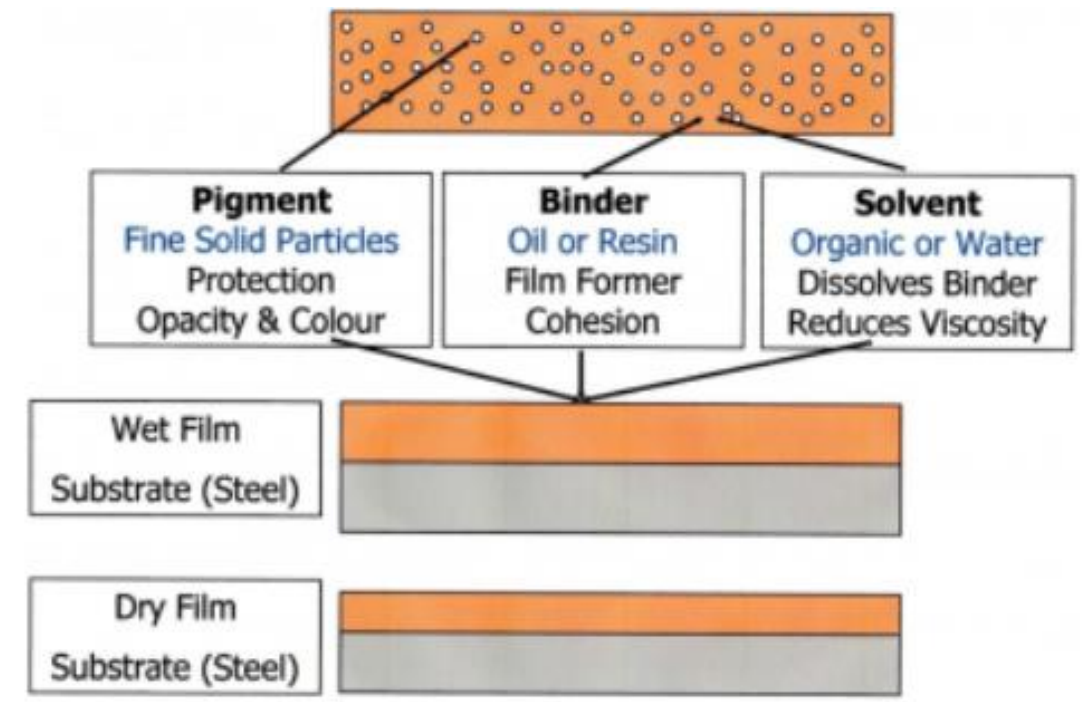
## **2.6 CORROSION PROTECTION**

Corrosion poses a significant threat to the structural integrity of materials across various industries, as described in the previous section 2.5.3 making the development of effective corrosion protection strategies essential.

Over the past years, a multitude of studies have focused on corrosion protection as a technique to safeguard structural integrity. Preventive measures taken during the planning and design stages of a structure, such as avoiding exposure to moisture and contaminated air, often encompass corrosion protection through paint coating in various industries. The process of painting involves the application of a protective film to the surface of a structure. This film is composed of three primary components: pigments, binder, and solvents.

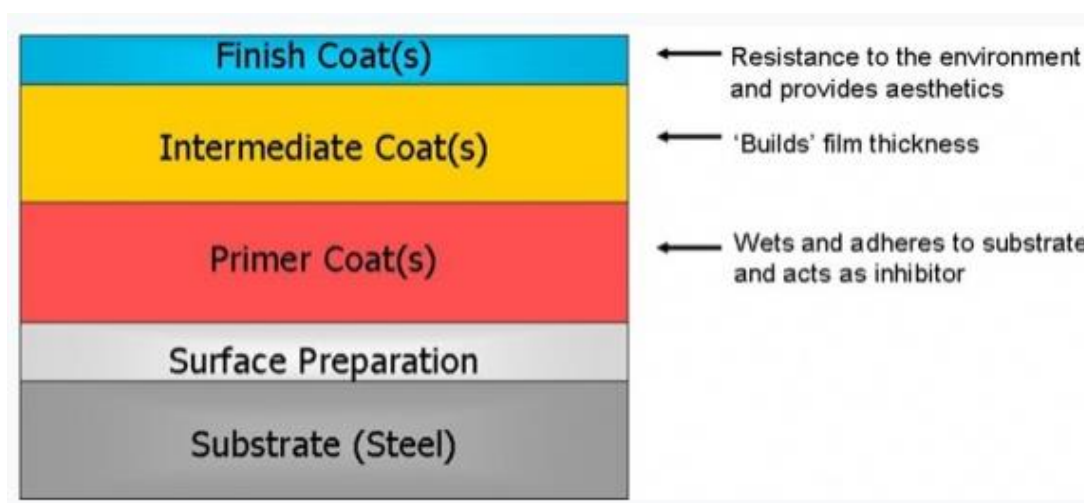
Pigments, whether organic or inorganic, are powders that contribute colour and film formation. The binder, typically consisting of oils or resins, facilitates the creation of the film. Solvents, which can be liquid or water-based, dissolve the binder, enabling the paint to be spread. (Boellinghaus, Wentland, Jassmann, Keller and Wolfrum, 2023; Karafyllias, Galloway and Humphries, 2021; Klufová, Kříž, Josef and Vostřák, 2021; Preston, Roy and Bewick, 2019).

Figure 2.9 illustrates the direct correlation between the degree of protection and the thickness of the film (Deacon and Hudson, 2012).



**Figure 2.9: Corrosion protection film (Deacon and Hudson, 2012)**

Figure 2.10 illustrates the painting coating system, which involves the sequential application of paint layers to establish a protective film. This approach to corrosion prevention has been in practice for many decades. Specific paint formulations tailored for diverse applications are readily accessible in the market. The specifications for primers are provided to ensure effective corrosion inhibition. Adherence to the prescribed film thickness specifications is of utmost significance in order to forestall untimely malfunctions. It is worth noting that human errors can indeed play a role in subpar coating application, ultimately leading to premature failures of the protective film.



**Figure 2.10: Schematic diagram of paint system (Chen, Zhang, Jia, Wellmann and Liu, 2020)**

## 2.7 MAINTENANCE DECISIONS

Maintenance of shaft structures is gaining increasing importance in underground mining operations for a variety of reasons. Mechanisms of deterioration related to shaft operation include corrosion, mechanical damage, fatigue damage, and wear. In addition, mechanisms stemming from rock movements, such as vertical strain, vertical closure, and squeezing, contribute to degradation (Krige, 2015).

Maintenance encompasses all systems and work management aimed at ensuring equipment performs as intended and restoring its specified functions. It holds significant importance in various industrial operations, with substantial investments made in maintenance systems as part of wider business strategies. Data collection through structural inspections or monitoring proves invaluable in comprehending structural conditions. Reliable information regarding structural conditions facilitates well-informed maintenance strategies, reduction of uncertainties, improvement initiatives, and future investments.

Effective data collection incurs associated costs, yet it has been demonstrated that understanding necessary maintenance contributes to reducing uncertainties, thereby prolonging the lifespan of engineering structures. A holistic approach entails planning, inspections, timing, monitoring, maintenance, cost optimisation, and a risk-based methodology that aligns with overall business strategies (Di Bona, Cesarotti, Arcese and Gallo, 2021; Eskandari, Charkhand and Gholami, 2020; Rastegari and Mobin, 2016).

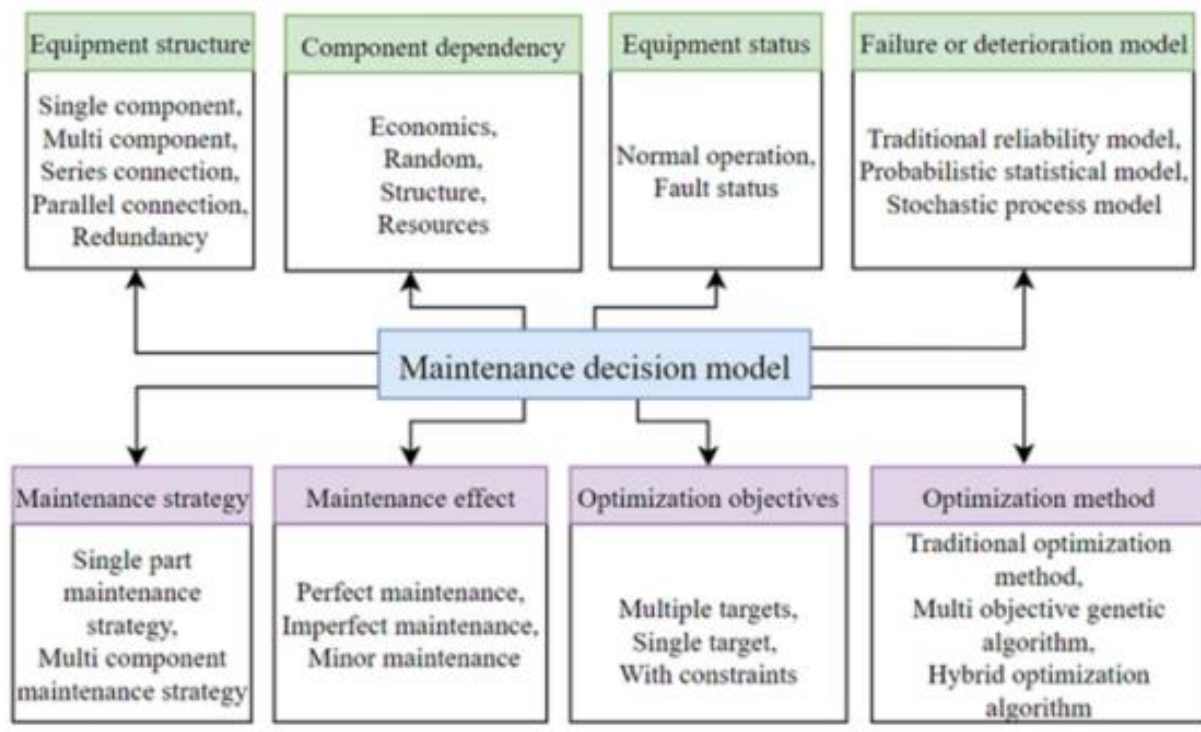
The landscape of modern industrial equipment is increasingly marked by complexity. To ensure high reliability and sustainability of industrial equipment, non-rigid maintenance strategies have garnered significant attention. Comparing maintenance strategies assists in selecting appropriate maintenance plans. This involves detailing geographical environments, characteristics, application prospects, and limitations of single-component maintenance strategies like corrective maintenance, preventive maintenance, and predictive maintenance from the standpoint of maintenance time (Shao and Hao, 2021; Zou, Banisoleiman, González and Faber, 2019).

Corrective maintenance (CM) stands as one of the earliest maintenance strategies, centred around the notion of ‘fix it when it breaks’, devoid of the need for monitoring or risk analysis. It revolves around repairing or replacing a component after repairing it has failed to restore its intended functionality.

While preventive maintenance (PM) is often economically preferable to reduce failure rates or extend equipment lifespan, it also requires decoupling the equipment from the process during maintenance. Although both CM and PM strategies necessitate process interruption until maintenance is completed, PM aims to reduce failure rates rather than eliminating them. In many cases, improper planning of PM

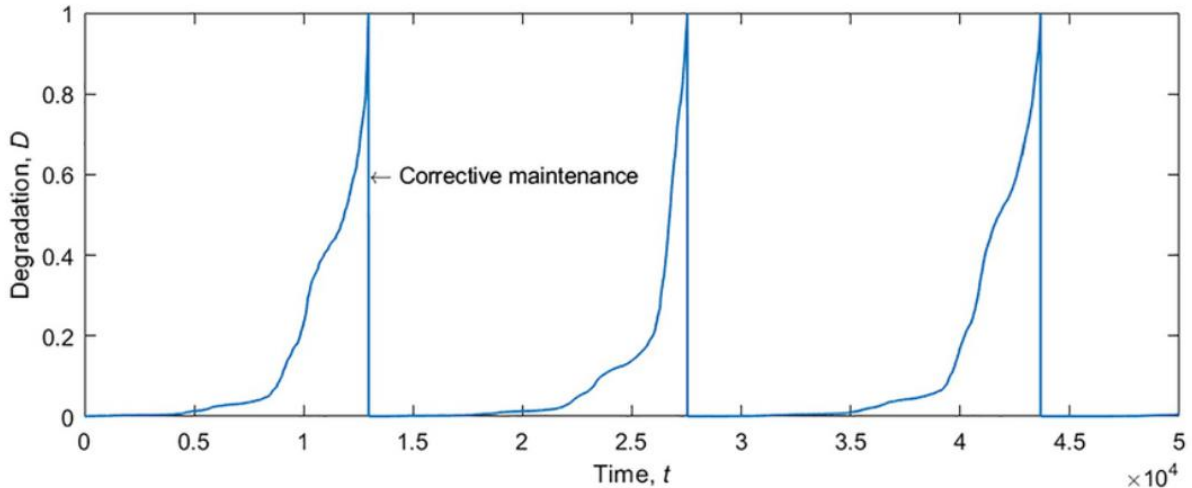
can incur more costs than CM. CM remains widely adopted in engineering practice in many companies, as it is seen to curtail unnecessary maintenance planning costs and resource utilisation (Ghaleb, Taghipour and Zolfagharinia, 2021).

Figure 2.11 illustrates scenarios involving maintenance of a single or multiple similar components, as well as dependencies among multiple components. Multicomponent maintenance strategies like batch maintenance, opportunity maintenance, and group maintenance may be employed to maximise system uptime. Industries can choose the most suitable maintenance strategy based on their environment, equipment characteristics, or refine their existing strategies based on specific business requirements (Furuta, Kameda, Nakahara, Takahashi and Frangopol, 2006; Zhao, Gao and Tang, 2022).



**Figure 2.11: Composition of the maintenance decision (Zhao, et al, 2022)**

Figure 2.12 illustrates time-based PM, encompassing regular maintenance tasks carried out at fixed intervals on functional components. Employed before components experience failure, time-based PM endeavours to enhance the current health of the component, albeit not restoring it to a new state. In other words, post-maintenance, the component's health improves beyond its initial state, yet falls short of a brand-new condition.



**Figure 2.12: PM and CM activities and their impacts**

CBM activities, conversely, adapt to the ongoing deterioration of components. This strategy is paired with methodical inspections aimed at identifying component degradation. Typically conducted at set intervals, inspections ascertain the component's state and degradation level without actively enhancing its condition. CBM mirrors preventive replacement driven by degradation, entailing the restoration of a deteriorated component to a 'good as new' state. The execution of CBM occurs when identified degradation surpasses a predetermined threshold, as depicted in the figure below (Sasitharan, Lazim, Lamsali, Iteng and Osman, 2020).

## 2.8 RISK-BASED MAINTENANCE AND RISK-BASED INSPECTION

Industries perpetually engage in risk management and daily decision-making. Every business choice, ranging from asset acquisition, commissioning, asset utilisation, to disposal and closures, carries an element of risk. The crucial aspect of effective decision-making stems from striking a balance and discerning the trade-off between risk and incentive. Companies that expose themselves to substantial risks for minimal incentives can expedite their exit from the business landscape.

Conversely, businesses that avoid risk altogether and become excessively cautious, miss out on progressive opportunities. In an industry where competitors thrive, companies with no risk appetite might find themselves falling behind (Caspeele, Frangopol and Tsompanakis, 2020; Eskandari, et al., 2020).

## 2.9 ESTIMATION OF USEFUL REMAINING LIFE AND THE LCC

Understanding the RUL of equipment is instrumental in shaping condition-based and predictive maintenance strategies (Yang, Frangopol and Han, 2021). Historically, maintenance practices for mechanical structures in South Africa have relied largely on a risk-based or reactive approach, where

repairs are conducted only as problems occur. This method can lead to inefficiencies and may compromise the overall reliability and operational efficiency of the equipment. However, the recent emphasis on SHM techniques has brought about a significant shift.

SHM techniques are now recognised for their role in evaluating structural health, predicting the RUL of structures, and implementing CBM for structures in varying states of degradation (Animah and Shafiee, 2018). This paradigm shift involves the integration of diverse sensors installed on structures to gather crucial data. Analysing this data helps in making reliable and cost-effective decisions concerning CBM across diverse operational conditions.

Estimating the total cost across the service life, often referred to as ‘net present value,’ stands as a crucial element in effective planning and budgeting. LCC analysis, derived from historical failures, repairs, and maintenance, excluding initial design and construction expenses, aids in these estimations (Frangopol, 1998). A proactive LCC approach considers design, construction, repair, maintenance, and structural failures. By evaluating these costs across various maintenance and repair strategies, it facilitates the selection of the most cost-effective option, either based solely on cost or, in complex scenarios, identifies Pareto optimal solutions involving multiple objectives.

Presently, the determination of a LoM plan primarily hinges on historical financial patterns (Bakker, Frangopol and Tsompanakis, 2018). This process, rooted in historical trends, serves as a financial projection tool, assuming past trends will mirror future occurrences. These interventions are intended to address the ongoing structural degradation and establish safety for long-term sustained productivity, aligning with the foreseeable operational lifespan of the mine (Caspelle, et al., 2020). A number of maintenance alternatives are modelled in the development of a cost-effective or LCC model (Bakker, et al., 2018).

## 2.10 REGULATION WITH REGARD TO STRUCTURES

The South African Mine Safety and Health Act of 1996 provides a guideline of what the mine shall comply with in making sure that the work environment is safe.

### *Regulation 16.73 Examination of winding plant and shaft*

*“The manager or subordinate manager and (an engineer or competent person appointed in terms of regulation, 2.13.2, as the case may be) shall, in respect of his area of responsibility, appoint in writing competent persons whose duty it shall be to examine carefully, to an extent to be clearly defined in their respective letters of appointment, at least once in each week, and at intervals not exceeding 10 days, the guides or rails and the shaft compartments and equipment, including the doors, gates and barriers and the ancillary equipment at stations, landing platforms and loading boxes.”*

*Regulation 16.77 Duty when defect discovered*

*"If on any examination required in terms of MHSR regulations 16.73, 16.74, 16.75 and 16.76 there is discovered any weakness or defect which may endanger the safety of persons, and such weakness or defect cannot be remedied immediately, the person making the discovery shall report such weakness or defect to the manager without delay. Until such weakness or defect is remedied the winding plant shall not be used except in so far as may be necessary to remedy such weakness or defect."*

Typical checks in the shaft include:

- electrical cables
- contact wire and insulators
- pipe columns, brackets and bearers
- guides, joints, wedges, brackets and bolts
- dividers and buntons
- shaft screens and bratticing
- clearances between landings and conveyances
- water rings
- side-walls
- water seeping into the shaft
- bratticing between shafts, spillage compartments
- penthouses
- typical checks on the stations
- station landings (rail mats) and shaft gates
- station screens, bratticing and barricades
- safety devices on station
- communication systems, lock-bell, call-bell and the telephone
- station and tip cross cut lights
- notice boards
- cage arresting devices (where applicable)
- shaft tips
- ore pass control boxes
- dust extractor fans, bags and enclosure (where applicable)

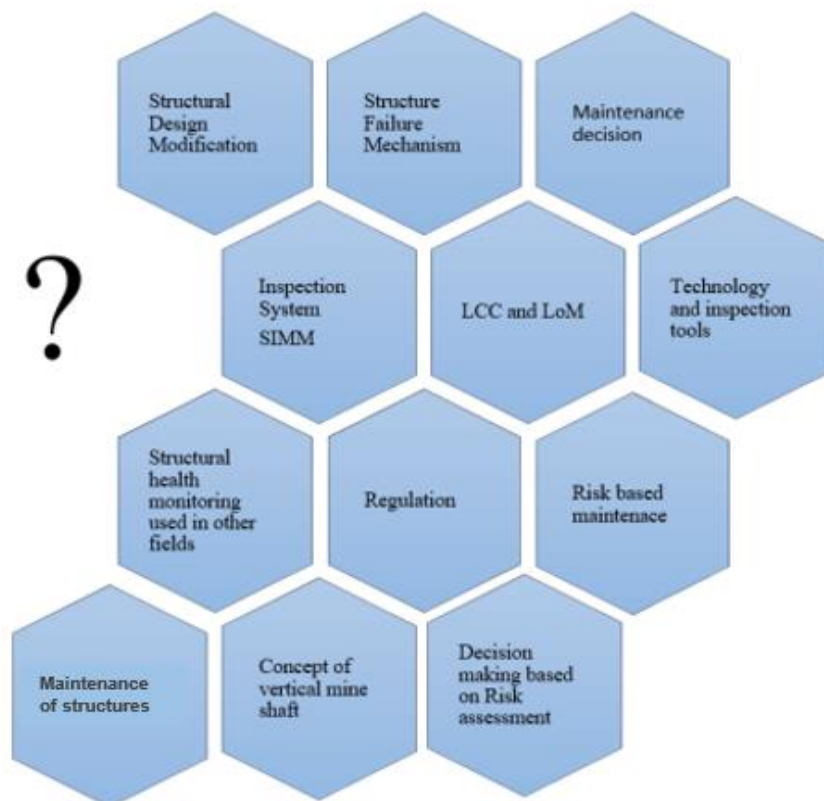
## 2.11 GAPS IN EXISTING LITERATURE

Figure 2.13 depicts interconnected themes that necessitate a comprehensive approach to enhance structural integrity and the implementation of an integrated system for structural inspection and maintenance management, aimed at effectively managing the remaining lifespan of structures within a vertical mine shaft.

From the literature reviewed encompassing structural inspection and maintenance in the mining sector, an opportunity for further development was identified, pointing towards critical areas needing attention:

The prevailing challenge lies in the management and monitoring of corrective measures suggested by structural engineers. Current practices often confine inspection reports to personal files or emails, resulting in recurring identification of similar defects in successive inspections, hinting at inadequate maintenance for mine shafts. This absence of reliable data impedes planning and investment in maintenance efforts, paving the way for periodic structural failures in mine shafts.

The lack of integration and the disconnect between mine structure inspection results and CMMS hampers efficient maintenance. This disjunction results in inconsistent handling of corrective actions highlighted by third-party inspections, leaving reported defects unaddressed and critical maintenance untracked within the CMMS platform.



**Figure 2.13: Link themes on literature review**

The failure to record maintenance activities effectively within CMMS leads to a lack of crucial data on costs, labour requirements, and resource allocation for structural upkeep. This deficiency makes accurate calculations of LCC and estimation of remaining LoM unfeasible, thereby impeding informed decision-making.

The utilisation of SIMM technologies in the realm of structural engineering is increasingly gaining popularity. However, the mining industry has been slow to adopt certain existing technologies. This research proposes identifying the most suitable technology, with a focus on its integration with current maintenance recording systems, particularly CMMS.

Engineers recognise the inaccuracy of this assumption when it pertains to the life expectancy of systems or equipment. As a shaft ages, steel exhibits signs of fatigue and strain. The activities required to sustain it and extend its operational life become increasingly costly. To circumvent sudden expenses associated with structural repairs or replacements, the establishment of a monitoring system that tracks annual inspection and maintenance activities is imperative. Such a system ensures accurate estimation of future costs and efforts.

Conducting a literature review on this subject has provided an invaluable opportunity to examine and draw insights from the contributions made by other researchers in the realm of structural integrity. A substantial body of prior work and research has been undertaken, and certain fundamental principles from this work have been adapted for application within the mining industry.

Nevertheless, there remains room for a novel contribution through further research aimed at expanding the understanding of structural integrity. A unique and significant contribution will emerge through the creation of a comprehensive methodology, centred on an integrated system for structural inspection and maintenance management. This system is specifically tailored for managing the remaining lifespan of structures within a vertical mine shaft.

## **2.12 CONCLUSION**

The exploration of literature surrounding structural inspection and maintenance within the mining sector has highlighted some gaps that pose challenges to the effective management and longevity of mine shaft structures. Despite the substantial knowledge available in this domain, critical deficiencies persist, notably the absence of a comprehensive implementation strategy for SIMM practices.

This void, coupled with the inadequate integration between inspection results and CMMS systems, has resulted in inconsistent handling of corrective actions and unresolved defects identified during inspections. Furthermore, the incomplete recording of maintenance activities within CMMS platforms has created information gaps, impeding accurate estimations of LCC and the remaining LoM. The issue

of managing recommended corrective measures remains unresolved, confined to personal files or emails, perpetuating recurring defects in mine shaft maintenance.

To address these profound gaps, this dissertation advocates for an iSIMM system tailored explicitly for vertical mine shafts within gold mines. This proposed system introduces standardised reporting tools and a monitoring system, enabling continuous assessment and swift execution of corrective actions identified during structural inspections. The proposed iSIMM framework promises substantial benefits, including bolstering safety measures by adopting a comprehensive approach to structural inspection and maintenance, thereby reducing the risk of structural failures and ensuring worker safety. Furthermore, by integrating inspection results into CMMS platforms, the framework aims to optimise maintenance efforts, enhance operational efficiency, and contribute to cost savings by accurately estimating remaining lifespan and defining work scopes for budget allocation. Emphasising sustainability through prudent risk management and responsible decision-making, this framework endeavours to foster safer and more sustainable mining operations.

The next chapter is dedicated to the development of an iSIMM system. It delves into the intricate design and development process of the structural inspection system. This chapter thoroughly explores the functionality of the integrated system, highlighting how its components synergise for efficient management. Moreover, it elucidates the underlying logic governing the system's operations, providing valuable insights into its comprehensive functionality.

## **CHAPTER 3: DEVELOPMENT OF AN INTEGRATED STRUCTURAL INSPECTION AND MANAGEMENT SYSTEM**

### **3.1 INTRODUCTION**

This chapter focuses on the development of an iSIMM, detailing its design intricacies and development process. The historical monitoring of structural inspection was done using different platforms that are not integrated and the information was captured manually. The chapter investigates how the integrated system functions, explaining the synergy among its components for efficient management. It also outlines the underlying logic that governs the system's operations, offering insights into its comprehensive functionality. Furthermore, it explores the crucial aspect of shaft baseline inspection, elucidating its fundamental process and its significance within the broader context of the iSIMM.

This chapter plays a crucial role in the dissertation, emphasising an innovative perspective on the iSIMM. It extensively explores the creation of the design for the structural inspection system, diving into its development in depth.

To appraise the efficacy of the proposed methodology, a field study was conducted at a gold mine situated in South Africa's Gauteng province, serving as a pilot initiative.

### **3.2 DEVELOPMENT OF THE STRUCTURAL INSPECTION SYSTEM**

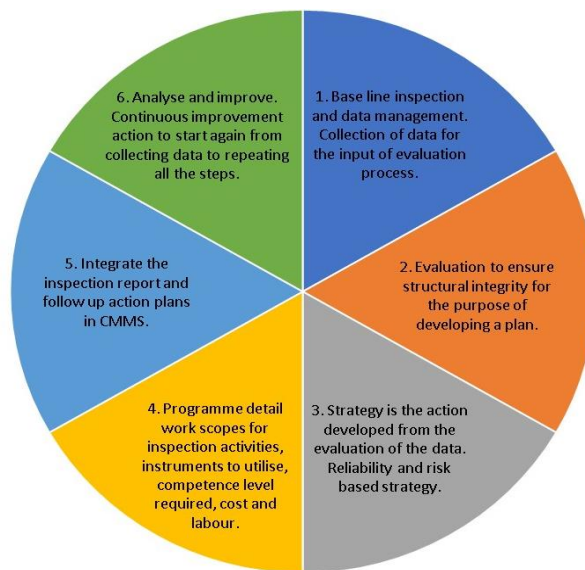
SIMM endeavours to establish a standardised guideline for structural management strategies. SIMM inspections predominantly entail visual assessments, thus a comprehensive outline detailing the specifics of visual inspections and their required level of detail is provided. This clarity ensures that both clients and third-party inspectors are well-informed about the expectations for each inspection. Subsequent to every inspection, a formal report must detail the condition of the structures.

During these inspections, the structural engineer is responsible for identifying all safety-critical findings—those features that compromise safety in any capacity in the shaft—and then compiling a formal report. Subsequently, collaboration between the mine engineer and the structural engineer is essential to promptly address all safety-critical findings. This process also involves recording overall observations, encompassing safety-related concerns, structural flaws, and maintenance issues that might hasten structural deterioration.

The integration and monitoring system is developed to pre-emptively address remedial actions aimed at managing the lifespan of the mine shaft. The implementation of an integrated monitoring system for the mine shaft will amplify visibility, enhance monitoring efficiency, and facilitate the effective execution of remedial actions detected during structural inspections. Consequently, this system

contributes to life-of-mine management and the computation of remaining mine life. By electronically documenting, managing, and overseeing the inspection and maintenance of structures, the system empowers mine managers and executives to carefully consider the future implications of their present decisions.

Figure 3.1 outlines the extent of the guideline encompassing planning and design, construction and commissioning, operation and maintenance, modification and repair, as well as decommissioning and demolition of all significant structures constructed from materials such as steel, concrete, timber, aluminium, and other structural materials. The subsequent figure elaborates on this process.



**Figure 3.1: Structural inspection system implementation plan**

### **SIMM REPORT SYSTEM**

The typical portable document format (PDF) report from the third-party structural engineer is designed to present significant discoveries using images to highlight areas of concern (Anglo American, 2011b). This report follows a comprehensive and typical audit-style format. A distinct process flow is currently in place, as depicted in Figure 3.2, which facilitates the documentation of engineering equipment tasks. However, the inspection of structures does not adhere to this same protocol. This discrepancy has its roots in history, where physical structures were habitually omitted from the asset register, along with the neglect of recording activities related to these structures.

Figure 3.3 illustrates a significant lack of consistency and control in the structural inspection processes. The figure shows that the number of captured remedial actions is lower than the number of deviations found during the structural inspection. This implies that the information from structural inspection reports is not captured consistently. Furthermore, it is evident that the inspection reports are not being effectively utilised to improve the condition of the mine shaft structures.

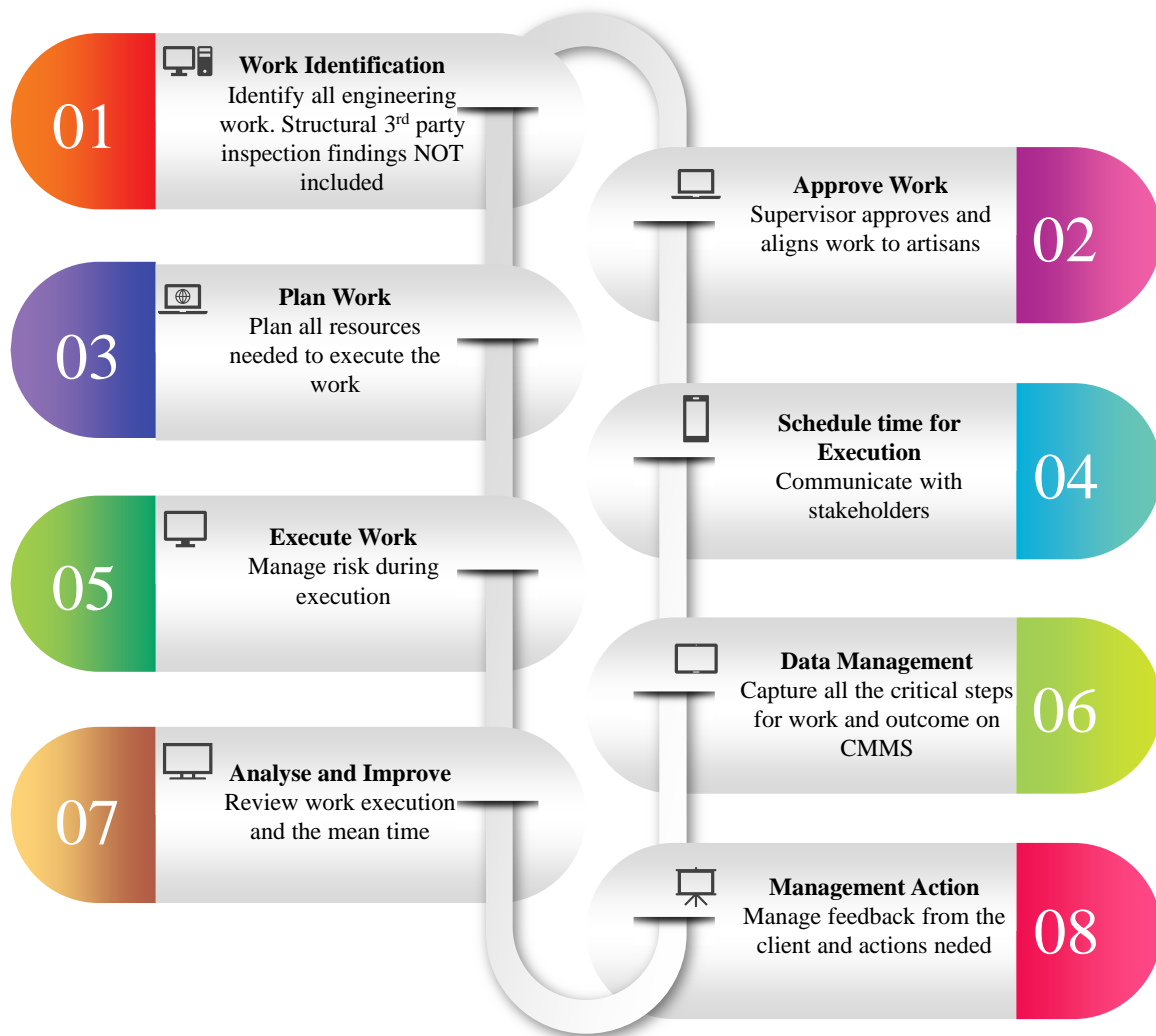


Figure 3.2: Maintenance work process flow

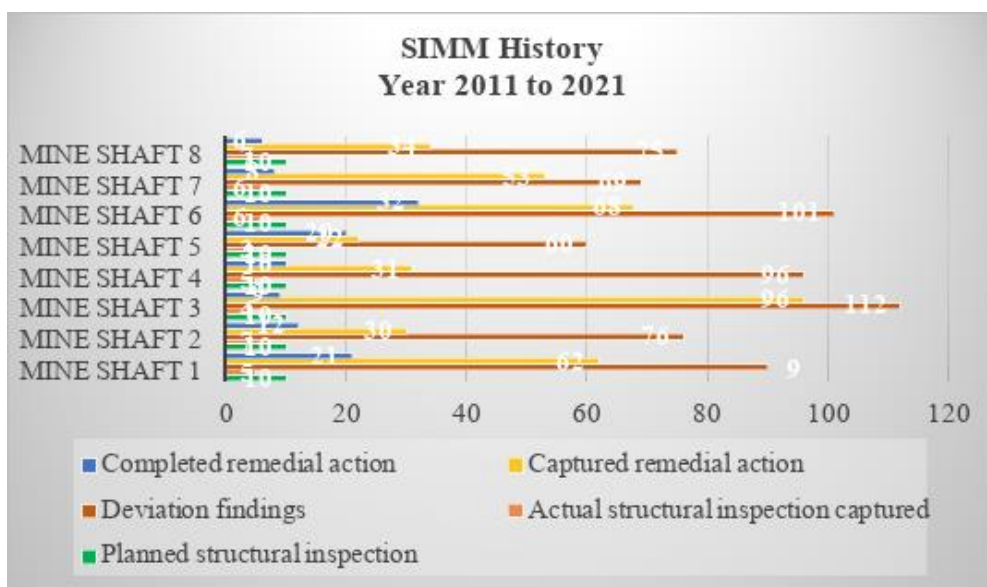


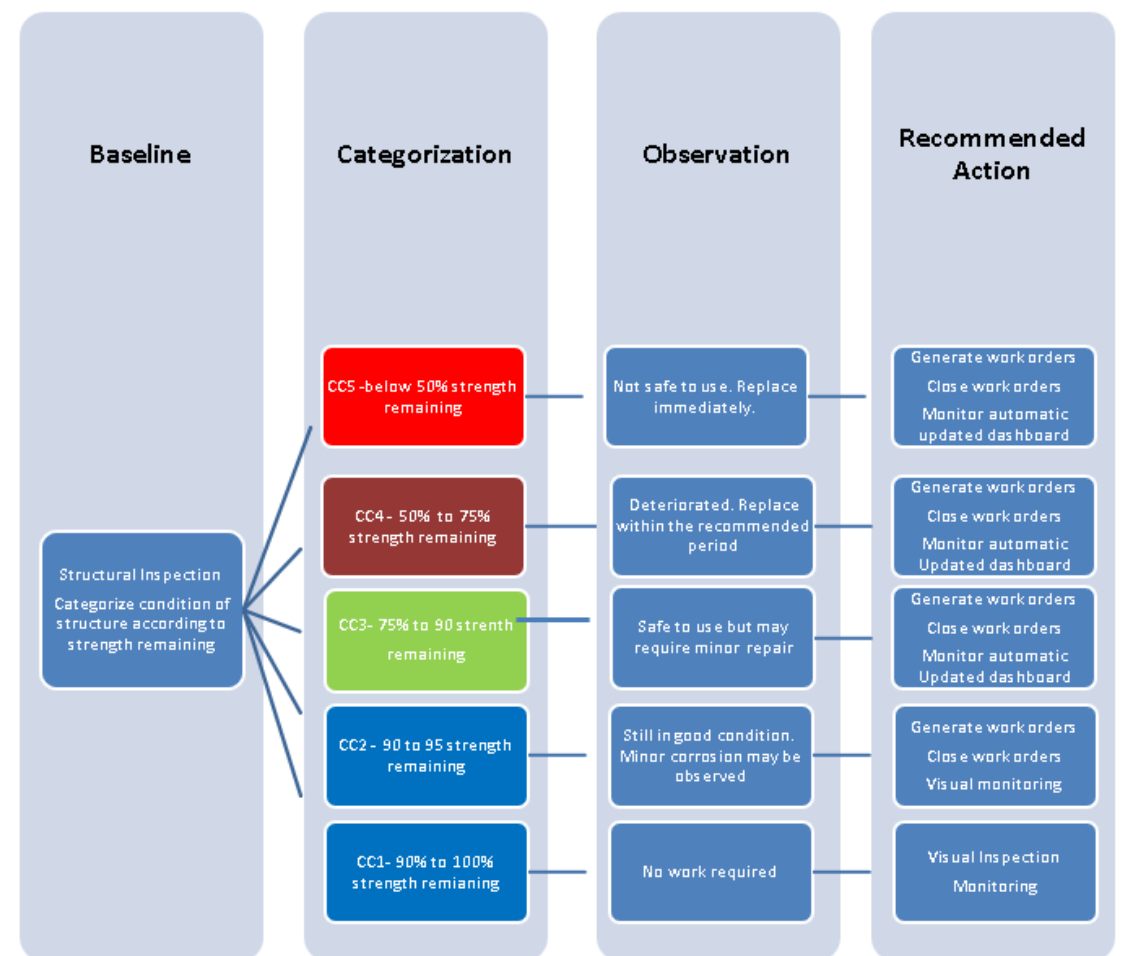
Figure 3.3: Third-party structural inspection history at gold mine

### 3.3 INTEGRATED SYSTEM FUNCTIONALITY

Figure 3.4 illustrates the simplified process of the key factors involved in iSIMM system implementation. The pivotal strategy lies in streamlining complexities, thereby facilitating seamless integration of the system into existing practices. This not only enhances the likelihood of widespread acceptance but also significantly contributes to the overall value proposition within the mining sector. When the structural engineer’s work order is completed, it is followed by a list of subsequent work orders addressing the findings and recommended improvements for the observed deviations.

These follow-up work orders are no longer captured manually; instead, the system is fully integrated. As deviations are resolved, the closure of each work order updates a dashboard, which indicates the number of findings from inspections, the number of deviations found, and the number of deviations corrected. This integrated system provides significant benefits, as the dashboard is accessible to all managers and engineers, empowering them as decision-makers.

Consequently, decisions regarding the time and budget required to address structural deviations and maintain or improve structural integrity become easier and more informed.



**Figure 3.4: Key elements of iSIMM system**

### **3.4 OVERALL LOGIC OF THE SYSTEM**

In South Africa, underground mines, notably platinum and gold mines, have been operational for over five decades. Owing to the passage of time, it is anticipated that mine shaft structures will exhibit considerable deterioration. Consequently, there is an increased emphasis on the protocols for structural inspection and maintenance of these shafts. In some instances, major failures have occurred in certain shafts, necessitating their closure for extensive steel replacements and maintenance to restore safe structural integrity. To address these challenges, Anglo American formulated a comprehensive guideline for structural inspection and maintenance several years ago. However, this guideline only covered what to inspect and report, without detailing how to effectively use the reported information to rectify deviations, integrate and monitor activities, or analyse the remaining life of the mine. This study will focus on integrated monitoring and the utilisation of mine shaft structural condition data for analysing the remaining life of the mine.

These guidelines from Anglo American have since been widely adopted across their business units and other mining entities. However, ongoing experiences have revealed a growing need for the revision of these guidelines, particularly in terms of integrated data collection and the seamless integration of data into the CMMS. In addition, the establishment of mechanisms to ensure the completion of appropriate actions to address findings identified during inspections is required. (Krige and Blitenthall, 2010).

In contrast, other fields of engineering have established standards for evaluating ageing systems. Notably, international standards like API 579-1/ASME FFS-1 2007, Fitness-For-Service are standards developed and published jointly by the American Petroleum Institute (API) and American Society of Mechanical Engineers (ASME). They are employed for assessing equipment in the refining and petrochemical sectors, designed according to ASME code. Additionally, the BS7910 Guide to methods for assessing the acceptability of flaws in metallic structures, published by British Standards, serves as a general approach for evaluating defects in and around welds across diverse industries. This standard is particularly focused on the assessment of fatigue, creep crack growth, and proximity to fracture (Ahmadzadeh and Lundberg, 2014).

### **3.5 INTEGRATED STRUCTURAL INSPECTION AND MANAGEMENT SYSTEM**

The initial inspection serves as a benchmark to assess the condition of the mine shaft. Having consistent procedures for inspecting structures and reporting on their condition is crucial to establish a comparison between the baseline and subsequent inspection reports. This allows for regular inspections conducted by trained mine personnel and high-level overview inspections carried out by competent structural engineers, ensuring effective follow-up on inspection findings. All major and minor structures,

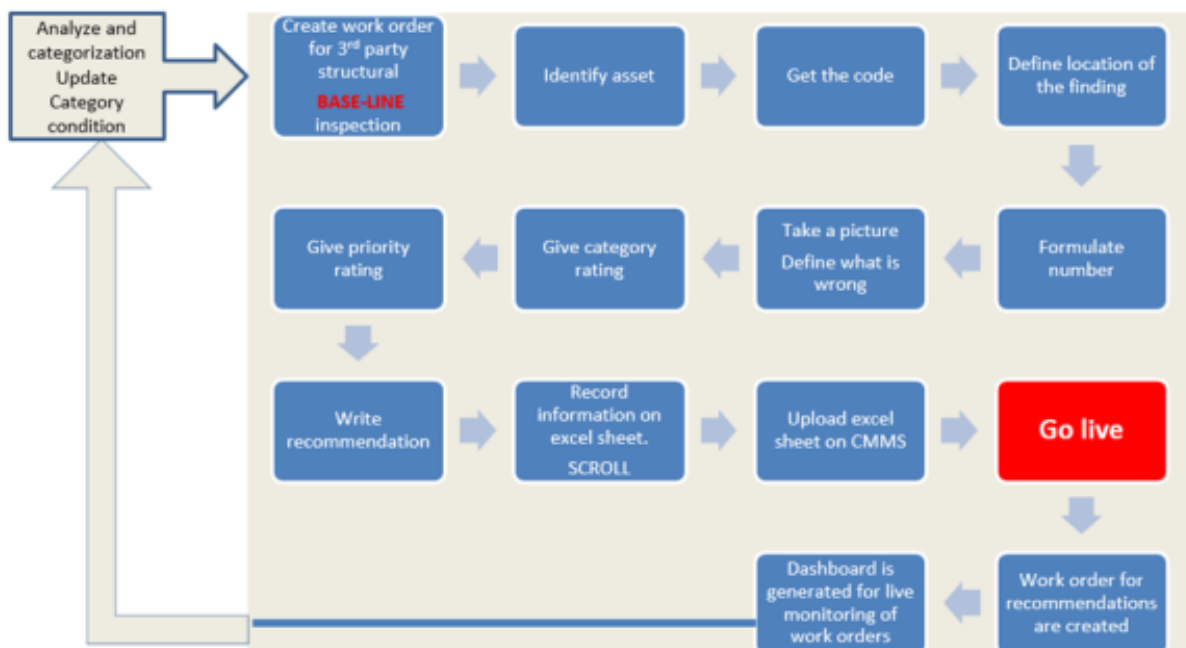
regardless of being constructed from steel, concrete, or other structural materials, are encompassed within this process.

While SIMM inspections do not offer certification of structural adequacy, they act as a best practice measure to proactively identify and address structural deterioration early on. The frequency of inspections conducted by different individuals is based primarily on the condition of the structures, with more deteriorated structures requiring more frequent inspections.

The maintenance programme and schedules at the site must adhere to appropriate standards, specifications, and guidelines. These guidelines include the Structural Inspection and Maintenance Management (SIMM) guidelines: Anglo American (2011b), Anglo American (2011c), and Anglo American (2011d), which are specific to SIMM for plants, shafts, and conveyances respectively.

The SIMM guideline aims to establish a standard guideline for structural management strategy. The scope of this standard encompasses various stages, including planning, design, construction, commissioning, operation, maintenance, modification, repair, and decommissioning and demolition of significant structures. These structures can be constructed from steel, concrete, timber, aluminium, or other materials.

Figure 3.5 depicted below illustrates the integrated SIMM flow process, encompassing inspection, the formulation of findings accompanied by images, descriptions of the finding's location, data capture into CMMS, and the monitoring of corrective actions through a live dashboard.



**Figure 3.5: iSIMM process Flow**

### 3.6 DATA COLLECTION MINE SHAFT CONDITION

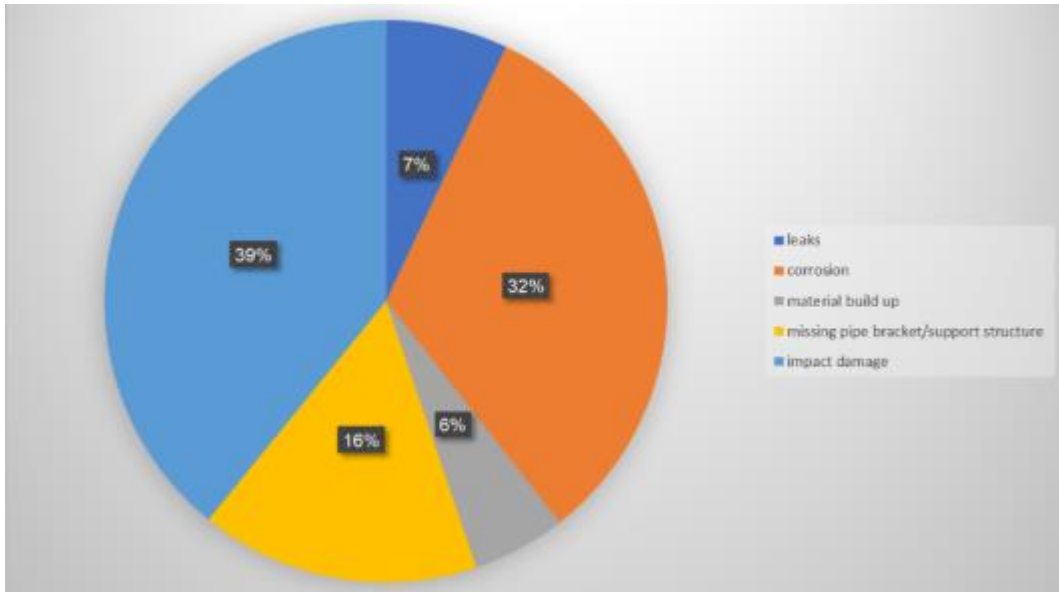
Conducting regular structural inspections has become a standard practice in the industry. These inspections are carried out collaboratively by structural engineers, site engineers, and the engineering team. The inspection team is transported using an inspection cage or canopy that travels at a speed of approximately 1.2 metres per second, enabling efficient examination of mine shaft structures.

The primary components of the shaft system include buntons, guides, pipe brackets, cable clamps, penthouses, brow beams, footwall beams, and station structures, which form the core framework essential for maintaining the shaft's operational and structural integrity. Each component plays a critical role in supporting the alignment and stability necessary for safe and efficient shaft operations.

In addition to the steel structures of shaft system, a concrete lining is a common feature for a typical mine shaft. However, issues with concrete lining are frequently encountered in the design phase, presenting unique challenges. The structural integrity of the concrete is paramount, as any degradation can compromise the precise alignment of the steelwork and affect the performance of the components it supports. Noting the condition of the concrete lining during inspection and ensuring the stability of the concrete structure is therefore vital to prevent misalignment or instability in the steel elements, which could ultimately impact the reliability and safety of the entire shaft system. During inspection, the condition of these components' steel and connections is thoroughly assessed. Any damage to the structure is evaluated by comparing its current strength to its original design and construction specifications. Historical reports from previous structural inspections are analysed to gain insights into the state of the mine shaft structures.

All safety incidents within the mine are reported and subjected to investigation, including root cause analysis. The investigation reports on safety incidents related to structural matters, offer insights into common failure points and their underlying causes. Figure 3.6 below presents an analysis of typical failure mechanisms extracted from past reports.

The structural steel and concrete components within mine shafts exhibit diverse behaviours and strength characteristics influenced by varying environments. Factors like environmental conditions such as moisture levels, extreme temperatures, properties of the surrounding rock mass and unstable wall rocks among others, significantly affect the observed failure modes. These failure modes encompass shear yielding, fracture, shear-out (or tear out), buckling, and the formation of cracks.



**Figure 3.6: Typical mine failure mechanisms**

### 3.7 CATEGORISATION OF THE STRUCTURAL CONDITION

Establishing definitive categories for structural conditions proved to be a nuanced and intricate task. Perception variations among individuals regarding the decline in structural strength introduce subjectivity into interpreting such conditions. To ensure consistency within the reporting system, it becomes imperative to develop a meticulously outlined framework for categorisation and clear guidelines for interpretation.

In the mining sector, the adoption of a standardised approach to categorising structural strength and assessing potential failure probabilities has been a collaborative process involving extensive discussions among structural engineers and key stakeholders.

This concerted effort led to the formulation of a universally accepted rating system utilised as a benchmark for evaluating structural conditions comprehensively. Particularly, the SIMM standard stipulates that steel sections experiencing a 25% reduction in their cross-sectional area due to corrosion must be replaced as they are deemed unsafe (Anglo American, 2011b; Anglo American, 2011c).

Shaft/station findings and their respective condition sheets include both category and priority designations. The category specifically aims to characterise the condition of structural components, and a detailed breakdown of these categories can be found in Table 3.1.

The priority defines the urgency and importance placed on the recommended remedial work. The priority categories are explained in Table 3.2.

**Table 3.1: Condition category and description**

Condition Category	Description	% strength remaining	Typical action
CC1	Slight reduction in strength.	95 to 100	Minor action.
CC2	Some reduction in strength. Repair and maintenance required to maintain, improve condition or avoid moving to Category 3.	75 to 95	Minor action.
CC3	Major reduction in strength. Safe use of the structure is compromised. Medium term action required.	50 to 75	Minor to medium size repair work may be required.
CC4	Little useful residual strength. Safe use of this structure is compromised. Urgent repair is required.	25 to 50	Major repair required.
CC5	Safe use of this structure is impossible. Immediately stop use of the structure till repair is done.	0 to 25	Urgent repair required.

**Table 3.2: Criticality priority**

Priority	Description
PM	Ongoing monitoring is required.
P1	Repair or replacement of structural members, or other recommended work, should be scheduled as soon as possible, but not later than one year from the date of this report.
P3	Repair, replacement, or other recommended work will be required within the next three years.
Pi	Repair or replacement of structural members, or other recommended work, requires urgent, immediate attention.
PX	Repair or replacement of the structural members must be completed before use of the structure.

### **3.8 EFFECTS OF USING LIMITED HISTORICAL DATA TO MAKE ‘FUTURE’ PREDICTIONS**

The utilisation of historical data serves as the cornerstone for predicting future outcomes, particularly through the development of a specialised structural asset life cycle and costing model tailored for a mine shaft. This model’s principal objective revolves around estimating the potential lifespan of the shaft under diverse scenarios, encompassing situations with no action, low action, medium action, and continuous investments dedicated to upholding the shaft’s safety. These investments account for both cost and time required for a maintenance programme that accommodates prevailing deterioration conditions over a 50-year span. Emphasising structural maintenance and long-term management requirements, this dissertation is focused on ensuring the durability and safety of the mine shaft, not only throughout its operational existence, but also well beyond the following 50 years.

By conducting an extensive SIMM analysis, evaluating the current state of the mine shaft, and comparing it with past SIMM assessments, a model was devised. This model was crafted based on theoretical deterioration patterns observed within the present shaft environment. The overarching goal was to determine the projected deterioration path and develop varied maintenance strategies to calculate the most practical and cost-effective repair approaches. These initiatives are strategically aimed at combatting ongoing structural deterioration and ensuring continued safety and productivity over the mine’s extensive operational lifespan.

### **3.9 CAPTURING OF DATA AND REPORTING**

Upon the completion of a shaft examination, an Excel spreadsheet must be furnished to the maintenance planner. This spreadsheet must consist of a total of five sheets.

- shaft data
- shaft findings
- station findings
- shaft condition
- station condition

The provided sheet requires certain information to be entered, including bunton spacing, shaft depth, winder start reading for bunton 1, and the site name. This data is essential for the shaft examination condition report. Additionally, the sheet must contain drawings depicting bunton sets and stations, along with allocated numbers for all components within a bunton set and station.

After each structural inspection, it is crucial to document all findings and assign specific action items to designated individuals. The Excel template in Table 3.3 should be utilised for reporting both third-

party inspections and internal structural inspections. All repair work must be agreed upon through collaboration between the structural engineer and the site engineer. They should also agree on scheduling the work within the CMMS. The responsibility of uploading the Excel report to the CMMS and monitoring the dashboard lies with the planner. The engineer holds the responsibility and accountability for completing work orders and providing comprehensive feedback to the planning department.

**Table 3.3: Excel template for shaft examination findings**

Reference	Operator Meterage Reading	Asset number	Deviation	Finding/Note	Category	Priority	Photo	Action	No Action	Target Date	Responsible Person

The explanation for the Excel sheet fields are:

1. The reference number needs to be a unique number per finding. This is required to be able to locate the finding in CMMS. Once the import has completed, the reference number may be the date of the inspection plus the number of the finding. An example is 20220325-D001. The inspection date will be the date that the inspection took place. The format of the date needs to be yyyy-mm-dd.
2. The operator meterage reading will be the meterage that the winder operator will provide. This is required to indicate which buntion set the deviation is on.
3. Asset Number?
4. Deviation?
5. The location number is a number that has been populated in the CMMS that will indicate what component has the deviation. An example is KS-141000-CLM-C.
6. The finding/note is the description of the finding.
7. The category is used to define the structural conditions of the component.
8. The priority defines the urgency and importance placed on the recommended remedial work. (Find description under Assessment of Risk above, refer to Table 3.2).
9. The photo column will need to contain a photo that has been taken of the deviation. The photo needs to be anchored to the row where the deviation is noted in the Excel sheet. Only deviations that have a photo linked to it will be imported into the CMMS.
10. The action indicates if any additional action is required.
11. The target date will indicate what date the deviation needs to have been actioned by. The format of the date needs to be yyyy-mm-dd.

12. The appointed area supervisor is required to indicate who is responsible to fix the deviation once a work order has been created with the import of specific details of the structure condition into the CMMS.

Table 3.4 provides an example of shaft examination findings which contain the condition of all the bunton sets and the stations.

**Table 3.4: Shaft examination findings**

Reference	Inspection Date	Location Number	Category	Priority	Operator	Meterage Reading - Start	Operator	Meterage Reading - End
20220325-C001	2022-03-25	KS-141000-GUI-B1	3	P3		0		2358
20220325-C002	2022-03-25	KS-141000-GUI-C1	3	PX		0		2358
20220325-C003	2022-03-25	KS-141000-GUI-D1	3	P3		0		2334
20220325-C004	2022-03-25	KS-141000-GUI-D1	3	PX		2340		2358
20220325-C005	2022-03-25	KS-141000-GUI-D2	3	P3		0		2358
20220325-C006	2022-03-25	KS-141000-GUI-D3	3	P3		0		2334
20220325-C007	2022-03-25	KS-141000-GUI-D3	3	PX		2340		2358
20220325-C008	2022-03-25	KS-141000-GUI-D4	3	P3		0		2358
20220325-C009	2022-03-25	KS-141000-GUI-D5	3	P3		0		2358
20220325-C010	2022-03-25	KS-141000-GUI-D5	3	P3		0		2358
20220325-C011	2022-03-25	KS-141000-GUI-F1	3	P3		0		2358
20220325-C012	2022-03-25	KS-141000-GUI-F2	3	P3		0		2358
20220325-C013	2022-03-25	KS-141000-GUI-F3	3	P3		0		2358
20220325-C014	2022-03-25	KS-141000-GUI-F4	3	P3		0		2358
20220325-C015	2022-03-25	KS-141000-GUI-F5	3	P3		0		2358
20220325-C016	2022-03-25	KS-141000-GUI-G1	3	P3		0		2358
20220325-C017	2022-03-25	KS-141000-FDR-01	3	P3		0		2358
20220325-C018	2022-03-25	KS-141000-CLM-A	3	P3		0		1506
20220325-C019	2022-03-25	KS-141000-CLM-A	4	P1		1506		1512
20220325-C020	2022-03-25	KS-141000-CLM-A	3	P3		1512		2358
20220325-C021	2022-03-25	KS-141000-CLM-B	3	P3		0		2358
20220325-C022	2022-03-25	KS-141000-CLM-C	3	P3		0		1608
20220325-C023	2022-03-25	KS-141000-CLM-C	5	P1		1608		1616
20220325-C024	2022-03-25	KS-141000-CLM-C	3	P3		1616		2358
20220325-C025	2022-03-25	KS-141000-CLM-D	3	P3		0		2358
20220325-C026	2022-03-25	KS-141000-CLM-E	3	P3		0		2358
20220325-C027	2022-03-25	KS-141000-ECA-01	3	P3		0		2358
20220325-C028	2022-03-25	KS-141000-BUN-A	3	P3		0		2358
20220325-C029	2022-03-25	KS-141000-BUN-B	3	P3		0		2358
20220325-C030	2022-03-25	KS-141000-BUN-C	3	P3		0		2358
20220325-C031	2022-03-25	KS-141000-BUN-D	3	P3		0		2358
20220325-C032	2022-03-25	KS-141000-BUN-E	3	P3		0		912
20220325-C033	2022-03-25	KS-141000-BUN-E	4	P1		912		918
20220325-C034	2022-03-25	KS-141000-BUN-E	3	P3		918		1188
20220325-C035	2022-03-25	KS-141000-BUN-E	4	P1		1188		1194
20220325-C036	2022-03-25	KS-141000-BUN-E	3	P3		1194		1278
20220325-C037	2022-03-25	KS-141000-BUN-E	4	P1		1278		1284
20220325-C038	2022-03-25	KS-141000-BUN-E	3	P3		1284		1776
20220325-C039	2022-03-25	KS-141000-BUN-E	4	P1		1776		1962
20220325-C040	2022-03-25	KS-141000-BUN-E	3	P3		1962		2334
20220325-C041	2022-03-25	KS-141000-BUN-E	5	P1		2334		2358
20220325-C042	2022-03-25	KS-141000-BUN-F	3	P3		0		1680
20220325-C043	2022-03-25	KS-141000-BUN-F	4	P1		1680		1686
20220325-C044	2022-03-25	KS-141000-BUN-F	3	P3		1686		2358
20220325-C045	2022-03-25	KS-141000-BUN-H	3	P3		0		2358

The sheet fields are:

1. The reference number needs to be a unique number per condition entry. This is required to locate the condition entry in CMMS once the import has completed. The reference number may be the date of the inspection plus the number of the condition entry. An example is 20220325-C001.
2. The inspection date will be the date that the inspection took place. The format of the date needs to be yyyy-mm-dd.

3. The location number is a number that has been populated in the CMMS and will indicate what the condition is of the component. An example is KS-141000-CLM-C.
4. The category is used to define the structural conditions of the component.
5. The priority defines the urgency and importance placed on the condition.
6. The operator meterage reading – start is used to indicate from what depth the condition of this component starts.
7. The operator meterage reading – end is used to indicate to what depth the condition of this component ends.

### **3.10 DASHBOARD MONITORING INTEGRATED WITH CMMS**

The system should have the capability to generate a real-time dashboard displaying the comparison between closed and created work orders. This feature will aid in assessing the risk posed by inadequate structural condition and how it is being addressed or resolved. Ongoing enhancement of the iSIMM might be required as feedback from end users is received.

The CMMS is commonly employed to oversee the planning, scheduling, and implementation of maintenance tasks. Among these tasks is the documentation of maintenance and activity expenses as well as historical data. An effectively utilised and properly managed CMMS can prove highly valuable in offering data for the detection or more precise assessment of defects.

Useful information from the CMMS may include reports containing:

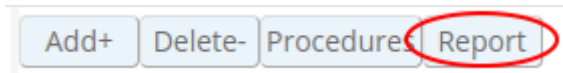
- Work Order and Notification Number
- Work Order and Notification Description
- Equipment Number (Functional Location)
- Equipment Description
- Estimated Hours
- Actual Hours
- Labour Rand
- Material Rand
- Outside Expenditure, such as contractors and outside shop, in Rand
- Total Rand, Labour + Material +Outside Expenditures

#### **Shaft Exam Module**

This Excel data is imported into the shaft exam module of CMMS. All the information captured on the Excel sheet may be recalled by accessing the shaft exam module or by drawing reports.

From the information in the shaft exam module a “Shaft Exam Dashboard” and “Shaft Condition Report” may be drawn.

To access the reports click on the “Report” button located next to the Procedure Button

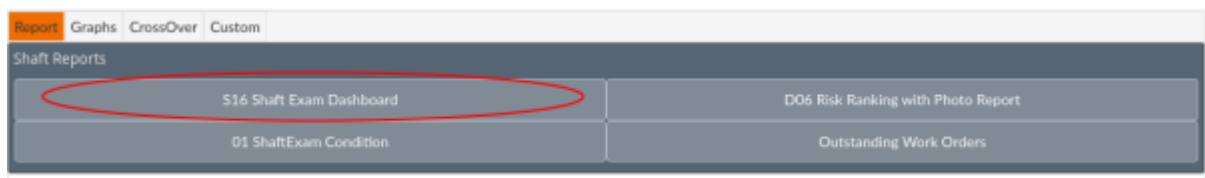


### Shaft Exam Reports

The report page consists of:

- The filters (located on the left) and
- The reports (located on the right).

Figure 3.7 shows the filter selections that may be used to filter the data. After completing the filters the relevant reports may be selected. The shaft exam dashboard report is then developed.



**Figure 3.7: Filter selections**

Table 3.5 shows “Shaft Exam Dashboard” Report displaying a summarised count of all deviations found during the shaft examination per condition category rating.

**Table 3.5: Dashboard report on CMMS**

No. Elements that require maintenance by % of strength	
<b>Main Shaft</b>	
100%	0
95 - 100%	0
75 - 95%	91
50 - 75%	143
< 50%	125
<b>Sub Shaft</b>	
100%	0
95 - 100%	3
75 - 95%	75
50 - 75%	165
< 50%	262

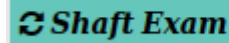
Figure 3.8 shows the inspection report with details, category rating and pictures. For a more in-depth view of the discrepancies, one can click on the respective category, which will prompt the report to



On the standard maintenance dashboard in the CMMS the shaft exam findings may be populated either for one site or all the sites. This information will be shown on one form and may be used to compare the conditions of the different sites. First select the dates that you want to filter on; if the findings are not between the date from and date to that is selected, no information will be shown.

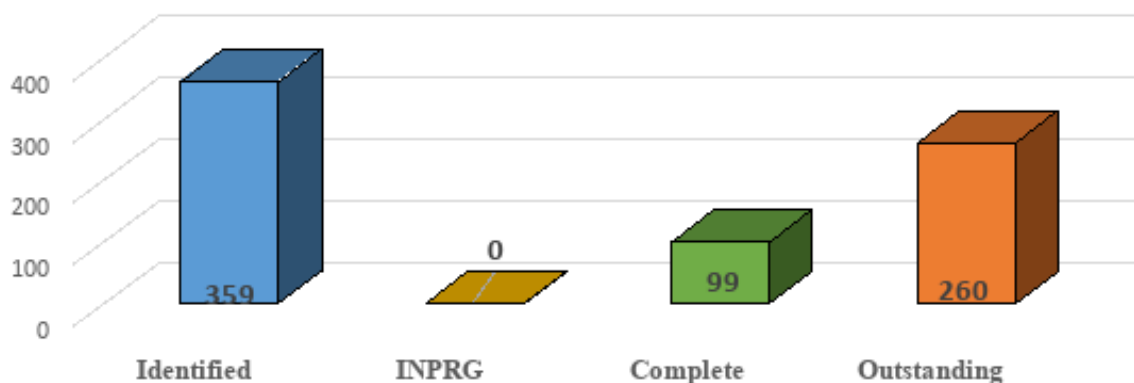
Next: select the User group;

Click on the “Shaft Exam” Button, this will calculate the findings per site, categories and construction types.



Once the calculation process is finished, the results are presented on the screen. Using this data, various graphs can be generated by clicking on the corresponding table headings. Upon completion of the maintenance calculation, the dashboard showcases all generated work orders, including the findings from the shaft examination.

Figure 3.9 illustrates the graphical representation on the dashboard for main shaft structural maintenance activities. These work orders will persist as pending until they are actioned by an artisan. This data can be exported either to an Excel file or depicted as a graph as illustrated below. The graph’s legend provides valuable insights into the progression of work order execution. “Identified” indicates the count of observations made during structural inspections. “In Progress (INPRG)” represents the work orders assigned and planned for specific artisans. “Completed” signifies executed work orders documented in the CMMS, and “Outstanding” denotes work orders yet to be carried out.



**Figure 3.9: Main shaft work order live dashboard**

Table 3.7 explains the meaning of each work order status in the CMMS. The structural inspection report offers a comprehensive snapshot of the mine shaft’s condition, pinpointed by specific meterage readings and findings. Through categorisation, a unified understanding of the shaft’s integrity is achieved, with the assigned priority guiding the timeline for necessary actions, as depicted in the following representation in Table 3.8.

**Table 3.7: Work order status definition**

Work order status	Definition
Raised	Total number of work orders for all third-party structural inspection findings.
INPRG	Approved work orders to be done in the next 1 to 2 weeks planning horizon- work order is issued to artisan/executor of the task.
Completed	Work done and captured on CMMS.
Outstanding	Work not done yet, not planned for near future, and is not issued to artisan/executor of the task.

**Table 3.8: Third-party inspection report**

Reference	Operator Meterage Reading	Asset number	Deviation	Finding/Note	Category	Priority
20220325-056	624	CLM-C	BM	Pipe Bracket Missing. Replace pipe brackets	5	P1
20220325-057	636	CLM-C	BM	Pipe Bracket Missing. Replace pipe brackets	5	P1
20220325-058	648	BUN-D	ID	Impact Damage on Bunton. Bunton still in tact and not adversely affected. Continue to monitor Bunton in weakly shaft exams by looking for sections that have corroded through.	3	P3
20220325-059	648	CLM-C	BM	Pipe Bracket Missing. Replace pipe brackets	5	P1
20220325-060	660	CLM-C	BM	Pipe Bracket Missing. Replace pipe brackets	5	P1
20220325-061	672	CLM-C	BM	Pipe Bracket Missing. Replace pipe brackets	5	P1
20220325-062	690	BUN-F	ID	Impact Damage on Bunton. Bunton still in tact and not adversely affected. Continue to monitor Bunton in weakly shaft exams by looking for sections that have corroded through.	3	P3
20220325-063	786	BUN-E	ID	Impact Damage on Bunton. Bunton still in tact and not adversely affected. Continue to monitor Bunton in weakly shaft exams by looking for sections that have corroded through.	3	P3
20220325-064	912	BUN-E	COR	Corrosion on Bunton connection. Material build-up to be removed and extent of corrosion to be assessed. If excessive corrosion is present local member repairs to be conducted (welded angle iron over affected area).	4	P1
20220325-065	1188	BUN-E	COR	Corrosion on Bunton connection. Material build-up to be removed and extent of corrosion to be assessed. If excessive corrosion is present local member repairs to be conducted (welded angle iron over affected area).	4	P1
20220325-066	1266	BUN-E	ID	Impact Damage on Bunton. Bunton still in tact and not adversely affected. Continue to monitor Bunton in weakly shaft exams by looking for sections that have corroded through.	3	P3
20220325-067	1278	BUN-E	COR	Corrosion on Bunton connection. Material build-up to be removed and extent of corrosion to be assessed. If excessive corrosion is present local member repairs to be conducted (welded angle iron over affected area).	4	P1
20220325-068	1338	BUN-D	ID	Impact Damage on Bunton. Bunton still in tact and not adversely affected. Continue to monitor Bunton in weakly shaft exams by looking for sections that have corroded through.	3	P3

### 3.11 BENEFIT OF DEVELOPING INTEGRATED SYSTEM

The benefits are:

- transparency – online-based remedial-actions monitoring system to view mine shaft condition in real time
- secure online record – track record of all inspections and conditions since base line inspection
- work scheduling and traceability
- estimation of life remaining for structures that support the LoM
- development of risk-based inspection programme
- estimate the life cycle costing
- increased productivity by reducing down time
- high quality data feedback
- ability to attach images of work performed
- improved data management and analytics
- improved data processing capacity and reporting time
- improved data security, compliance, accountability and auditability

### 3.12 REPORTS GENERATED BY THE ISIMM DASHBOARD

The iSIMM dashboard, as detailed in Chapter 3.10 is a crucial structural engineering tool that ensures the integrity, durability, and safety of mine shafts by integrating data from Structural Inspection and Maintenance Management (SIMM) reports with a Computerised Maintenance Management System (CMMS). This integration enables real-time monitoring, comprehensive tracking, and prioritisation of maintenance tasks, centralising structural health information to support proactive decision-making. By importing SIMM inspection data into the CMMS, the iSIMM dashboard generates critical reports on shaft conditions and work order statuses, continuously updating as new inspections and maintenance activities occur. This seamless integration provides engineers and management with up-to-date insights into structural conditions and maintenance requirements, enabling immediate identification and mitigation of potential risks to operational safety. The iSIMM dashboard produces several key reports, each supporting specific operational and management needs:

- **Shaft Exam Dashboard**

This report summarizes all deviations detected during shaft examinations, categorising them by condition ratings (CC1 to CC5). This report is essential for engineers and maintenance planners to quickly assess shaft conditions, prioritise corrective actions, and schedule maintenance based on severity.

- **Shaft Condition Report**

The Shaft Condition Report provides a comprehensive visual overview of the entire shaft, including specific conditions of critical components such as buntons, guides, and beams. This report is invaluable for tracking deterioration trends and planning long-term maintenance interventions.

- **Work Order Status Report**

Detailing work orders by status—"Identified," "In Progress (INPRG)," "Completed," or "Outstanding"—this report ensures that maintenance activities are on schedule and helps planners to track the execution of tasks. It enables effective tracking of both completed and pending work orders, supporting timely completion and preventing backlogs.

### 3.13 PURPOSE AND USE OF THE REPORTS

Each report generated serves a unique purpose and is used by different personnel:

- **Maintenance Engineers and Managers**

These professionals rely on the reports to assess the structural condition of the shafts and schedule appropriate maintenance activities. The reports allow them to allocate resources strategically, prioritise tasks, and ensure that all structural components remain in compliance with safety standards.

- **Safety Officers**

Safety officers use these reports to evaluate any safety-critical structural findings. They ensure that high-risk conditions are promptly addressed to protect workers and reduce environmental risks.

- **Executive Management and Stakeholders**

Higher-level management uses the dashboard reports to make strategic decisions, allocate budgets, and monitor long-term maintenance effectiveness. These reports help them evaluate the performance of maintenance strategies and justify future funding needs.

### 3.14 ACCESS MANAGEMENT FOR THE ISIMM DASHBOARD

The dashboard's access is controlled through the CMMS, with permissions set according to user roles:

- **Super Users**

Individuals with administrative privileges can configure the dashboard, manage permissions, and generate comprehensive reports, ensuring data integrity and security.

- **Maintenance Teams**

Maintenance personnel have access to the reports relevant to their tasks, enabling them to perform work accurately and efficiently.

- **Management and Executive Users**

Decision-makers access high-level summary reports, allowing them to monitor structural conditions and maintenance performance without needing to engage in detailed operational data.

### 3.15 CONCLUSION

The exploration of the iSIMM in this chapter has been fundamental in uncovering its intricate design, operational functionalities, and the significance of shaft baseline inspection within this system. This section has played a pivotal role in illustrating the innovative approach adopted for the iSIMM. It has provided an in-depth understanding of the system's development, emphasising its capabilities in proactively addressing remedial actions to manage the lifespan of mine shafts. The integration of an advanced monitoring system promises heightened visibility, improved monitoring efficiency, and streamlined execution of corrective actions identified during structural inspections. This system is pivotal not only in contributing to the overall life-of-mine management but also in accurately computing the remaining mine life.

Moving forward, the subsequent chapter is set to illuminate the development of a critical prognostic and risk/economics-based maintenance decision-making model. This upcoming section will intricately detail the methodology underlying the iSIMM system, elaborating on its complexities and the innovative integration of prognostic and risk-based models for maintenance decision-making. It aims to delve deeper into the proactive strategies employed within the iSIMM framework, providing an in-depth comprehension of its operational intricacies and the strategic decision-making processes integrated within this innovative model. Through this exploration, the dissertation endeavours to offer a comprehensive view of the cutting-edge methodologies transforming the structural inspection and maintenance landscape within the mining industry.

# CHAPTER 4: DEVELOPMENT OF PROGNOSTIC AND RISK/ECONOMICS-BASED MAINTENANCE DECISION-MAKING MODEL

## 4.1 INTRODUCTION

This chapter presents the development of a critical prognostic and risk/economics-based maintenance decision-making model. It extensively details the methodology of iSIMM, delving into the complexities of this innovative system that integrates prognostic and risk-based models for maintenance decision-making. The chapter examines the significant impacts of corrosion rates and corrosion probability on structural health, shedding light on their implications within mine shafts. This aspect is a novel contribution of this study, as previous research in this field has not covered the integration of prognostic models and risk-based maintenance decision-making in such depth. By addressing these areas, the study provides new insights and methodologies that enhance the understanding and management of mine shaft structural integrity.

Furthermore, it investigates the effects of impact damage through FEA experiments, meticulously studying the combined failure mechanisms and predicting potential failures. In addition, it evaluates the condition of structural elements within mine shafts and analyses the LCC based on the results of the FAT, aiming to optimise maintenance decisions from an economic perspective.

This chapter holds significant importance in the dissertation, highlighting a forward-thinking approach to managing mine shaft structures.

## 4.2 PREDICTIVE FAILURE MODELLING IN MINE SHAFT STRUCTURAL ASSESSMENT

The following data in Table 4.1 was captured during the shaft inspection for the shaft's life cycle modelling in the gold mine in 2022.

**Table 4.1: Mine shaft environmental data**

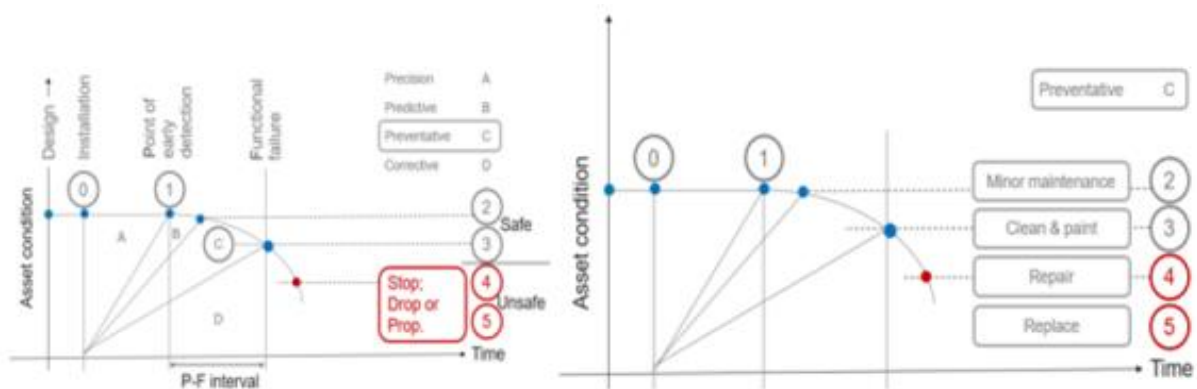
<b>Bunton Set</b>	<b>Humidity [%]</b>	<b>Temperature [°C]</b>	<b>Average Thickness [mm]</b>
50 (B)	51	26.4	10.67
100 (B)	52	26.4	10.84
150 (B)	51	26.4	8.8

To replicate the modelling of failures, two distinct failure mechanisms are explored: corrosion rate and damage resulting from falling objects.

During a third-party assessment of the mine shaft’s structural integrity, each component within the shaft was categorised using a range of condition classifications from CC1 to CC5. CC1 to CC5 is defined in Table 3.1. In this categorisation system, CC1 represents a new or slightly weakened component, while CC5 designates a component that has deteriorated to the extent of being incapable of fulfilling its intended function.

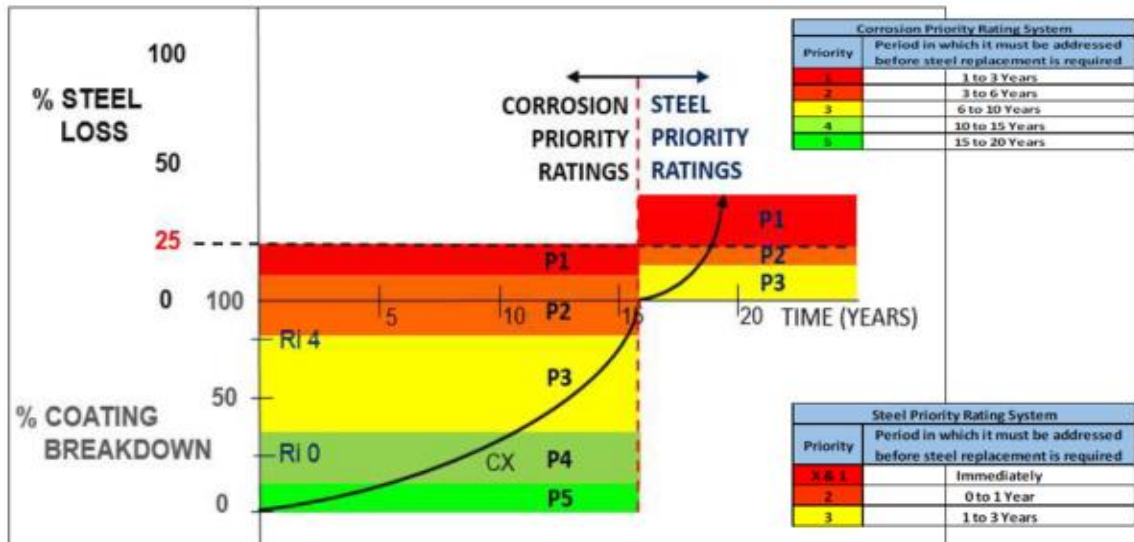
A detailed breakdown of the significance of these categories is elaborated upon in Table 3.2. These assigned categories served as initial variables for predicting the potential timeframe until failure for each individual component within the shaft. The prediction process frequently involved utilising the Monte Carlo simulation method. As per the SIMM guideline with regard to the condition of structure classification, steel sections that have experienced a 25% reduction in their cross-sectional area due to corrosion are considered unsafe and necessitate replacement.

The performance-failure diagram depicted in Figure 4.1 illustrates the typical degradation of the structure in general mine shaft condition and the corresponding corrective action effort relative to the condition category.



**Figure 4.1: Theoretical structural deterioration curve**

As illustrated in Figure 4.2, the steel priority rating suggests a timeframe of approximately three years for the replacement of steel components. This timeframe is established through the condition evaluation performed during the inspection process. Conversely, the corrosion priority rating proposes a more extended timeframe compared to that of steel replacement, which varies according to the specific condition category. When the suitable corrective or preventive action is identified, it provides an opportunity to either reverse the deterioration of the condition or uphold it to avert further deterioration, thus avoiding potential breakdowns. Such actions may involve replacing steel components or applying protective coatings, commonly referred to as corrosion protection.



**Figure 4.2: Priority rating for corrosion protection and steel replacement (Wannenburg, 2023)**

In addition to the alternatives of steel replacement and corrosion protection, there exist other strategies, both temporary and permanent, that can be implemented. As depicted in Figure 4.3, three immediate measures are at hand to enhance the safety of a structure. A structurally compromised element can be secured by reinforcing it with propping or support. When a structure is deemed irreparable and poses a safety risk, it is often barricaded, removed, or secured to prevent unauthorised access while repair plans are developed, effectively minimizing the risk of injury. In cases where immediate removal or restricted access is not feasible, an emergency work order is issued, and a team is deployed to ensure the structure is made safe.



**Figure 4.3: Measure of deterioration and alternative actions**

The integration of a change management protocol within the domain of structural engineering holds immense importance. As a result, the educational materials and operational procedures incorporate detailed guidelines outlining the sequential steps for initiating a change, the mandatory approval processes, and the essential consultations with structural engineers as warranted. This meticulous

approach plays a pivotal role in cultivating a resilient framework for the methodical and discerning progression of structural configurations.

#### 4.2.1 Corrosion rates

Corrosion rates play a pivotal role in ascertaining the lifespan of structures made from metal. They provide insight into factors such as weight or thickness loss and the speed at which deterioration occurs within metal-based structures (Srivaranun, Akiyama, Bocchini, Christou, Frangopol, Fukushima, et al., 2021). Moreover, corrosion rates offer indications about the extent of steel replacement and repair work necessary to uphold or extend the structural life. Deeper or older mine shafts may necessitate regular risk-based inspections and forward-looking maintenance planning, taking into account the calculated and monitored corrosion rates (Wang and San, 2010). Introducing a corrosion protection system, often referred to as painting, can be a partial remedy to diminish the corrosion rate.

The application of a painting system can significantly enhance the resistance of metals to corrosion when executed accurately, adhering to the appropriate paint specifications and application methods. Anticipating the lifespan of mine shaft structures and components in engineering contexts is gaining increasing significance.

The proposed method for predicting structural life encompasses: (a) Corrosion-based design approach (CBDA), (b) Probability of falling object and casing damage and (c) Fatigue of concrete shaft lining (Sun, et al., 2020). To convert corrosion rate to millimetres per year (mm/y), the following equation can be used to convert millimetres per year to micrometres per year ( $\mu\text{m}/\text{y}$ ). Rate of Metal Corrosion is derived from the corrosion rate ( $r_{corr}$ ) using ISO 9223 (ISO 9223, 2012) as shown below:

$$r_{corr} = 1.77P_d^{0.52}e^{0.02RH+f_{st}} + 0.102S_d^{0.62}e^{0.033RH+0.04T} \quad (4.1)$$

where:

$P_d$ : the average annual deposition rate of  $\text{SO}_2$   $\left[\frac{\text{mg}}{\text{m}^2 \cdot \text{d}}\right]$

$RH$ : average annual relative humidity in %

$f_{st}$ :  $0.15(T - 10)$  for air temperature less than  $10^\circ\text{C}$  and  $-0.054(T - 10)$  for air temperatures greater than  $10^\circ\text{C}$

$S_d$ : the average annual chlorine deposition rate in  $\left[\frac{\text{mg}}{\text{m}^2 \cdot \text{d}}\right]$

$T$ : average annual temperature in  $^\circ\text{C}$

(All these variables are inputs to the model based on each respective shaft)

The condition over time can be expressed as a general power-law as shown below:

$$condition = 1 - mt^b \quad (4.2)$$

In the case of corrosion,  $m$  is the corrosion rate divided by the thickness of the thinnest section of the member:

$$condition = 1 - \frac{r_{corr}}{a} t^b \quad (4.3)$$

So, the time to achieve a certain condition is as below by rearranging Equation (4.3):

$$t = \left( \frac{a}{r_{corr}} (1 - condition) \right)^{\frac{1}{b}} \quad (4.5)$$

The equivalent loss of time due to the initial condition ( $c_1$ ) is as below.  $c_1$  can be between 0 – totally degraded to 1 – perfect condition. If  $c_1$  is 1, then the equivalent time lost  $t_1$  is 0.

$$t_1 = \left( \frac{a}{r_{corr}} (1 - c_1) \right)^{\frac{1}{b}} \quad (4.4)$$

The power-law adapted for time lost due to the initial condition is therefore:

$$condition = 1 - \frac{r_{corr}}{a} (t + t_1)^b \quad (4.4)$$

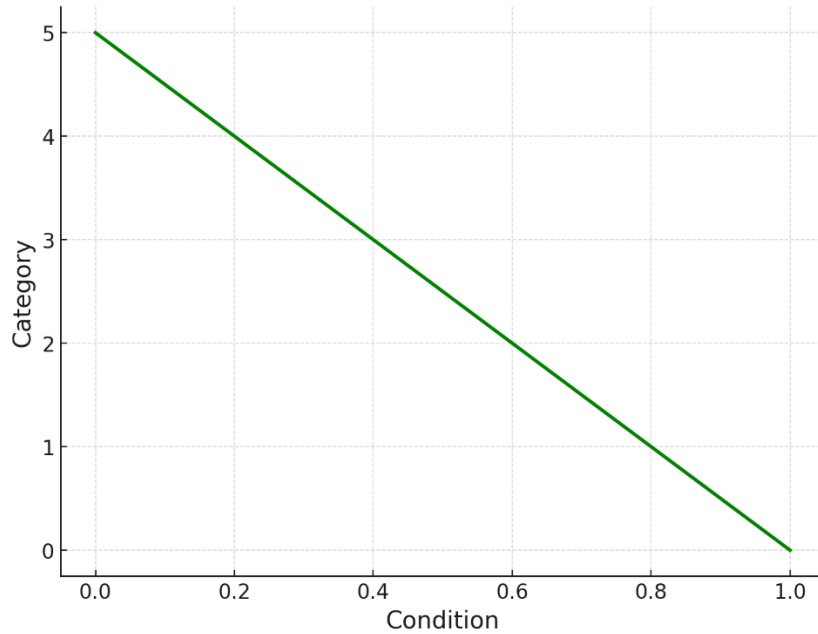
$$condition = 1 - \frac{r_{corr}}{a} \left( t + \left( \frac{a(1 - c_1)}{r_{corr}} \right)^{\frac{1}{b}} \right)^b \quad (4.5)$$

Where the condition (%) over time ( $t$ ) in years can then be defined using this corrosion rate, the initial condition ( $c_1$ ), thinnest section of the member ( $a$ ) in  $\mu\text{m}$ , and a shaping factor ( $b=0.8$ , for corrosion).

The following equation was used to transform the condition (%) to a condition category.

$$category = -cat_{max} \times condition - cat_{max} \quad (4.6)$$

Where  $cat_{max}$  is the maximum category. Equation (4.6) is just a linear relationship shown in **Figure 4.4** for  $cat_{max} = 5$ . The variable  $cat_{max}$  was used to give the possibility of going above CC5 for example to give CC5 and PX members a rating of CC8.



**Figure 4.4: Linear relationship between condition and category**

where:

Strength remaining of a structure = 100% is Category 0,

Strength remaining of a structure = 75% is Category 3, and

Strength remaining of a structure  $\leq$  50% is Category is 4.

### 4.3 CORROSION PROBABILITY

When certain substances in the air or water interact with most steel or metal types, a chemical reaction occurs, compromising the material's structural integrity. This process, known as corrosion, can be triggered by elements like oxygen, sulfur, salt, and various others, each capable of initiating distinct forms of corrosion. As shaft steel or concrete undergoes corrosion or deterioration, it loses its capacity to perform as intended in its original design, unable to sustain the same loads or fulfil the same functions. Gradually, corrosion can create hazardous conditions within a mine shaft as shown in Figure 4.5. Therefore, vigilant monitoring and effective management of corrosion are crucial to prevent structural failure. The steelwork shown below has not had any corrosion protection since its installation.

The corrosion rate of each individual member is influenced by probability factors, meaning that certain members may experience more severe environmental conditions and thus corrode at a faster rate compared to others (such as due to prolonged exposure to water leakage). Information about a specific member that exhibited a particularly high corrosion rate was utilised to calibrate a probability density function, enabling its incorporation into the model (ISO, 2012).

Figure 4.6 portrays a representative example from Set 5 of the BUN-02, where the 8 mm web corroded through. The beam's age at the time was 27 years. This instance was regarded as the average corrosion rate, considering that while numerous members displayed less corrosion, there were also a significant number that exhibited more extensive corrosion, similar to situations such as Figure 4.7.



**Figure 4.5: Pipe supports severely corroded**



**Figure 4.6: BUN-02 Set 5 recently corroded through**



**Figure 4.7: PST-04 set 33 severe corrosion**

Corrosion probability is determined using Weibull distribution analysis. The Weibull distribution is widely used in reliability analysis and can provide valuable insights into the behaviour of corroding materials. The Weibull distribution is a statistical probability distribution commonly used to model the distribution of lifetimes or failure times of objects or events. It is often employed in reliability engineering and survival analysis to analyse and predict the behaviour of systems or processes over time.

The Weibull distribution has two parameters: shape (also known as the Weibull slope) and scale (related to the characteristic life or scale factor). The shape parameter determines the pattern of the distribution, whether it is increasing, decreasing, or constant, while the scale parameter determines the magnitude of the distribution's values. The Weibull distribution can represent a wide range of patterns, from early-life failures to wear-out failures, making it a versatile tool for modelling various types of data in different fields.

The Weibull distribution offers a powerful tool for analysing data related to material degradation processes like corrosion (Zhang, Liu, Liang, Ye and Li, 2023). It provides a probabilistic model that enables quantification of failure rates over time. This information is essential for evaluating the reliability and lifetime expectancy of materials subjected to corrosive environments. Two key parameters define Weibull distribution: shape parameter ( $\beta$ ) and scale parameter ( $\eta$ ). The shape parameter characterises the failure mode exhibited by a system; values less than one indicate early failures while values greater than one represent late failures. The scale parameter determines how quickly failure rates increase or decrease over time (Zhou, Meng, Zeng, Sun and Tafsirojjaman, 2023).

In analysing corrosion characteristics using Weibull distribution, various statistical techniques are employed. One common technique is maximum likelihood estimation (MLE), which estimates the parameters of the distribution based on observed data. Another approach is least squares regression analysis, which fits a curve to the experimental data to determine the best-fitting Weibull distribution parameters (Zhang, et al., 2023).

Data collection played a crucial role in accurately analysing corrosion characteristics using Weibull distribution. The data provides a graph displaying cumulative failure probability against time that can highlight failure rates over different periods, providing information about the reliability and lifetime expectancy of materials subjected to corrosive environments.

The use of Weibull distribution in analysing corrosion characteristics provides valuable insights and helps inform decision-making processes to mitigate the detrimental effects of corrosion on mechanical systems. Part of these decisions is to ensure structural safety for structures falling within condition categories 4 or 5 can be improved through the following measures:

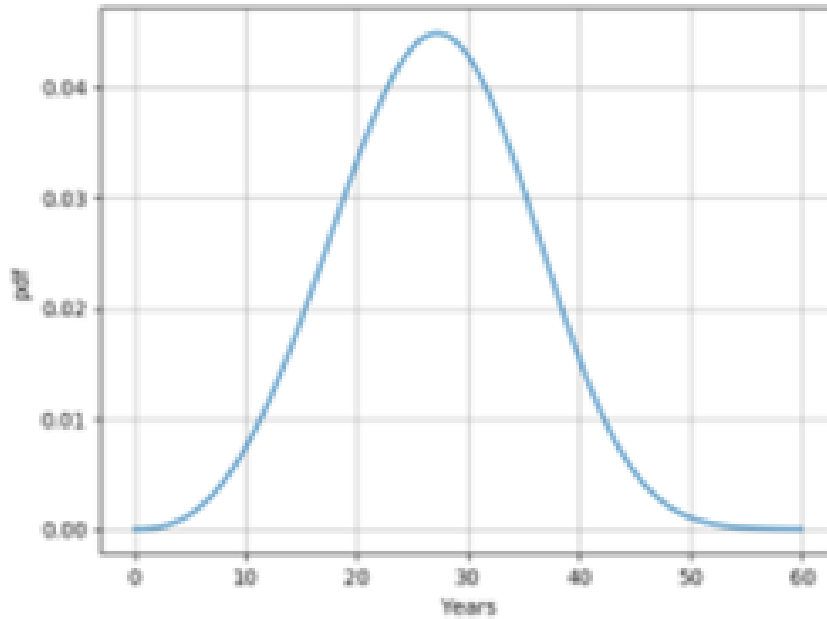
- implementing propping
- offloading or reducing load
- temporarily stopping production or reducing throughput
- identifying viable alternative load paths
- setting up barricades in unsafe areas

The 50% point of a symmetric Weibull distribution was used as a reference point. The scale factor ( $\lambda$ ) was then determined by calculating the remaining value.

This was taken as the 50% point of a symmetric Weibull distribution with  $k = 3.5$ . The remaining scale factor ( $\lambda$ ) could then be calculated using:

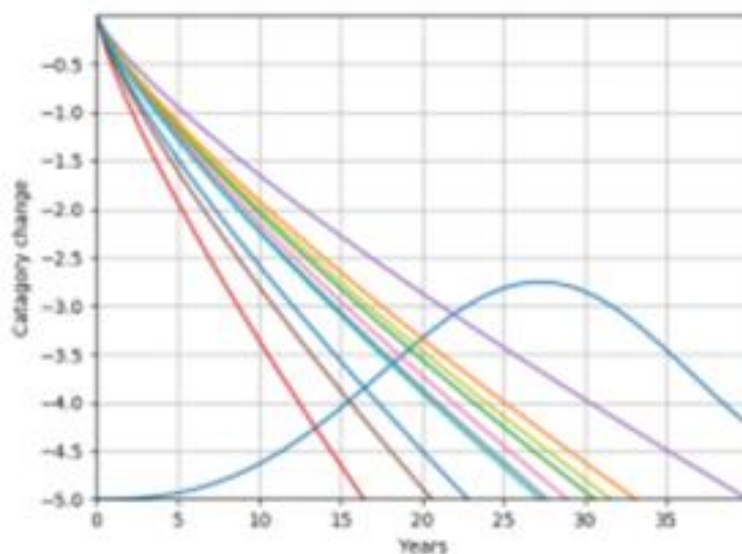
$$\lambda = \frac{27}{(-\log(1 - 0.5))^{\frac{1}{3.5}}} \quad (4.9)$$

This led to the Weibull distribution shown in Figure 4.8. Random corrosion curves can be generated using the Weibull distribution for time to failure, with variations in  $S_d$ , the average annual chlorine deposition, as illustrated in Figure 4.8.



**Figure 4.8: Weibull distribution**

The graph illustrates the progression of condition categories for structures in a mine shaft, starting from newly installed structures rated as condition category (CC) 0 or 1, and showing their deterioration over time to condition category 5. The different colours in the graph represent various structural components within the mine shaft. This Weibull distribution graph demonstrates that all structures experience a decline in condition over time. Furthermore, the rate at which these structural members degrade from category 1 to category 5 is influenced by the effectiveness of corrosion protection measures and maintenance practices.



**Figure 4.9: Randomly generated corrosion curves**

Ultimately, it is possible to formulate a function ( $f_{\text{determine } t_f}$ ) that returns the time to reach a given category based on the randomly generated corrosion curve.

#### 4.4 NUMERICAL EXPERIMENT USING FEA EXPERIMENT FOR IMPACT OF FALLING OBJECTS INTO MINE SHAFT

FEA was employed using ANSYS software to acquire the mechanical behaviour insights of the buntons, which constitute the primary components of vertical mine shaft structures (Wannenburg, 2023).

FEA is a technique utilised to investigate the behaviour of various objects under diverse working conditions, aiming to replicate real-life scenarios. This dissertation provides an overview of FEA simulations focused on the damage assessment of vertical mine shaft structures caused by falling objects. Through this assessment, a deeper understanding of geometric, material, load variation, stress distribution, and strain characteristics can be obtained. The alignment between anticipated effects using FEA and historical insights has been observed. In recent decades, FEA has evolved into a standard tool within industrial product development, enabling virtual design analysis, swift result generation, and timely implementation (Santosh, Mishra, Mahanta, Dharmarajan, Varma and Shoor, 2021; Singh, Mehta, Kumar and Sapra, 2022)

Figure 4.10 illustrates the Geometry Representation as show below:

- beam material models
- structural steel
- construction dimensions
- beam fixed at both ends

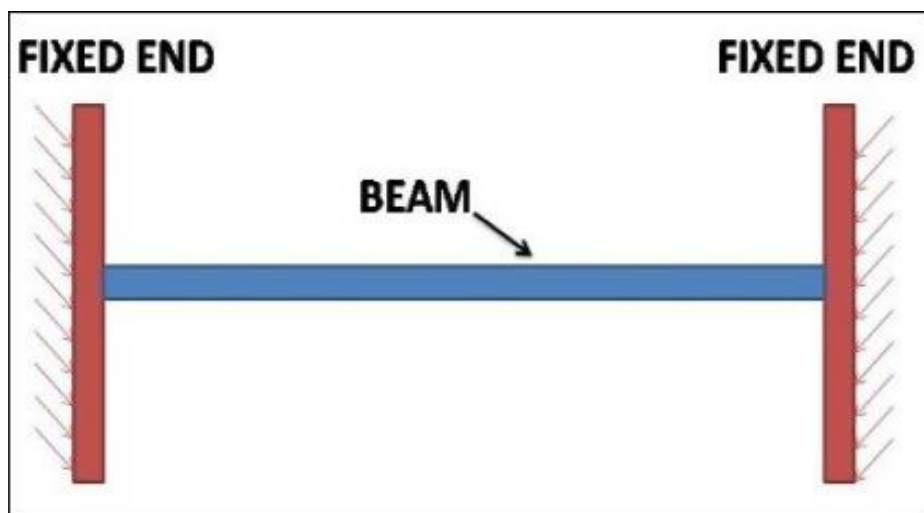
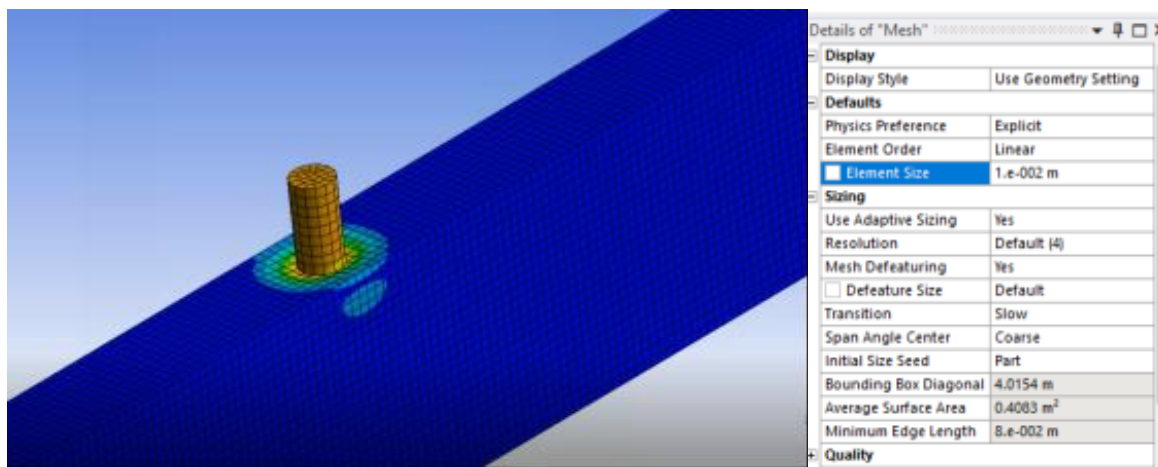


Figure 4.10: Geometry representation

FEA mesh variations were created by generating multiple mesh models that represent different structures for simulation purposes. It is important to note that all these models have demonstrated a satisfactory level of agreement in their results and have displayed minimal computational artefacts. The meshing process involves the use of designations such as ‘solids’ and ‘parts’. Solids contribute to creating a coherent mesh, whereas parts are constituted by multiple solids in contact. During the meshing process, these local meshes are interconnected using shared nodes, resulting in a unified part mesh. Specifically, the Johnson Cook stress-strain curve was defined, incorporating values derived partly from the analysis of disc fragments penetrating the plate. Figure 4.11 below depicts one of the finite element meshes used in this process:



**Figure 4.11: Finite element meshes used in this process**

#### 4.4.1 Damage from a falling object

Anglo American’s technical division conducted an analysis of objects that have the potential to fall down the mine shaft. This analysis was part of an investigation aimed at determining a method to assess the probability of the safety-detaching hook being struck by a falling object within the shaft. This scenario could lead to the opening of the detaching hook and subsequently causing the conveyance to fall down the shaft, resulting in a catastrophic incident.

This dissertation delves further into the analysis of falling objects within the shaft to evaluate their contribution to impact damage on vertical mine structures, with a specific focus on the bunton, which serves as a primary component in the mine shaft. To determine the probability of a member failing due to impact damage, the following were required:

- distribution of object masses
- energy of a falling object
- amount of damage the object will cause

In this context, ‘damage’ refers to alterations introduced to the structural elements of the mine shaft that disrupt their current state or future performance in an adverse manner. This definition highlights the significance of damage when comparing two distinct condition categories. In addition, damage in the context of structural and mechanical systems refers to modifications in material and/or geometric properties of the structures, resulting in changes to condition categories as per the SIMM guideline referred to in Table 3.1 and overall system performance.

The modelling of impact damage or damage caused by falling objects is approached from a probabilistic standpoint. Figure 4.12 provides an example of impact damage sustained by a pipe divider, which led to its classification as a CC3 category condition. Condition Category 3 indicates that the strength of the structure remaining is 50% to 75% which means that it is still safe to use. Refer to Table 3.1 which sets out the condition category and description.



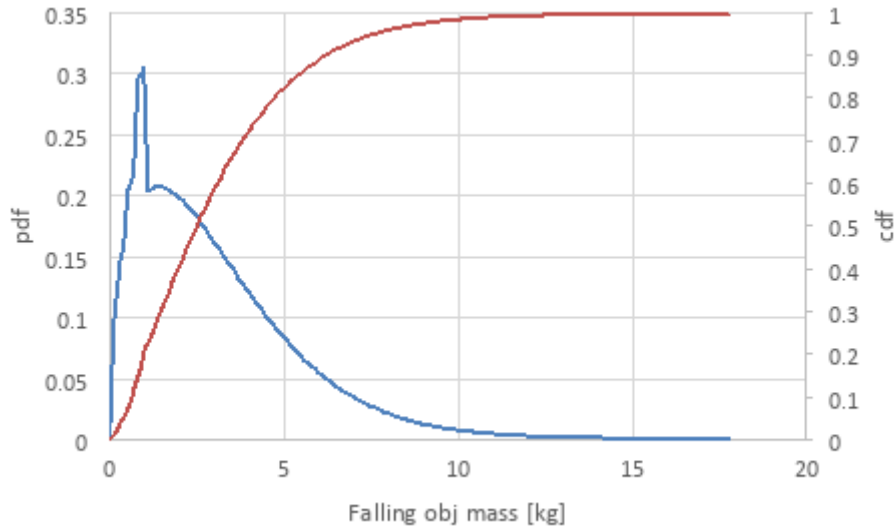
**Figure 4.12: Impact damage example (Cat. 3)**

#### **4.4.2 Mass of falling object**

Falling objects mass refers to the mass of objects that are dropped or fall from a certain height due to gravity. The mass of a falling object is a key factor in determining its potential impact force and the damage it can cause upon impact. Heavier objects generally possess more kinetic energy upon impact, which can lead to more significant consequences in terms of damage or destruction when they collide with a surface or structure.

The distribution of the object masses was determined with the data from a questionnaire that was sent to the engineers of 10 mine shafts. Figure 2.12 provides a statistical analysis of the information. The shaft engineers returned the frequency of occurrence of the different masses.

These individual distributions were consolidated into a single distribution, as depicted in Figure 4.13.



**Figure 4.13: Combined distribution of mass of falling objects**

This was achieved by adding up all the distributions  $f_i$  multiplied by their respective occurrence frequencies  $n_i$  and then dividing the result by the sum of all occurrence frequencies, as demonstrated with the equation below:

$$f_{combined} = \frac{\sum f_i(x) \times n_i}{\sum n_i} \quad (4.10)$$

#### 4.5 ENERGY OF OBJECT

The relationship between impact velocity and damage caused by falling objects is a fundamental concept in physics and engineering. In general, the kinetic energy of an object increases with the square of its velocity. When an object falls from a height and strikes a surface, the impact velocity can play a significant role in determining the amount of damage caused. The impact energy is directly related to the square of the velocity and mass of the falling object. Higher velocities can result in more energy being transferred upon impact, potentially leading to more severe damage to the object itself or the surface it strikes.

In engineering and safety assessments, understanding the impact velocity is crucial for designing structures and safety measures that can withstand or mitigate the potential damage. Different materials and structures have varying levels of resilience to impact forces, and these factors are considered when designing buildings, protective barriers, and other safety measures to minimise the potential damage from falling objects.

It is important to note that the relationship between impact velocity and damage can be influenced by various factors such as the shape of the object, the material properties of the impacted surface, and the

angle of impact. Furthermore, other factors like the potential for deformation, the distribution of forces upon impact, and the specific characteristics of the objects involved should also be considered when assessing the potential damage.

Velocity plays a significant role in determining the extent of damage caused by a falling object's impact on structural steel. Higher velocities result in more severe damage because of increased force upon collision. To assess damage based on velocity, engineers employ theories or models specific to each type of structure being impacted. For example, FEA was utilised to successfully simulate low-velocity impacted damage in sandwich composites. Their findings contributed valuable insights for predicting structural behaviour under impact loads.

In this research, the structural response to impact loads is assessed by considering both velocity and mass. The impact energy is calculated using a cylindrical object as a representation of a rock falling down the shaft, providing a realistic model of the forces involved. When an object falls freely under the influence of gravity, its velocity and energy change as it falls from different heights. The relationship between these factors can be explained using the principles of kinetic and potential energy.

The potential energy ( $PE$ ) of an object at a certain height is given by the formula:

$$PE = m \times g \times h \quad (4.11)$$

Where:

$m$  is the mass of the object,

$g$  is the acceleration due to gravity (approximately  $9.81 \text{ m/s}^2$  on the surface of the Earth), and

$h$  is the height from which the object falls.

Kinetic Energy ( $k$ )  $Um, g, h$ : The kinetic energy of an object in motion is given by the formula:

$$Um, g, h = 0.5 \times m \times v^2 \quad (4.12)$$

Where:

$m$  = the mass of the object,

$v$  = the velocity of the object.

Solving for  $v$  gives:

$$v = \sqrt{(2g \times h)} \quad (4.13)$$

This equation shows that the velocity of the falling object is directly proportional to the square root of the height from which it falls. As the object falls from greater heights, it will gain more kinetic energy and therefore have a higher velocity upon impact. This relationship is important in understanding the potential impact force and damage that the falling object can cause when it hits a surface.

In reality, air resistance may slow down the object's acceleration, and additional factors might come into play depending on the specific situation.

$$U(h, m) = 0.5 m v_{tf}^2 \quad (4.14)$$

Where  $v_{t_f}$  is the final velocity after falling for time  $t_f$  calculated using:

$$v_{t_f} = v_f \tanh \left( \sqrt{9.81 \frac{k}{m}} t_f \right) \quad (4.15)$$

Where  $v_f$  is the terminal velocity calculated with:

$$v_f = \sqrt{\frac{2 \cdot 9.81 m}{\rho_{air} C_d A_{obj}}} \quad (4.16)$$

and  $t_f$  is the time to fall height  $h$ ,

$$t_f = \frac{\cosh^{-1} \left( \exp \left( h \sqrt{\frac{9.81k}{m}} \frac{1}{v_f} \right) \right)}{\sqrt{\frac{9.81k}{m}}} \quad (4.17)$$

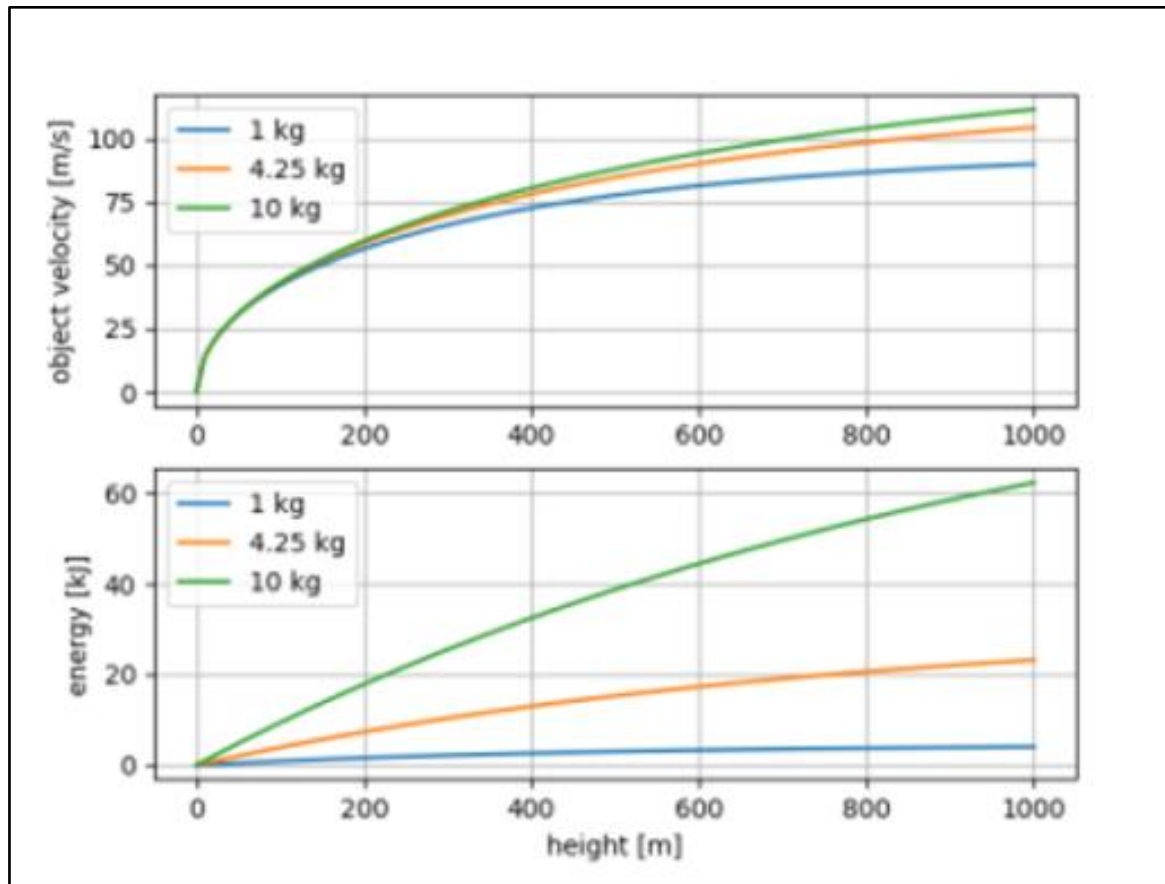
$$k = 0.5 \rho_{air} C_d A_{obj} \quad (4.18)$$

A simplified cylindrical object where the length is equal to the radius is chosen because it reduces the number of variables. For this, the bottom area ( $A_{obj}$ ) of the cylinder is calculated using:

$$A_{obj} = (\sqrt{\pi} \times V_{obj})^{\frac{2}{3}} \quad (4.19)$$

Where  $V_{obj}$  is the volume of the object using the density of steel or rock.

Figure 4.14 shows the final velocity and energy of the object after falling from different heights.

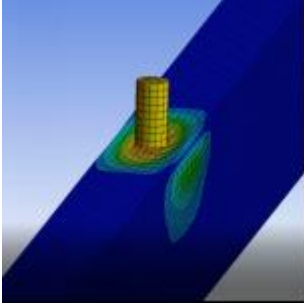
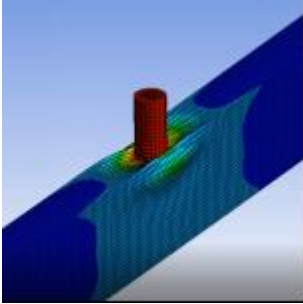
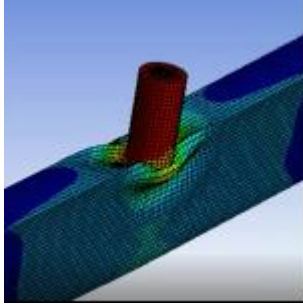
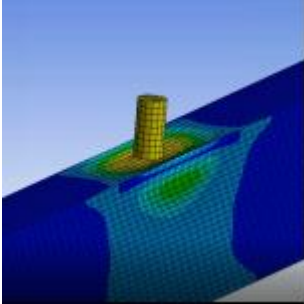
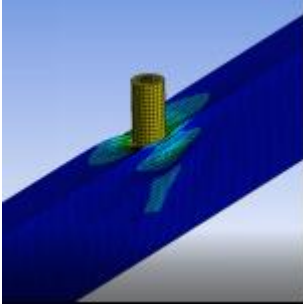
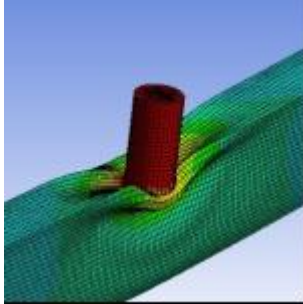


**Figure 4.14: Velocity and energy of cylindrical objects dropped from different heights**

#### 4.5.1 Determining category change from energy (FEM)

The category change caused by different energies of objects was determined by conducting a FEA on ANSYS. The result of the FEA is shown in Table 4.2 below.

**Table 4.2: Result of the FEA**

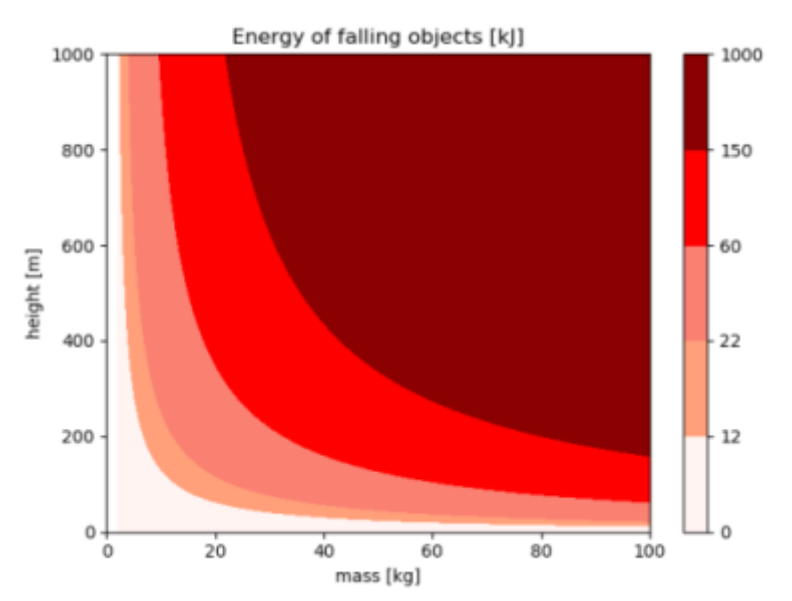
		Mass		
		1 kg	4.25 kg	10 kg
<b>Height</b>	<b>5 00 m</b>	$U = 3 \text{ kJ}, V = 77 \text{ m/s}$ 0 category change 	$U = 15 \text{ kJ}, V = 85 \text{ m/s}$ 2 category change 	$U = 38 \text{ kJ}, V = 88 \text{ m/s}$ 2 category change 
	<b>1 000 m</b>	$U = 4 \text{ kJ}, V = 90 \text{ m/s}$ 0 category change 	$U = 23 \text{ kJ}, V = 104 \text{ m/s}$ 2 category change 	$U = 62 \text{ kJ}, V = 112 \text{ m/s}$ 3 category change 

According to these findings, the energies that lead to the corresponding changes in categories were selected as demonstrated in Table 4.3.

Figure 4.15 shows the plot of the final energy of different masses (x-axis) falling from different heights (y-axis) and the category change bands. In this case, the initial cause of structural integrity degradation originates from the impact of falling objects. When different mechanisms are at play, the resulting deterioration may present distinct characteristics.

**Table 4.3: Energy required to affect category change**

	Energy [kJ]
1 category change	12
2 category change	22
3 category change	60
4 category change	150



**Figure 4.15: The plot of the final energy for different masses falling from different heights**

#### 4.5.2 Probability of category change due to impact

Monte Carlo simulation is a computational technique used to estimate outcomes and analyse complex systems by simulating random variables and their interactions multiple times. It is named after the famous casino in Monaco due to the element of chance involved in the simulations. Monte Carlo simulations provide insights into how a system might behave under different conditions and help decision-makers make more informed choices by considering a wide range of possible outcomes.

The utilisation of a Monte Carlo simulation established the likelihood of a specific category alteration (*cat*) resulting from the mass of a falling object. In this context, it was assumed that the object descends from the summit to the base of the shaft. Random generation of 100 000 masses was carried out according to the probability distribution. In each simulation iteration, a random selection process was

used to determine whether an object was characterised as steel or rock. The results showed that 18% of the falling objects surveyed were identified as rocks.

Following this, the object's energy was computed using the function  $U_{h,m,g}$  capturing its specific height and mass values. The associated category change that such a mass would trigger, if any, was then recorded.

The probability linked to a certain category change due to mass ( $P_{(cat, mass)}$ ) was subsequently deduced by dividing the count of occurrences corresponding to that category by 100 000—the total number of simulations performed. In this case, the initial cause of structural integrity degradation originates from the impact of falling objects and category changes owing to more impact from falling objects. When different mechanisms are at play, the resulting deterioration may present distinct characteristics. The resultant probabilities are presented in Table 4.4 below for objects descending from a height of 900 m:

**Table 4.4: Probability of category change due to mass**

		Probability
1 category change	$P_{1,mass}$	23.5%
2 category change	$P_{2,mass}$	20.4%
3 category change	$P_{3,mass}$	1.1%
4 category change	$P_{4,mass}$	0.3%

The combined probability of a specified category change ( $cat$ ) due to impact was calculated by:

$$P_{cat,impact} = P_{cat,mass} \times P_{area} \times P_{angle} \times P_{height} \quad (4.20)$$

Where:

$P_{area}$  is the probability that the member was in the cross-sectional area where the object fell

$$P_{area} = \left( \frac{P_{member\ area/2}}{P_{shaft\ area}} \right) \quad (4.21)$$

$P_{angle}$  is the probability adjustment for the angle of attack (0.1).

$P_{height}$  is the probability adjustment for the height above the member ( $k$ ) from which the object is falling.

This was also determined using a Monte Carlo simulation for each member:

1. A loop of  $i$  iterations was created.
2. In each iteration the following was done:
  - a. The percentage of height exposure was determined (100% for the bottom-most member and 0% for the top-most) and multiplied by the total yearly number of objects from the questionnaire and saved as  $N_{yearly,k}$ .
  - b. For each  $N_{yearly,k}$  a random percentage was generated between 0 and the percentage of height exposure. This was multiplied by  $P_{cat,mass} \times P_{area} \times P_{angle}$ . If the result was smaller than a randomly generated number, it was counted in a vector with a length of 4 (for each category ( $cat$ )).
3. The final vector was divided by  $i$  to give the probability of impact failure.

To compensate for a shaft that is not operational, this probability can be multiplied by 1/10.

#### 4.5.3 Probability of failure due to impact

A new or undamaged member can solely experience failure (reaching category CC5) as a result of a significant event inducing a four-category alteration. Conversely, a more aged or already compromised member (e.g., a CC4 member) can fail owing to either a substantial event causing a four-category shift or a less impactful yet more probable event causing a one-category change as shown in Figure 4.16.



Figure 4.16 Failure tree

In conclusion, the yearly probability ( $P_{cond_i,impact\ failure}$ ) of a member failing from its initial condition ( $cond_i$ ) due to impact was determined with the product of the relevant probabilities of category change.  $t$  is the time in years. For example:

$$P_{4,impact\ failure}(t) = (P_{1,impact} \times P_{2,impact} \times P_{3,impact} \times P_{4,impact}) \times t \quad (4.22)$$

The outcomes for a rectangular section (340 Depth  $\times$  100 Width  $\times$  8 Wall thickness ) in bunton located at the base of a 900-metre shaft are provided in Table 4.5 which presents the annual probabilities of impact failure for this bunton configuration within the specified shaft depth.

**Table 4.5: Yearly probabilities of impact failure for a bunton at the bottom of a 900 m shaft**

	To	
	Category	5
From	1	$P_{1,impact\ failure}(1) = 0\%$
	2	$P_{2,impact\ failure}(1) = 0.5\%$
	3	$P_{3,impact\ failure}(1) = 7\%$
	4	$P_{4,impact\ failure}(1) = 16.8\%$

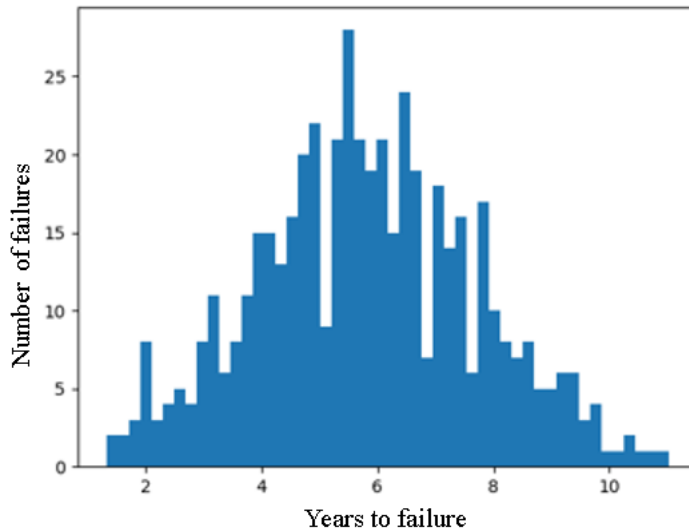
#### 4.5.4 Combination of failure mechanisms

A Monte Carlo simulation method was employed to anticipate both the number of replacements needed and the amalgamation of corrosion and failure mechanisms resulting from impacts.

For predicting replacements, random times to failure ( $t_f$ ) were generated for individual members using mean ( $\mu$ ) and standard deviation ( $\sigma$ ) parameters. These values were extended by three separate random times to failure (based on parameters  $\mu_0$  and  $\sigma_0$ ), indicating anticipated times to failure upon replacement for each specific member. All these  $t_f$  values were organised in ascending order and resampled in accordance with corresponding years, iterating this process 1 500 times. Ultimately, mean and standard deviation values were derived from the simulation outcomes to estimate the times to failure for each year.

A simulation process was established to simulate both corrosion progression and failure due to impacts. This process involved generating random corrosion curves determining transition times between initial and subsequent condition categories. Meanwhile, random numbers ( $x_{impact}$ ) determined whether an impact failure occurred. Throughout the simulation, the possibility of failure due to impact was assessed at distinct intervals. Based on the simulation outcomes, histograms reflecting failure times were constructed for each member, facilitating predictions of expected failures annually. In addition, a failure distribution for new condition 1 was calculated using different parameters ( $\mu_0$  and  $\sigma_0$ ) to consider failure from this starting condition.

Figure 4.17 below shows an example of final failure distribution.

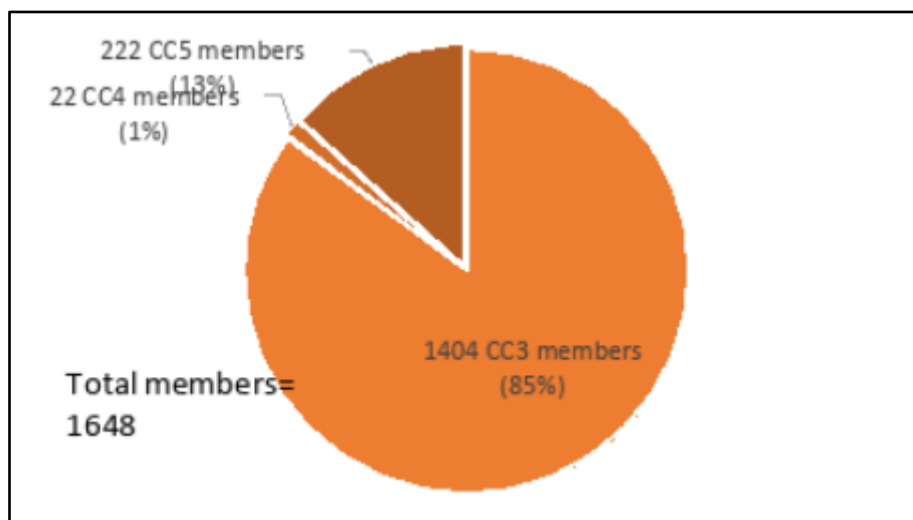


**Figure 4.17: Final failure distribution**

#### 4.5.5 Mine shaft structural members' condition

A yearly inspection by a third-party structural engineer was carried out to assess and provide an overview of the condition of all the horizontal members considered within this model.

The results are shown in Figure 4.18. A total of 222 members, accounting for 13% of the total, were identified to be in CC5 (failed) condition. Consequently, these members will need to be replaced within the upcoming 12 months (Van der Wat, 2022)



**Figure 4.18: Members' condition (September 2022)**

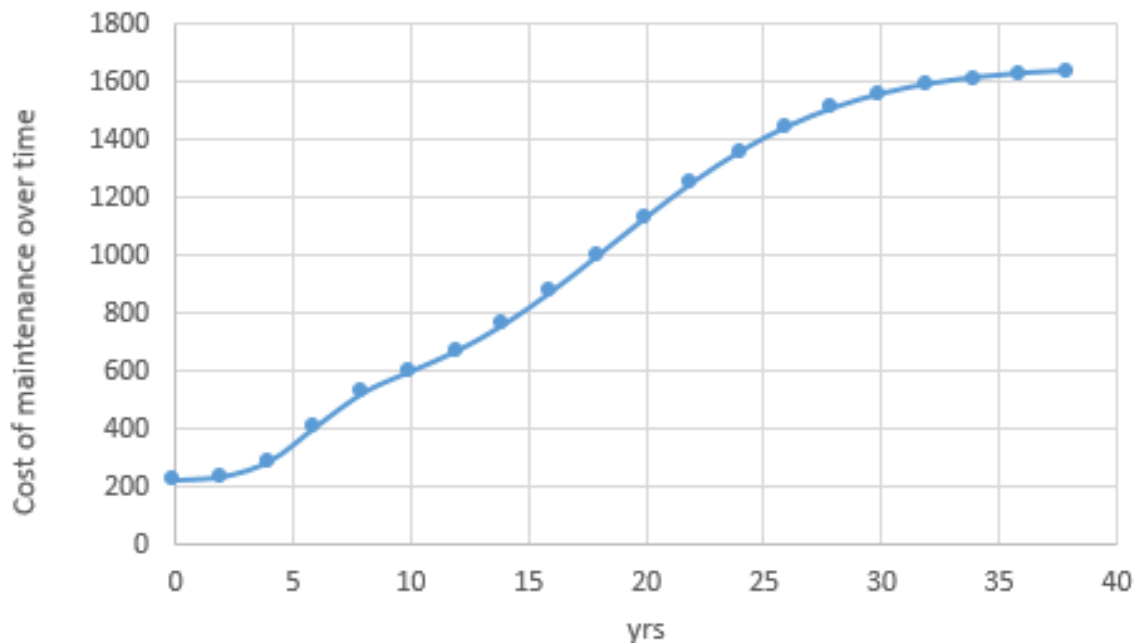
The outcomes of the third-party inspection were utilised as the initial conditions for the members, combined with the values presented in Table 4.6, which were employed as inputs for the model. The ensuing section delineates the outcomes yielded by the model.

**Table 4.6: Model inputs**

Description	Value	Unit
Average annual relative humidity	100	%
For >10C	-2.16	–
Average annual deposition rate of Cl-	1	$\frac{\text{mg}}{\text{m}^2 \cdot d}$
Average annual temperature	50	°C
Shape factor	0.8	–
Cross-sectional area of shaft	113.10	m <sup>2</sup>
Total number of buntun levels	150	
Distance between buntuns	6	m
Height of shaft	900	m
Yield strength of steel	2.5E + 08	Pa
Youngs modulus of steel	2E + 11	Pa
Ultimate tensile strength	2.00E + 09	Pa
Fracture strain	0.01	–
Gravity constant	9.81	m/s <sup>2</sup>
Coefficient of drag	0.82	–
Density of air	1.75	kg/m <sup>3</sup>
Density of steel	7700	kg/m <sup>3</sup>
Density of rock	2400	kg/m <sup>3</sup>
Length-to-diameter ratio (assuming cylinder)	2	
Is the shaft operational? [yes/no]	no	–

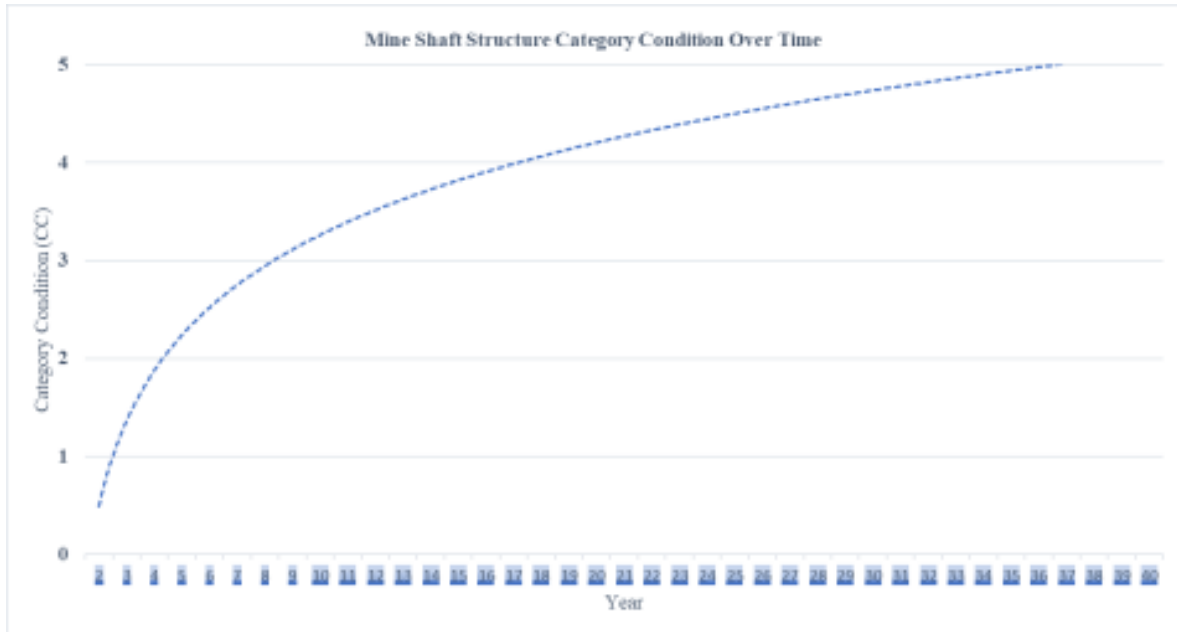
#### 4.5.6 LCC based on the FAT results

In this content, maintenance cost refers to the total accumulated expenses incurred in the repair or replace a member of a structural system or subsystem, excluding costs related to downtime, production loss, or injuries. While downtime and production loss expenses differ greatly across operations, estimating maintenance costs is typically more consistent. For instance, it is generally feasible to approximate the time needed to replace a member like a bunton and to determine its price. Future maintenance cost estimation requires choosing one or more maintenance strategies; it is essential to estimate the total maintenance cost incurred over its life cycle. As multiple maintenance activities are performed over the vertical mine shaft lifetime, the total maintenance cost can be estimated as the sum of corrective maintenance, time-based planned maintenance and condition-based maintenance costs as shown in Figure 4.19.



**Figure 4.19: Time-based planned maintenance and condition-based maintenance costs**

Figure 4.20 presents a chart illustrating the projected number of structural members expected to fail if no replacements are conducted. Although all members will eventually reach Condition Category 5 (CC5) over time, the mine shaft would be considered unsafe well before then because of the excessive number of members falling into the CC5 and PX (critical) states, as detailed in Table 3.2. This indicates that the condition of the structural members will progressively deteriorate, worsening over time and necessitating pre-emptive actions to maintain safety.



**Figure 4.20: Predicted number of failed members (with no replacements)**

#### 4.5.7 iSIMM System: Evaluating structural integrity and safety

The iSIMM (Integrated Structural Inspection and Maintenance Management) system actively manages the structural integrity, physical condition, durability, and safety of structures, employing a dual-rating system that evaluates both durability and safety risk, and prioritizes maintenance actions accordingly. The **Condition Category (CC)** rating (Table 3.1), ranging from CC1 to CC5, measures the remaining strength of the structure, serving as an indicator of its durability. Lower ratings, such as CC1 or CC2, suggest that the structure’s strength is intact and safety is uncompromised. However, as conditions progress to CC3, CC4 or CC5, the structural integrity is deterioration, and further action is required to maintain safety and functionality.

The **Safety Priority (P)** rating (Table 3.2) assesses the level of risk the structure’s condition poses to people and the environment, determining the urgency of required repairs. When the safety level is acceptable and the probability of failure is low, ratings like P1 (with a one-year repair timeframe) or P3 (allowing up to three years) are applied. These ratings indicate that, while repairs are necessary, there is no immediate threat to safety, and the condition is managed within standard maintenance schedules. Conversely, in situations where the risk to safety is unacceptable where the probability of failure is high or almost certain, the structure is rated with **Priority Immediate (Pi)** or **Priority Exclusion (Px)** to ensure safety concerns are addressed promptly. **Pi** indicates an immediate need for intervention, as any delay could lead to structural failure, risking harm to individuals or damage to property. **Px** signifies restricted access for example on a certain station platform until repairs are made; if access cannot be restricted, the rating defaults to Pi to ensure immediate action.

The approach to addressing compromised structures is flexible rather than fixed; the decision to repair or replace depends on the time and cost involved in each option. iSIMM enables engineers to make data-driven choices, balancing safety and operational needs with resource allocation, ensuring that both short-term and long-term structural performance objectives are met.

#### **4.6 CONCLUSION**

This chapter details the development of a prognostic and risk/economics-based maintenance decision-making model, emphasising the methodology of iSIMM and exploring various facets such as corrosion rates, corrosion probability and impact damage. The corrosion rate highlights the importance of the failure rate in determining structural lifespans and examines predictive models for remaining useful life (RUL).

FEA is a computational technique used to simulate how a product or structure will respond to real-world forces, such as heat, vibration, fluid flow, and other physical effects. In this case the FEA is used to determine the impact of a falling object on the structural member. By breaking down a complex structure into smaller, manageable elements, FEA allows engineers to predict the behaviour of the entire structure under various conditions. Moreover, it highlights the importance of impact damage analysis using FEA and the probabilistic evaluation of falling objects within mine shafts. This extensive examination serves as a fundamental building block for comprehensively understanding and managing mine shaft structures, promoting safety, sustainability, and economic efficiency.

The next chapter embarks on the application and validation through a case study conducted at Harmony Gold Mine. It introduces Harmony Gold Mine as the chosen site for the case study, offering insights into the mine setting and its relevance. The chapter delves into assessing Harmony's existing reporting system, outlining its framework, and identifying limitations. In addition, it elucidates the integration of the developed iSIMM within Harmony, outlining the calibration process and necessary adjustments for seamless alignment within Harmony's operational context.

# **CHAPTER 5: APPLICATION AND VALIDATION OF iSIMMS AND PROGNOSTIC/DECISION-MAKING MODEL TO A REAL-WORLD CASE STUDY**

## **5.1 INTRODUCTION**

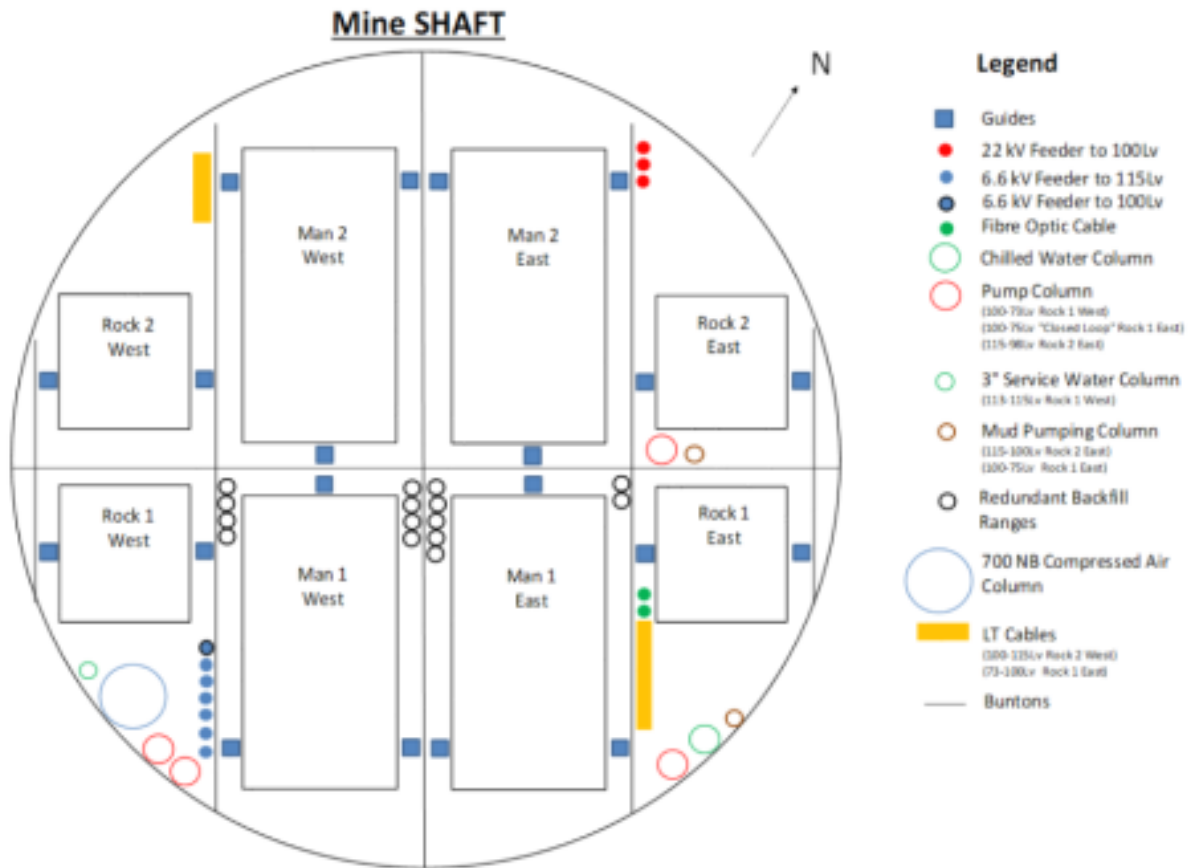
This chapter focuses on the application and validation through a case study conducted at Harmony Gold Mine (Harmony). This chapter introduces Harmony as the chosen site for the case study application, offering insights into the mine setting and its relevance. It delves into an assessment of Harmony's existing reporting system, illustrating the current framework and its constraints. The chapter then outlines the implementation of the newly proposed ISIMM solution at Harmony, elucidating how the developed iSIMM is implemented in the context of Harmony. It also underscores the calibration process, emphasising the necessary adjustments and fine-tuning essential for successfully integrating and aligning iSIMM within Harmony's operational framework.

## **5.2 SHAFT DESCRIPTION**

To assess the effectiveness of the suggested methodology, a field study was executed at Harmony located in the Gauteng province of South Africa, serving as an initial trial. This shaft has eight compartments of which four are used for mine output and four for the transportation of employees, with three-deck cages each. See Figure 5.1 below.

Mine shafts are usually divided into compartments when they are used for hoisting. Steel is used to make compartments sets either horizontal or vertical. Horizontal members are called buntons and vertical members are called guides. Top hat sections and hollow structural sections are the two main choices for steel shaft guides. Top hat segments offer more benefits than hollow structural sections. They comprise simpler installation and are also more resistant to corrosion.

Ropes installation is easy as is its maintenance and replacement. The workers are hoisted in cages that reside in the largest compartments. These cages are effectively like elevators in a multiple floor level building. The cages may be single or multiple deck, up to four decks. Safety systems are installed to use in case of unforeseen failure. Ore is hoisted to the surface in the second largest compartment. The third compartment is used for an emergency exit. The fourth compartment is used for moving material, fuel, cable, pipes, transfer of water, compressed air, etc.



**Figure 5.1: Shaft layout diagram**

The surface over the shaft is occupied by a structure called the head frame. The top of the head frame is equipped with a hoist motor or a sheave wheel. Steel bins are used to store extracted ore and the extracted ore is hoisted out from underground through the mine shaft to surface. A ventilation infrastructure is also connected to the head frame. The headgear is the superstructure above the shaft bank used for normal winding including overrun space.

### 5.3 APPLICATION OF METHODOLOGY

Table 5.1, delineated in the Excel scroll, illustrates a discernible trend wherein substantial concerns cluster predominantly in the upper sections of the mine shaft, with fewer significant issues identified in the lower segments. Notably, Condition Category 3 denotes a relatively favourable state, necessitating minimal actions to fortify or uphold the structural integrity.

Acknowledging the potential variability in mine shaft designs, the selected approach for the pilot project was intentionally crafted to exhibit adaptability. Such flexibility markedly diminishes both the time investment and computational expenses entailed in decision-making processes. The results derived from this methodological approach validate the reliability of scrutinised data, presenting it in graphical

formats conducive for confident utilisation by executives and managers from diverse organisational backgrounds.

The principal aim revolves around streamlining the integration of manual reports into the CMMS while concurrently developing an intuitive dashboard to oversee the resolution of identified issues. This concerted effort seeks to amass data conducive for comprehensive analysis concerning the progressive evolution of mine shaft structural conditions. The meticulous selection of an appropriate method stands pivotal in ensuring precise decision-making rooted in the available data corpus.

The present study endeavours to furnish an encompassing framework for the decision-making continuum, leveraging data culled from comprehensive structural inspection reports. The iSIMM platform embodies a multifaceted array of graphical representations, integral for informed decision-making processes.

These graphical depictions offer nuanced insights into problematic areas within the shaft, complemented by the Excel scroll shown in Table 5.1 portraying the entire mine shaft delineated with colour-coded gradations signifying the condition prevailing at each level.

**Table 5.1: Manual report for structural inspection**

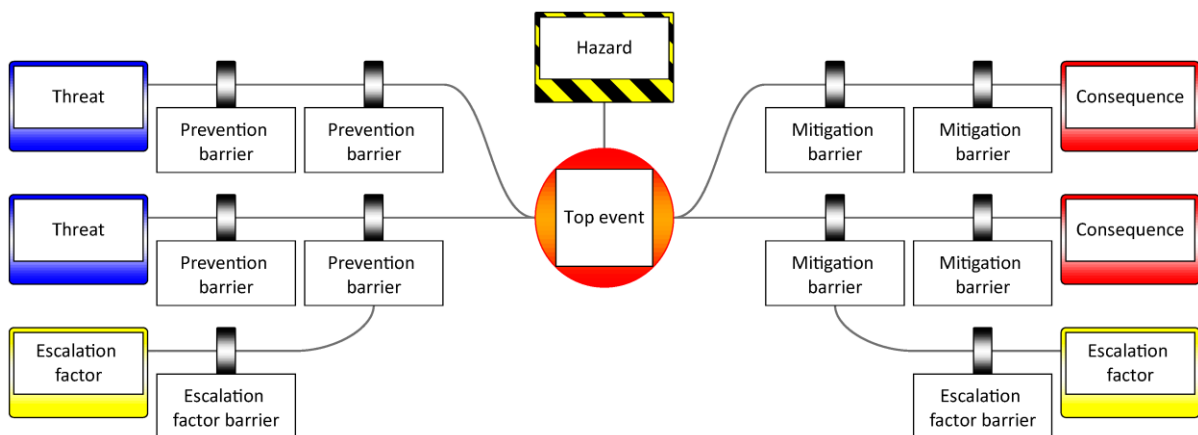
Reference	Inspection Date	Location Number	Category	Priority	Operator Meterage Reading
20220325-C033	2022-03-25	KS-141000-BUN-E	3	P3	912
20220325-C034	2022-03-25	KS-141000-BUN-E	4	P1	918
20220325-C035	2022-03-25	KS-141000-BUN-E	3	P3	1188
20220325-C036	2022-03-25	KS-141000-BUN-E	4	P1	1194
20220325-C037	2022-03-25	KS-141000-BUN-E	3	P3	1278
20220325-C038	2022-03-25	KS-141000-BUN-E	4	P1	1284
20220325-C019	2022-03-25	KS-141000-CLM-A	3	P3	1506
20220325-C020	2022-03-25	KS-141000-CLM-A	4	Pi	1512
20220325-C023	2022-03-25	KS-141000-CLM-C	3	P3	1608
20220325-C024	2022-03-25	KS-141000-CLM-C	5	P1	1616
20220325-C043	2022-03-25	KS-141000-BUN-F	3	P3	1680
20220325-C044	2022-03-25	KS-141000-BUN-F	4	P1	1686
20220325-C039	2022-03-25	KS-141000-BUN-E	3	P3	1776
20220325-C040	2022-03-25	KS-141000-BUN-E	4	Pi	1962
20220325-C003	2022-03-25	KS-141000-GUI-D1	3	P3	2334
20220325-C006	2022-03-25	KS-141000-GUI-D3	3	P3	2334
20220325-C041	2022-03-25	KS-141000-BUN-E	3	P3	2334
20220325-C001	2022-03-25	KS-141000-GUI-B1	3	P3	2358
20220325-C002	2022-03-25	KS-141000-GUI-C1	3	PX	2358
20220325-C004	2022-03-25	KS-141000-GUI-D1	3	PX	2358
20220325-C005	2022-03-25	KS-141000-GUI-D2	3	P3	2358
20220325-C007	2022-03-25	KS-141000-GUI-D3	3	PX	2358
20220325-C008	2022-03-25	KS-141000-GUI-D4	3	P3	2358
20220325-C009	2022-03-25	KS-141000-GUI-D5	3	P3	2358
20220325-C010	2022-03-25	KS-141000-GUI-D6	3	P3	2358
20220325-C011	2022-03-25	KS-141000-GUI-F1	3	P3	2358
20220325-C012	2022-03-25	KS-141000-GUI-F2	3	P3	2358
20220325-C013	2022-03-25	KS-141000-GUI-F3	3	P3	2358
20220325-C014	2022-03-25	KS-141000-GUI-F4	3	P3	2358
20220325-C015	2022-03-25	KS-141000-GUI-F5	3	P3	2358
20220325-C016	2022-03-25	KS-141000-GUI-G1	3	P3	2358
20220325-C017	2022-03-25	KS-141000-FDR-01	3	P3	2358
20220325-C018	2022-03-25	KS-141000-FDR-02	3	P3	2358
20220325-C021	2022-03-25	KS-141000-CLM-A	3	P3	2358
20220325-C022	2022-03-25	KS-141000-CLM-B	3	P3	2358
20220325-C025	2022-03-25	KS-141000-CLM-C	3	P3	2358
20220325-C026	2022-03-25	KS-141000-CLM-D	3	P3	2358
20220325-C027	2022-03-25	KS-141000-CLM-E	3	P3	2358
20220325-C028	2022-03-25	KS-141000-ECA-C1	3	P3	2358
20220325-C029	2022-03-25	KS-141000-BUN-A	3	P3	2358

## 5.4 PRIORITY UNWANTED EVENTS IN SHAFT SYSTEMS IDENTIFIED THROUGH BOW TIE ANALYSIS

Within the realm of safety, health, and environmental considerations, particularly concerning the bowtie methodology, controls encompass actions, engineered items, or systems with the purpose of preventing or reducing undesired incidents. The application of bow tie analysis within Harmony affirms that the infrastructure of the mine and the intricate network of mine shafts, including the conveyance systems, represent pivotal assets. Meticulous management is necessary to forestall substantial adverse events. This is achieved by pinpointing paramount controls that warrant consistent monitoring at specified intervals.

Figure 5.2 portrays a fundamental guiding principle of bowtie analysis, which serves as a technique for evaluating and overseeing the efficacy of controls linked to an undesirable incident. It is worth noting that within the terminology of bowtie analysis, the subsequent synonyms are employed:

- The term ‘top event’ is interchangeable with ‘initiating event’
- ‘Preventive controls’ can also be denoted as ‘control measures’ or ‘prevention measures’
- The concept of ‘threats’ can likewise be addressed as ‘causes or mechanisms of release’



**Figure 5.2: Bowtie analysis guiding principles (Aust and Pons, 2020).**

Upon identifying potential risks, it becomes imperative to establish mechanisms for monitoring the efficacy of the approach aimed at either eradicating or alleviating these risks. The integration of technology, innovations, and advanced management concepts concerning crucial controls becomes indispensable, particularly in instances where the level of risk is deemed unacceptable. It is crucial to incorporate novel strategies in response to emerging risks, indicating that this is an ongoing, iterative process rather than a one-time endeavour. Consistent risk evaluation and continuous surveillance stand

as pivotal factors in effectively steering business risk management (Meland, Bernsmed, Frøystad, Li and Sindre, 2019).

Unplanned events in vertical shaft operations can significantly impact safety and operational continuity, posing risks to both personnel and equipment. Priority unwanted events in shaft management include:

(i) Uncontrolled movement of the winding plant during maintenance: This can lead to severe equipment damage and endanger workers within or around the shaft.

(ii) Ignition of fires within or near the shaft: Fires can compromise the shaft's structural integrity and produce hazardous smoke, threatening the safety of personnel and equipment.

(iii) Structural failure: Failures in the shaft lining, support structures, or headgear can destabilise the entire system, risking collapse and significant operational delays.

(iv) Conveyance exceeding upper or lower operational limits: Over-travel or under-travel of the conveyance can cause mechanical damage, potential entrapment, or safety hazards.

(v) Large objects falling from headgear, conveyors, or into the shaft: This can damage the conveyance or guides and pose serious risks to workers and equipment below.

(vi) Contact with or entrapment by rotating equipment: Personnel working near the shaft face the risk of being caught in or struck by moving machinery.

(vii) Exposure to live electrical conductors: Unplanned contact can result in electric shock or electrocution, posing severe safety risks.

(viii) Exposure to heat and noxious gases: Workers in sumps, trenches, ducts, and confined spaces may encounter extreme heat or toxic gases, potentially causing illness or incapacitation.

(ix) Unexpected water or ore inflow: Water or a mixture of water and ore from dams, sumps, silos, or skips can flow into the shaft, causing flooding, structural strain, or damage to electrical systems.

(x) Failure of over-wind or under-wind protection systems: Malfunctions in these safety systems can result in conveyance over-travel or under-travel, leading to collisions or derailments.

(xi) Excessive closure of the shaft walls due to mining activities: This can exert additional pressure on the shaft structure, increasing the risk of deformation and failure.

(xii) Derailment of the conveyance due to guide misalignment: Misaligned guides can lead to conveyance derailment, causing equipment damage, operational disruptions, and safety hazards.

These events highlight the critical need for thorough maintenance, continuous structural monitoring, and stringent safety protocols to prevent and mitigate risks in vertical shaft operations.

Figure 5.3 below shows the physical evidence of the damages caused by falling objects on the mine shaft steel work.



**Figure 5.3: Bunton impact damage on buntons from falling objects**

## 5.5 STAKEHOLDER MANAGEMENT

Stakeholders play a pivotal role in the decision-making process. Engineering managers consult at each project stage, ensuring their input guides the subsequent steps. The project's success and iSIMM's effectiveness hinge on the endorsement of engineering leadership. Managing the influx of information into the system is crucial to prevent irrelevant data that could lead to inaccuracies about the structure's condition and required maintenance activities.

The level of commitment from stakeholders can significantly impact on the system's development outcome. Particularly in system development, stakeholder buy-in and their active participation in providing input are crucial to ensure the final system's adoption. When highly involved and highly important stakeholders are fully engaged, they become advocates who help propel change. In cases where important stakeholders exhibit less commitment, strategies should focus on increasing their involvement. Table 5.2 illustrates the stakeholder impact analysis conducted for outreach.

**Table 5.2: Stakeholder impact analysis**

Stakeholder group	Description (Impact of the change)	Number impacted	Severity of change (based on numbers)
Senior Executives	Awareness and buy-in	7	High
Middle Management	Awareness and buy-in	12	Medium
Engineering Foreman	Manage the artisans	229	High
Data Capturers	Reduced work load	27	Medium
Planners	Super users for business continuity	27	High
Artisans	Users new reporting template	1 753	Medium

### 5.5.1 Competence of people

Identifying and rectifying skills gaps remains a pivotal ongoing process aligned with the solution objectives. This entails meticulously examining existing skill sets and proactively addressing any deficiencies to ensure that the team stays well-equipped to meet the desired goals and outcomes. The implementing of iSIMM is done together with the training for various roles within the team, including senior engineers, engineers, planners, and the shaft examination team comprising artisans, timber men/women, and engineering supervisors.

The iSIMM training programme is thoughtfully designed to cater to the diverse needs of different stakeholder groups. For senior engineers and managers, the focus is on providing an overview of the functionality of the iSIMM tool. This ensures they grasp the broader aspects and strategic implications of its use within the operations. Conversely, the training for engineers delves into the details necessary for analysing data obtained from both third-party structural engineer inspections and internal team inspections. This detailed training equips engineers with the skills needed for comprehensive analysis, facilitating informed decision-making for future planning, maintenance work, and budgeting purposes.

The iSIMM training extends to the examination team, covering the identification of defects, the reporting system, and the accurate recording of their reports. This segment of the training is particularly crucial in maintaining a robust system for defect identification, reporting, and documentation, contributing significantly to the overall effectiveness of the operations.

Structural alterations and adjustments may become imperative to rectify the temporary integrity of a structure or to enhance its existing design. The implementation of a change management protocol for structures assumes paramount significance in this context. Consequently, the training materials and operational procedures have been meticulously crafted to encompass explicit guidelines delineating the initiation of change, the requisite approval processes, and the imperative consultation with a structural engineer, where deemed necessary. This comprehensive approach ensures not only the safety and integrity of the structure but also underscores the conscientious and rigorous procedures embedded within the realm of structural modification

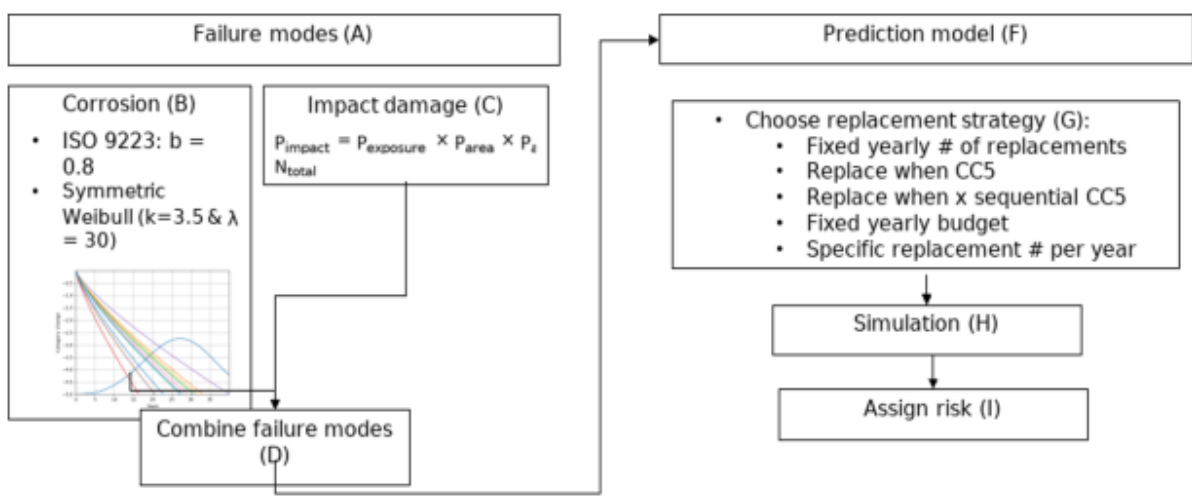
## **5.6 LoM PREDICTION MODELLING**

This prognostic model functions as a crucial tool for formulating an annual strategy and financial plan concerning the replacement of horizontal members within a vertical mine shaft. Its core aim is to maintain the risk within an acceptable range during the entire operational lifespan of the mine. Leveraging insights from third-party structural shaft inspections, this model initially establishes the conditions and then forecasts the time until failure, incorporating two principal failure mechanisms: corrosion and damage from falling objects.

The condition of all members is represented on a spectrum ranging from CC0 (100% strength) to CC4 (25% to 50% strength), including supplementary categories like CC3 (50% to 75% strength) and CC5 (0% to 25% strength) within this predictive framework. Risk assessment relies on the evaluation of both consequences and likelihood of failure, assigning a rating of 4 for operational shafts and 5 for non-operational ones in terms of consequences. Likelihood is computed based on the highest category and the maximum number of consecutive occurrences of that category.

Modelling data to predict the lifespan of a mine involves utilising information derived from third-party inspections and category ratings. The primary objective is to forecast the economic and productive duration of the mine while considering variables such as ore reserves, production rates, costs, and maintenance required to ensure safety. This model facilitates the estimation of the efforts needed for varying life expectancies and simplifies scenario analysis. With minimal input, it provides comprehensive responses. An illustrative overview of the model is depicted in Figure 5.4 below.

Figure 5.4 serves as a crucial integrative element that ties back to the discussions and analyses presented in the previous chapters. The graph synthesises the earlier work on corrosion rate analysis and the impact of falling object analysis. By combining these two critical factors, the figure demonstrates how their interaction influences the selection of an appropriate maintenance strategy and the determination of optimal maintenance intervals. This integration is essential for ensuring the safe and continuous operation of the mine while effectively managing the lifespan of its infrastructure.



**Figure 5.4: Modelling overview**

The model exhibits the capability to process diverse inputs, yielding valuable insights into the safety and maintenance requisites of the mine. For instance, when furnished with the anticipated lifespan of the mine shaft, the model calculates the annual count of required replacements for buntons or support brackets. Conversely, by inputting the planned annual replacement count for buntons, the model presents details concerning the associated risk level and the anticipated secure duration of the mine. Upon validation, the model aids in foreseeing the mine's future performance, encompassing maintenance timelines, cost projections, and ascertaining the point at which the mine's profitability might decrease, necessitating closure.

Insights derived from this modelling enable informed decisions by mine engineers and stakeholders regarding production optimisation, cost management, resource exploration, and even closure and reclamation planning. The accuracy of the estimated mine lifespan hinges upon the quality and relevance of the data. Continuous updates and refinements to the model are imperative, adapting to the evolving operational context of the mine and integrating new data as it becomes available.

Strategies pertaining to member replacement significantly influence group management, delineating criteria-driven approaches for the timing and method of member replacements. The examples provided highlight these replacement strategies.

### 5.6.1 Do nothing strategy

The level of risk will persist at its current state, and over time, it will escalate, potentially leading to a scenario where either all members become compromised, or a section of the shaft fails, resulting in the closure of the mine or even severe safety incidents. Figure 5.5 indicates the structural members that are in worse condition and which require urgent replacement to eliminate the risk of structural failure.

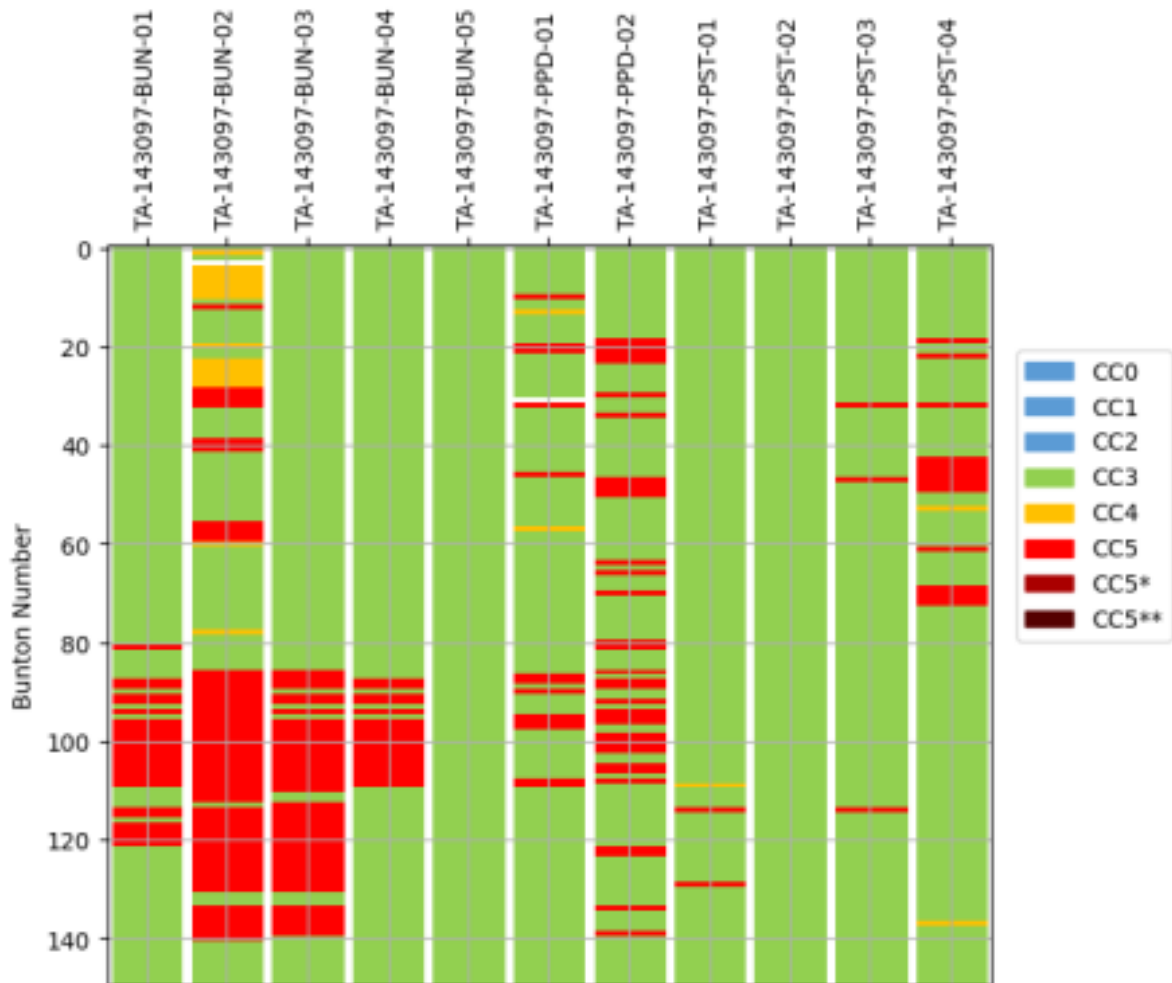


Figure 5.5: Do nothing strategy risk profile

### 5.6.2 Above Category 4 category replacement

Within this strategy, a particular category and a set number of iterations are chosen. Each year, the members with the highest rankings in the chosen category undergo substitution. This approach entails the greatest degree of risk. Specifically, this refers to Categories 4 and above.

The model predicts a notable reduction in risk over the upcoming two years. Nevertheless, members in Category 3 are expected to transition into Category 4, consequently elevating the risk level. By consistently replacing members in Categories 4 and 5, the mine's safety can be enhanced, leading to a shift in risk classification from significant to moderate as shown in Figure 5.6.

Choose a yearly replacement strategy:

All above cat.  
  1 in a row  
  Fixed yearly budget  
  Fixed yearly number  
  Specific yearly numb

Replace members above category

## Results

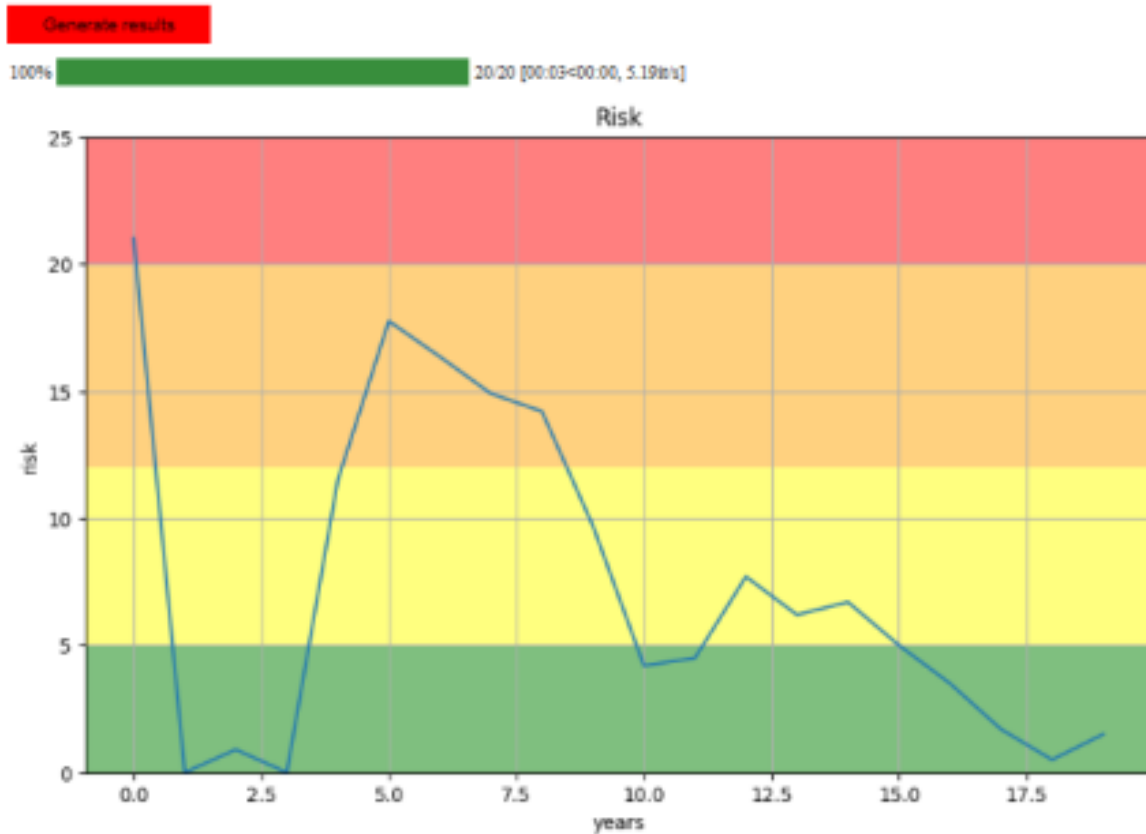


Figure 5.6: Above Category 4 category replacement

### 5.6.3 Fixed yearly budget strategy

This approach entails the selection of an annual budget. Consequently, members are replaced according to prioritised criteria until the assigned budget is fully utilised. The prioritisation is centred on risk factors. As an example, a fixed budget of R2 million per year, designated for the replacement of structures in the poorest condition, i.e., those falling under Category 5, could be considered. Once the budget becomes available, the focus shifts to Category 4 structures. However, given the current state characterised by a significant number of structures in categories 5 and 4, the replacement of the worst structures initiates a cycle where additional structural members deteriorate.

Consequently, this leads to a lag in addressing the replacement of deteriorating structures, ultimately placing the mine shaft in a precarious position as illustrated in Figure 5.7.

Choose a yearly replacement strategy:

All above cat.	1 in a row	<b>Fixed yearly budget</b>	Fixed yearly number	Specific yearly numb
Yearly budget <input type="text" value="2000000"/>				
Replace members above category <input type="text" value="5"/>				

## Results

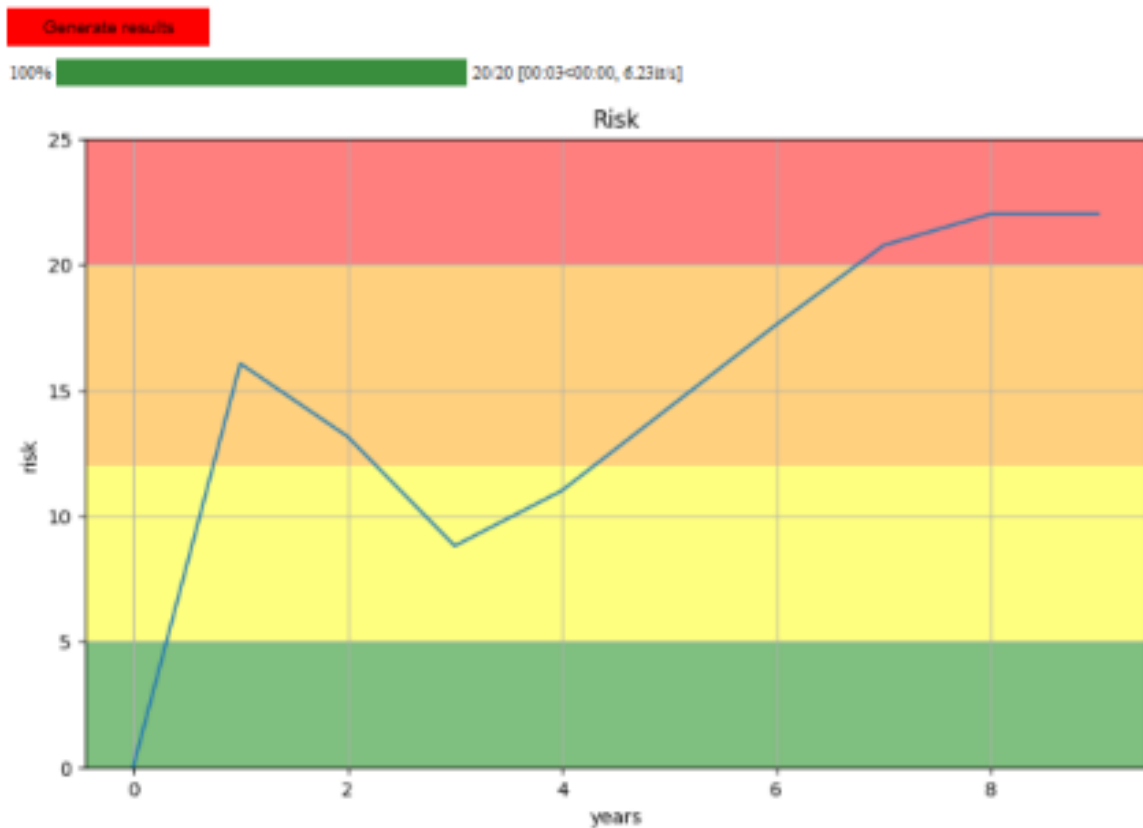


Figure 5.7: Fixed yearly budget strategy

### 5.6.4 Three in a row Category 4 and 5 members replacement strategy

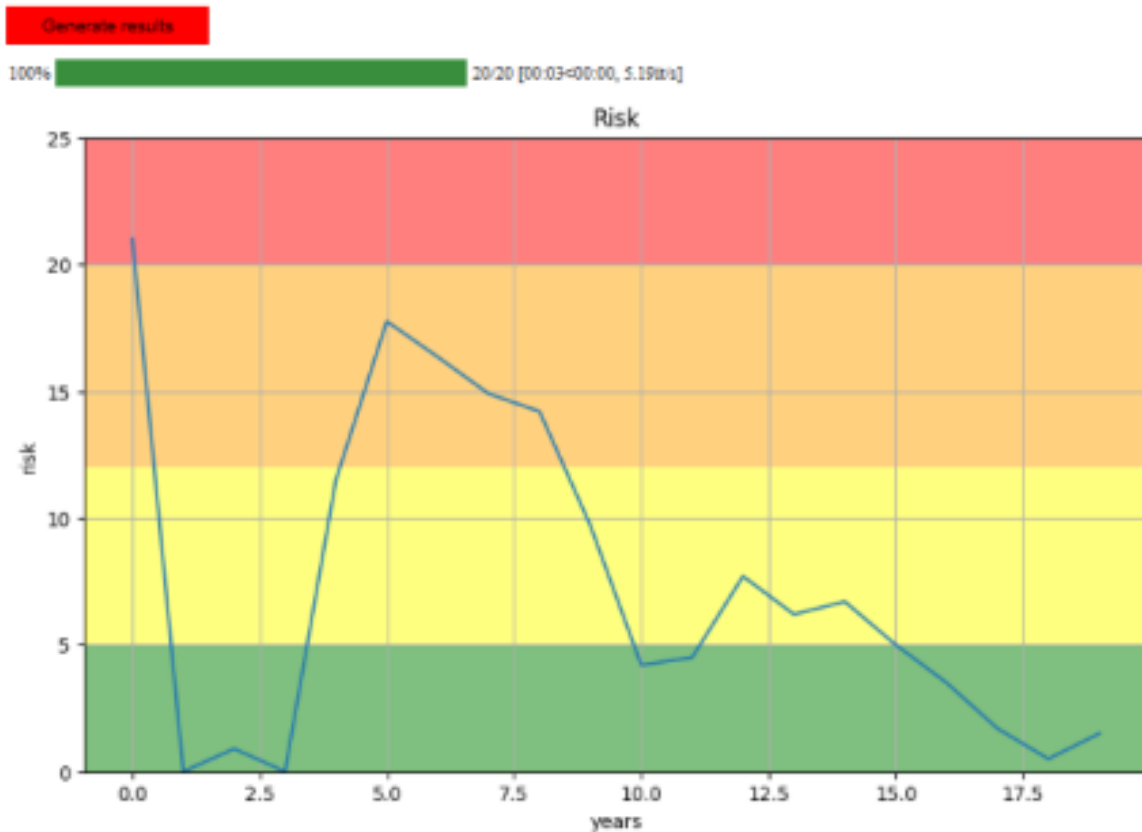
The presence of three members categorised as 4 and 5 entails a higher susceptibility to triggering a complete collapse of the structure, consequently affecting the entire shaft's ability to maintain secure and uninterrupted production. The reason for this is because guide rails can typically have a maximum length of 17 m, so three failed buntons will lead to them being unsupported. Through risk mitigation measures, the danger can be alleviated to an acceptable degree, enabling the continuation of safe operational activities as shown in Figure 5.8.

Choose a yearly replacement strategy:

All above cat.  
  1 in a row  
  Fixed yearly budget  
  Fixed yearly number  
  Specific yearly numb

Replace members above category

## Results



**Figure 5.8: Three in a row Category 4 and 5 members replacement strategy**

### 5.6.5 Fixed yearly number of replacements strategy

Under this strategy, a predetermined number of replacements is set for each year. Members are replaced according to prioritised criteria until the fixed replacement count is met. Under this approach, a specific number of replacements are selected for each year. Members are then substituted according to prioritised criteria until the predetermined replacement count is attained. These strategies offer diverse methods for handling member replacements, permitting organisations to tailor their approach in line with their priorities and available resources.

To minimise operational disruptions, it could be agreed upon to allocate one weekend per month for engineering work. In this scenarios, an assumption is made to replace 4 buntions during each weekend, totalling 48 buntion replacements annually.

According to this strategy, the risk is projected to be effectively managed to an acceptable level for a duration of eight years. Subsequently, beyond this point, the risk is anticipated to become significant, potentially challenging the continuation of safe operations, see Figure 5.9.



**Figure 5.9: Fixed yearly number of replacements**

### 5.6.6 Role of data in enhancing business continuity and safety decision-making

This content emphasises the pivotal role of data in fostering informed decision-making, particularly in ensuring business continuity and safety protocols. It explores various facets of evidence-based decision-making, such as risk assessment, contingency planning, resource allocation, continuous improvement, and regulatory compliance, all driven by reliable data analysis. The utilisation of data allows businesses

to proactively manage risks, respond to unforeseen challenges, and uphold safety measures, ultimately creating a more resilient and secure environment for all stakeholders involved.

The presence of data plays a crucial role in facilitating informed decisions regarding both business continuity and the safety of individuals.

- Evidence-based decision-making: Data provides tangible evidence and insights that guide decision-makers in understanding the current state of affairs. It enables them to assess risks, identify trends, and make decisions grounded in real-world information rather than relying on assumptions or intuition.
- Risk assessment and mitigation: Data allows businesses to conduct thorough risk assessments. By analysing historical data and current trends, they can identify potential hazards, vulnerabilities, and risks to business operations and the safety of people. This information is essential for formulating effective risk mitigation strategies.
- Contingency planning: Data-driven insights aid in the development of comprehensive contingency plans. Businesses can anticipate potential disruptions or emergencies, such as natural disasters or supply chain interruptions, and create plans that address various scenarios, ensuring the continuity of operations and the safety of personnel.
- Resource allocation: Data helps allocate resources efficiently. Businesses can analyse data to determine the optimal allocation of funds, personnel, and equipment to maintain both business continuity and safety measures. This prevents wastage and ensures resources are deployed where they are most needed.
- Continuous improvement: Data allows for continuous improvement in safety protocols and business continuity strategies. Regularly analysing data allows businesses to identify areas for enhancement and implement changes that lead to better outcomes over time.
- Communication and transparency: Data-backed decisions enhance transparency and communication. When stakeholders, including employees, customers, and regulatory authorities, see that decisions are based on credible data, it fosters trust and confidence in the organisation's commitment to safety and continuity.
- Regulatory compliance: Many industries are subject to safety regulations and compliance requirements. Having accurate and up-to-date data ensures that businesses can adhere to these regulations and demonstrate their commitment to safety and continuity during audits or inspections.

- **Adaptability:** Data-driven insights enable businesses to quickly adapt to changing circumstances. Whether it is responding to market shifts or unexpected disruptions, having access to data allows organisations to pivot their strategies and plans more effectively.

In essence, data serves as a foundation for making well-informed decisions that prioritise both the ongoing operations of a business and the safety of its people. By utilising data, organisations can proactively manage risks, respond to challenges, and create a safer and more resilient environment for everyone involved.

## **5.7 DATA CALIBRATION AND APPLICATION TO THE CASE STUDY**

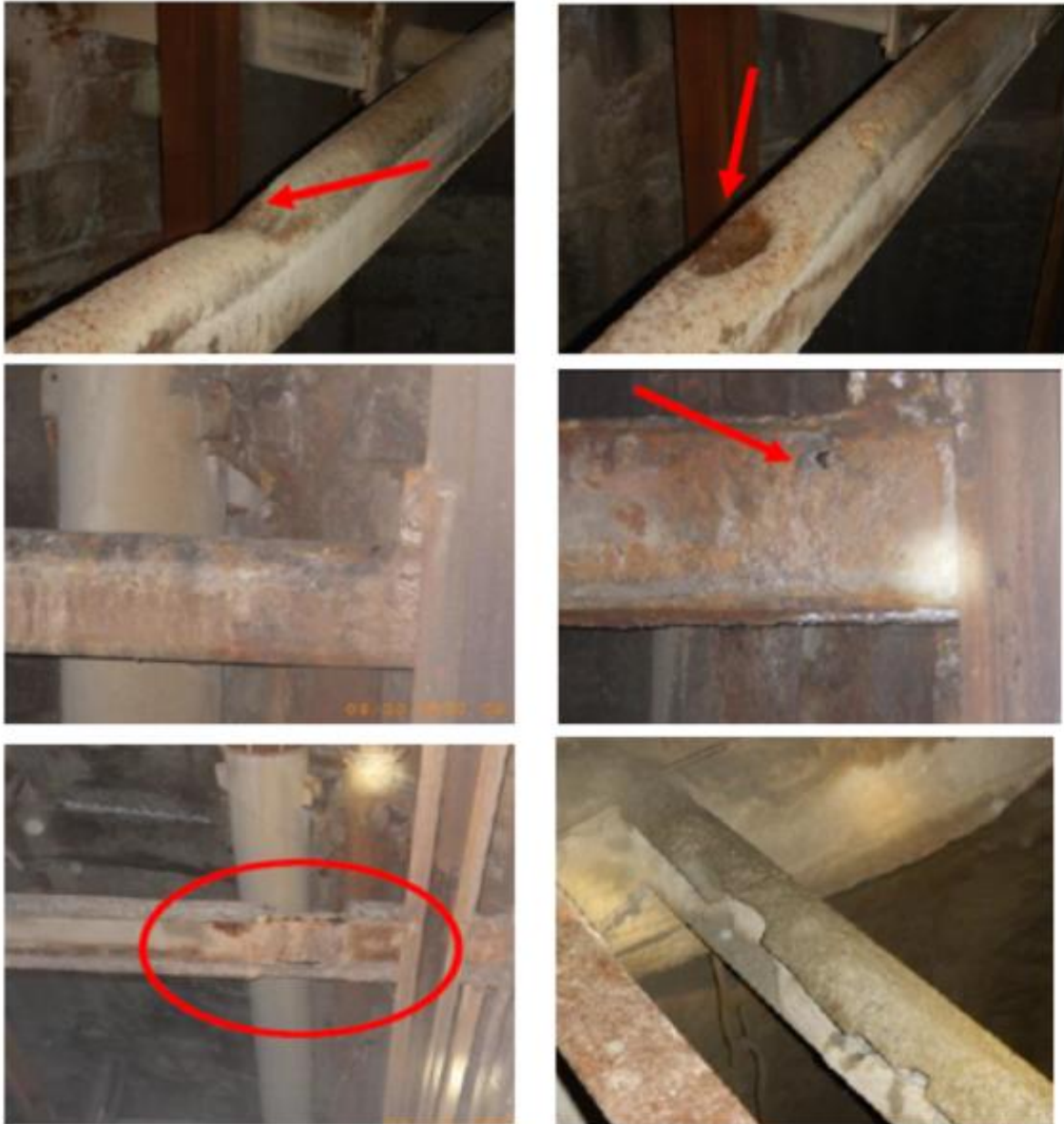
### **5.7.1 Current condition**

The experimental work carried out in simulating falling objects in the mine shaft, showed damages similar to the damages observed during the annual third-party inspection.

There are robust grounds that connect the simulation and physical observation. The current condition is taken as a baseline. Where corrosion is an issue, corrosion protection should be applied and it is required to monitor buntons in weekly shaft exams and repair if material loss starts to occur. To calibrate the simulation results, continuous third-party inspections will be done annually and plotted on the graph to compare with the predicted forecast for the future and track the behaviour. When repair work or corrosion protection work is done, a new condition rating will be defined to calibrate the forecasted graph.

Figure 5.10 below shows that conditions will get better or worse over time depending on the work done on the structures and the environment of the mine shaft.

Mine shaft structure trends of degradation can be predicted using the historical data and calibrated with actual data captured during the annual inspection. The data capturing will be compared with the previous year's data to analyse the condition changes, performance degradation or resistance to failure. The methods of prediction generally include two categories which are data-collection methods and model-driven methods.



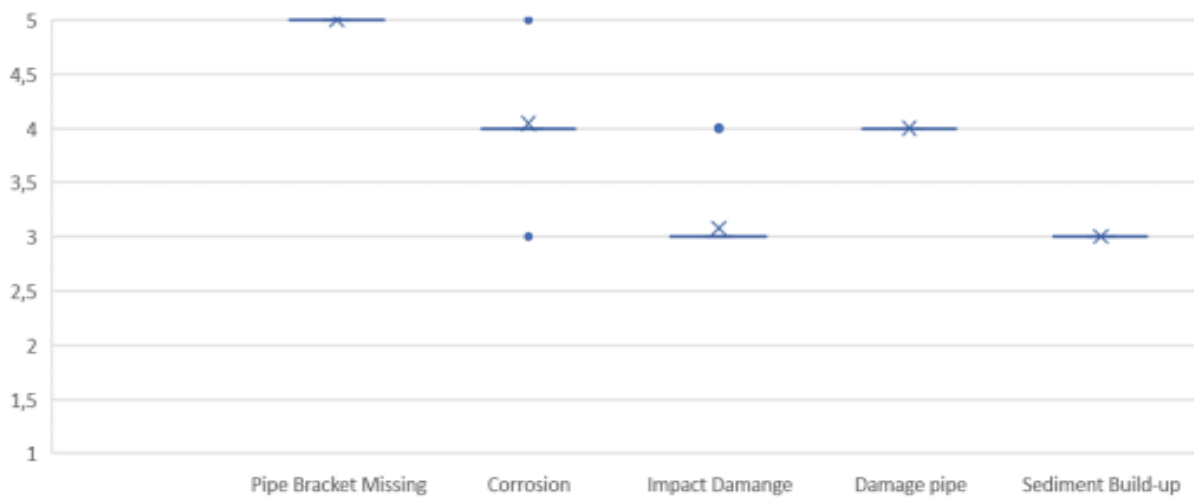
**Figure 5.10: Condition of mine shaft structure: illustration of corrosion and impact damage**

### **5.7.2 Analysing condition categories and their distribution within mine shaft structures**

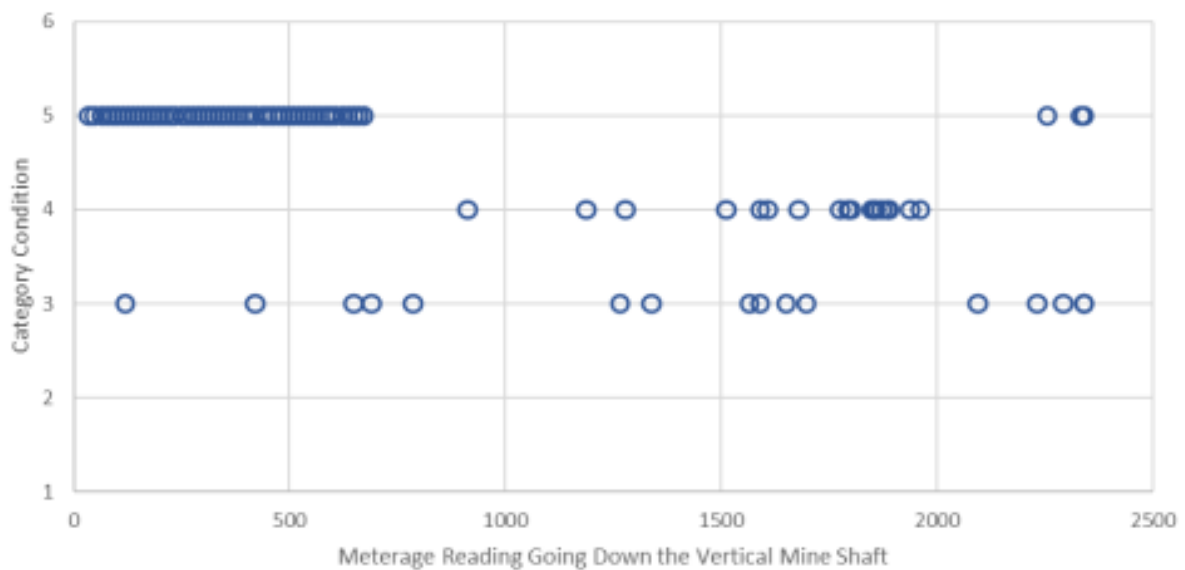
Figures 5.11 and 5.12, displayed below, provide a visual representation of the condition categories observed at various levels within the gold mine shaft. Inspectors maintain ongoing communication with the winder operator to document the downward travel distance of the shaft, ensuring precise location recording. Pictures are taken for each identified issue requiring repair or replacement, aiding repairers in locating the exact spot and facilitating before and after comparisons of repairs and condition categories.

Accurate recording of distance from the top level to each issue location is crucial for consistent comparison and ease of finding for repairers. In this mine, most CC5 conditions are observed at the upper section of the shaft, often caused by impact damage from falling objects. Damage from falling objects generally affects buntons, requiring significant impact over time for a shift from CC1 to CC5. Conversely, pipe brackets experience fewer damages or removals due to falling objects.

When a pipe bracket is lost or removed, its primary function of supporting the pipe is compromised, resulting in zero remaining strength categorised as CC5. Further down the mine shaft, corrosion rates are notably higher due to increased water and chemicals, leading to concentrated instances of CC4, along with several CC3 and CC5 categories.

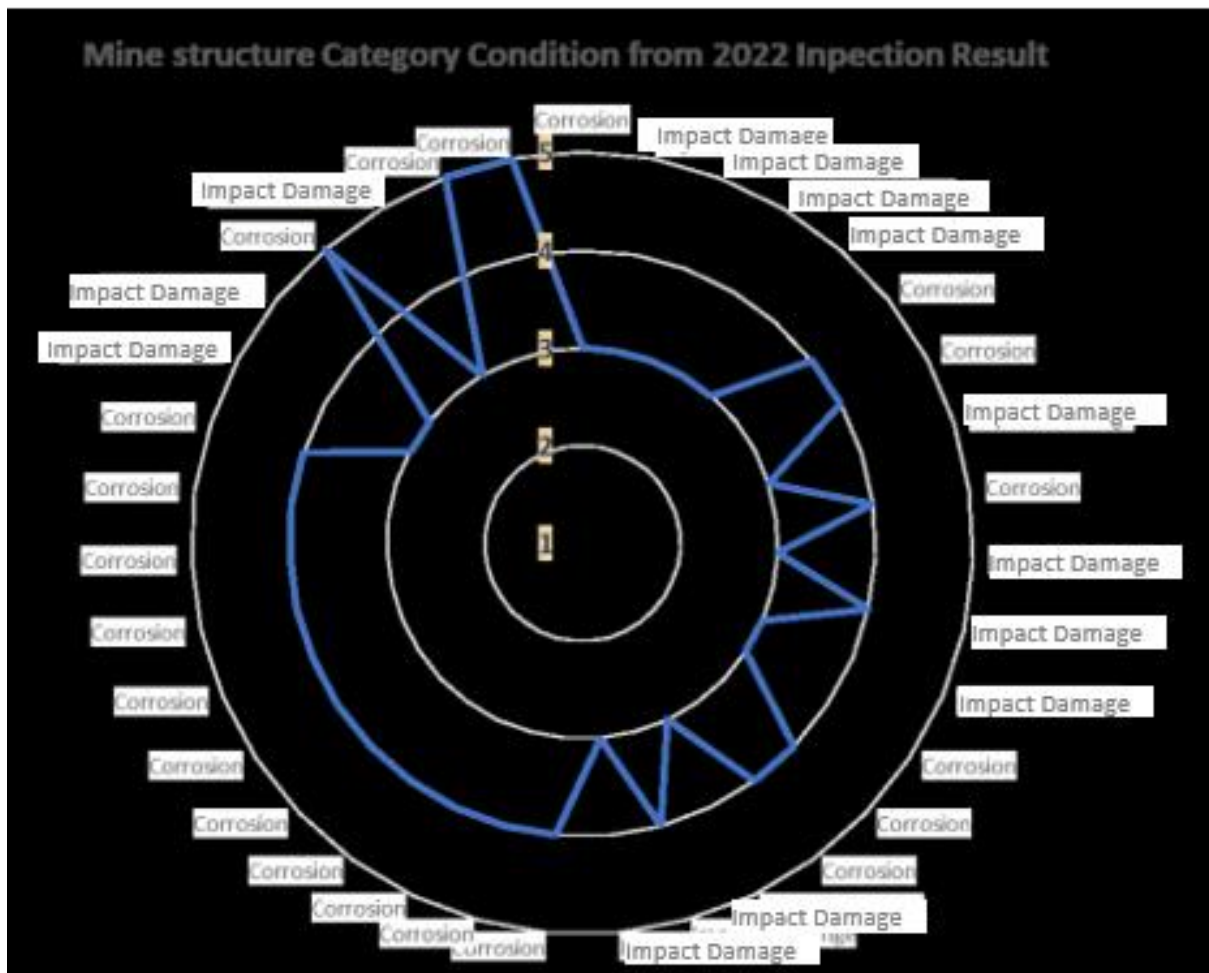


**Figure 5.11: Category condition mechanisms (finding from 2022 report)**



**Figure 5.12: Category condition in different levels of the shaft (2022 inspection results)**

Figure 5.13 below illustrates the failure mechanisms that were observed during the third-party annual structural inspection done in 2022.

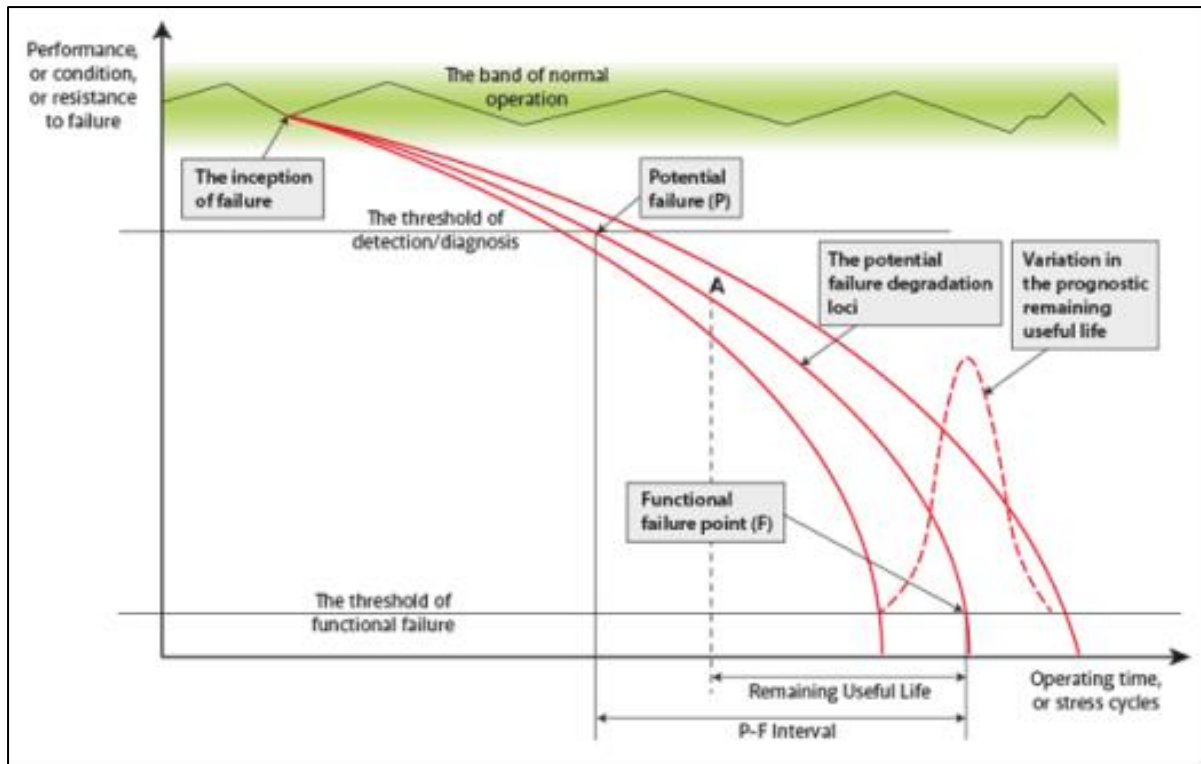


**Figure 5.13: Results of inspection failure mechanisms**

### 5.7.3 Life cycle of structures

The monitoring on maintenance work of the structures and the prognostic model offers sensible means to optimise life cycle phases, starting from the initial design and construction to upgrading or replacing of failed structure members and extending the original intended life of structures up to disposal of the system at the end of its service life.

Figure 5.14 below provides an illustration of extension of remaining life of the mine shaft structures by replacing deteriorated members. The continuous programme for repairs and replacement of structure members allows the continuous extension of remaining life without major disruption to the production plans.



**Figure 5.14: Behaviour of time of structures condition vs failure point**

The performance, condition, or failure resistance of structures, particularly steel structures, is highly reliable because of their exceptional durability. Exposure to harsh environments without protection and preventive maintenance will however speed up the degradation process. The current gold mines in South Africa are over seven decades old but are still standing and can be maintained to operate for another seven decades. However, to achieve another seven decades of safe operation, proper integrated SIMM is required as well as the discipline to follow up and monitor the implementation of appropriate actions that support the maintenance strategy. The point of failure inception refers to the loss of structural integrity realised at the early stage. The condition categorisation process monitors the failure inception which is usually observed to be a 5% loss of structural integrity observed between the first and fifth years depending on the harshness of the environment.

The threshold of detection or diagnosis aims to raise the awareness and urgency to take action before the failure occurs. In this case, a CC4 is a warning that action to repair or replace a structure member must be done within 12 to 36 months. Failure to take action will result in the structure members reaching a point of failure which is CC5, which may result in potential failure of the entire mine shaft system.

Potential failure for the mine shaft structural system probability is influenced by age and the amount of effort put into addressing the harsh environment, corrosion protection and the monitoring and execution of corrective action when early detection of degradation of structure members occurs. Lack of an integrated SIMM and monitoring system will result in potential failure degradation to occur faster.

Variation in the prognostic remaining useful life is dependent on the amount of effort applied into structural care and maintenance. Useful life remaining can be maintained or increased to suit the operation's service time referred to as LoM. The LoM depends on a number of decisions. This includes the availability of reserves of mineral to be extracted. It also includes the appetite for investors to continue investment on the work required to extract minerals underground in a way that is safe, sustainable and in compliance with legislation.

The prerequisite to continue mining requires well defined effort which involves taking care of the integrity of the mine shaft structures. The effort for mine shaft integrity is not the same for all mine shafts; it depends on how many years it is intended to continue mining. In the specific mine shaft where the study was conducted, the mining operation has an estimated LoM of eight years. To achieve the eight years safe production, the effort of maintenance is medium, meaning there is no need to work on the CC3 members. CC3 members are still good enough at the integrity strength of up to 75% which will degrade to CC4 in a few years. The degradation from CC3 to CC4 can be further slowed down by implementing a corrosion protection system. The CC3 member can remain safe for another decade and more.

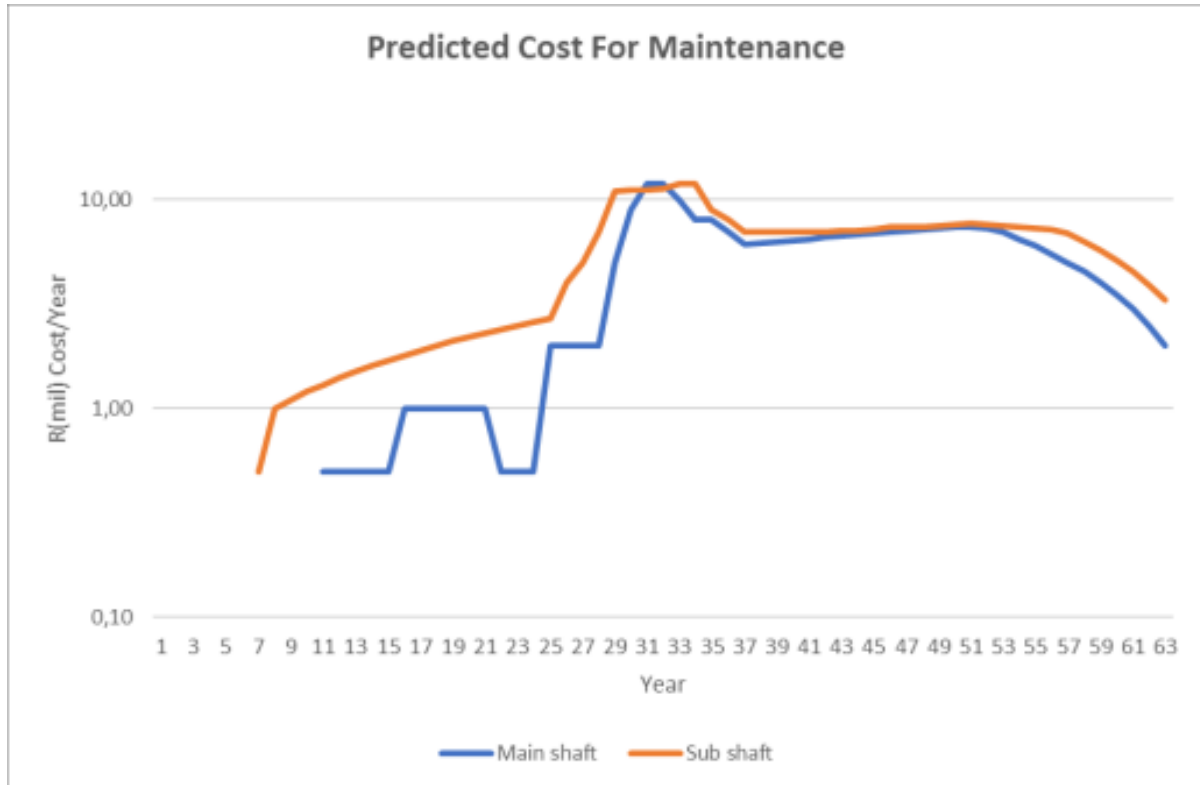
The priority for replacement of structural members is to start with CC5 structural members which are already at the functional failure point to avoid total collapse of entire mine shaft structure, followed by the CC4 members which are also critical because they have already reached failure point threshold. Depending on the rapidity to replace CC4 members, each year would have CC4 members degrading to functional failure point CC5 and becoming a priority for replacement. This process is continuous and can be expected from an old mining operation which has an expected LoM of eight years. Investors may decide to extend the LoM depending on the survey and risk evaluation in terms of return on investment. Upon extension of the LoM, the maintenance strategy must be reviewed to match the new condition of structure.

#### **5.7.4 Life cycle cost**

LCC methods provide a framework that describe the amount of work required to keep the structure safe as well as the recommendation for replacement of components and the mine shaft to enable the reliable performance while extending the LoM. There are certain principles upon which such an approach is based. Predicting performance is understood by analysis of historical failures, visual inspection and critical measurements such as NDT, or thickness testing of particular pieces of structures.

The predicted cost could be determined as shown in Figure 5.15. This figure can be used to create a budget into the future. The cost is calculated using the unit price of the steel buntun and pipe lines multiplied by the number of buntun and pipe lines that must be replaced in line with the structural

inspection report. For the first year which is the 29th year since the mine was commissioned, up to R11 million and R12 million for main and sub-shaft respectively will be needed to replace all CC5 members. The figure below shows a more detailed breakdown of this year's CC5 members. Stability will be reached after three years and reduction of members to be replaced will reduce the amount to R7 million in average to maintain a safe condition for the period of LoM. Maintenance effort will be reduced towards the end of LoM to only condition monitoring and structure members will only be replaced if it will result in disruption of the mine shaft system functionality.



**Figure 5.15: Predicted cost of maintenance**

### 5.7.5 Advantages of integrated monitoring system for structural inspection and maintenance

The benefits that the iSIMM will deliver expressed in measurable terms against the situation as it exists prior to the iSIMM implementation include:

- integration of data/information for all mine shaft and shaft elements into one system
- one source of data and/or information for decision-making and reporting
- improvement in operational excellence, through synergies
- reduced costs by building in efficiencies
- automation and enforcement of controls (including delegation of authority and segregation of duties)
- proactive and reliable close out of remedial actions

- systematic management of records
- better monitoring and evaluation of defined key performance areas and indicators thereof
- facilitate compliance with applicable regulations

### **5.7.6 Identification and critical shortcomings in the system**

Technology brings change in the way people do things. Like many online or integrated platforms, iSIMM requires human intervention for it to work as intended. Resistance to change by those that are accustomed to using the existing processes and tools no matter how inefficient they are, is a risk to the success of new systems. Upfront engagements, stakeholder analysis and stakeholder management processes aid to overcome the resistance to change.

### **5.7.7 Identification of required upgrades**

This section outlines the functional requirements and objectives that a proposed iSIMM solution is expected to meet. The proposed solution is expected to perform the following functions to meet business needs accordingly.

The system should have controlled user access:

- system control to allow user functionality per requirement (certain users only has access per region or per function within the system)
- defined super users (admin users)

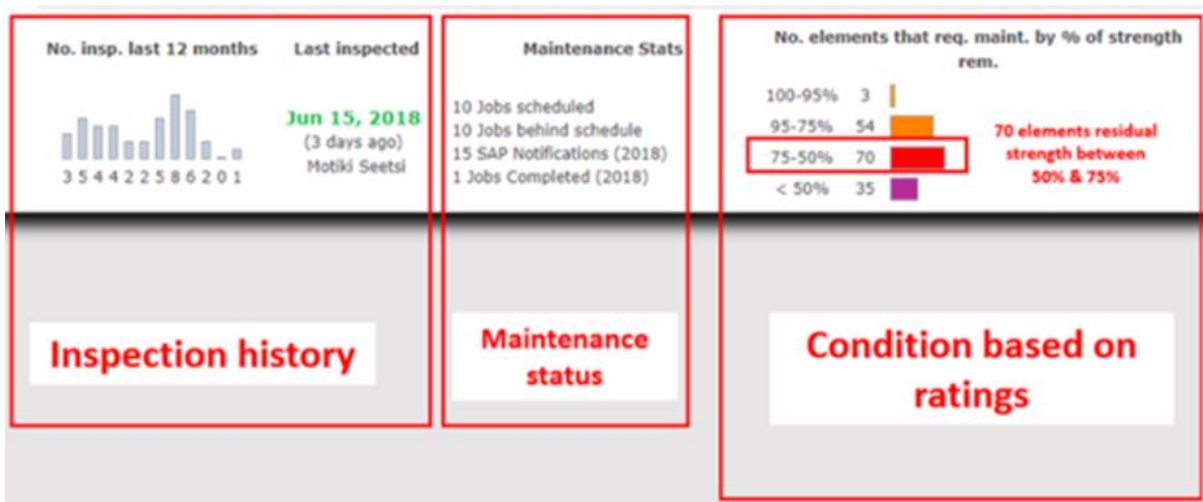
### **5.7.8 iSIMM system functionality**

iSIMM manages maintenance work orders for mine shafts, ensuring a comprehensive system for historical maintenance requests without duplicating work orders. An interface with financial management is essential for cost centre management and expenditure analysis to aid future budgeting decisions. In addition, the system should generate reports on all property assets and offer functionality to flag items under warranty or guarantee agreements. A search feature for findings or actions is crucial.

The system enables importing and secure storage of external documents in PDF, JPEG, Excel, and CSV formats, ensuring compliance with internal policies and external regulations. Incorporating geographical information and monitoring system functions, the system allows for layering and additional feature incorporation by the user. Standardisation of business processes, templates, forms, and reporting structures is essential, aligning with industry best practices in data management.

The iSIMM is a web-based or server-based system, using English as the primary language, with a user-friendly interface allowing easy navigation between screens/links. It features real-time reporting, data processing, scalability, security with user profile-based access, auditability, and confidentiality, which is easy to maintain.

Figure 5.16 depicts a dashboard exemplifying the work order status derived from corrective actions recommended in the structural inspection report. The iSIMM platform provides a comprehensive dashboard displaying inspection history, maintenance status, and the condition of mine shafts based on ratings from competent structural engineers.



**Figure 5.16: Example of iSIMM**

## CHAPTER 6: CONCLUSION

Remaining useful life of mine shaft structures can be adjusted by replacing deteriorated members. A continuous programme for repairs and replacement of structure members allows the continuous extension of remaining life without major disruption to the production plans. Investors may decide to extend the LoM depending on the survey and risk evaluation in terms of return on investment. Upon extension of the LoM, the maintenance strategy must be reviewed to match the new depend of structural performance.

### 6.1 THE RESEARCH OBJECTIVE

Chapter 6 serves as the conclusion of the research, providing a comprehensive summary. This section encapsulates the essential insights derived from the research, highlighting major learnings, and offering suggestions for potential future research directions.

#### 6.1.1 A reflective examination of the research objectives achieved

With this work, the study achieved all of its stated objectives:

##### **a) Development of a methodology for structural inspection of a mine shaft:**

The research resulted in the creation of an iSIMM. This system was applied and tested at Harmony, and the results were evident through the visibility of maintenance work recommended by structural engineers, being executed and planned for in short, medium, and long-term durations. All these activities were captured in the CMMS.

##### **b) Interpretation of data using the model for economical, risk-based maintenance decisions:**

The study successfully utilised data from inspections to inform economic and risk-based maintenance decisions. This tool proved to be useful in budgeting and planning resources for structural maintenance work, ensuring efficient allocation and use of resources.

##### **c) Development of a prognostic and risk/economic-based maintenance decision model:**

This objective was met through the creation of a model that integrates prognostic and risk-based approaches for making maintenance decisions. The model helps in predicting future conditions and planning maintenance activities accordingly.

#### **d) Case study application and validation:**

The application and validation of the developed iSIMM in a real mining environment at Harmony confirmed the practical utility of the research. The case study demonstrated the successful implementation and effectiveness of the system in a real-world scenario.

#### **e) Use of inspection data to manage the remaining life of structures in a mine shaft:**

The objective of managing the remaining life of structures using inspection data was achieved. The research involved using this data to make informed decisions about maintenance, repairs, and predictions regarding the remaining LoM shaft structures. This approach ensures the continued safety and functionality of the mine infrastructure.

#### **f) Overall achievements**

The research made substantial progress in meeting all the stated objectives. The development and practical application of the iSIMM, along with the integration of inspection data for decision-making, demonstrated a comprehensive alignment with the outlined goals. The annual inspections also provided a means to calibrate the previously estimated life of the mine, project the future condition of the mine structures, and forecast budget requirements. This detailed analysis highlights the effectiveness of the methodologies and systems developed through this research, ensuring the long-term safety and efficiency of mining operations.

## **6.2 EXPERIENCE AND KEY LEARNINGS**

Numerical and experimental investigation of structural condition behaviour over time is based on corrosion rate and falling object impact of vertical mine shaft steel structures. Impact probability from falling objects was tested assuming mining condition by applying a static load to the buntons. The numerical model validates the impact of corrosion rate on each member that is subject to probability i.e., some members will be exposed to worse environmental conditions and thus corrode quicker than others (for example if there was water leaking onto it for a period). The information on a known member that had a very high corrosion rate was used to calibrate a probability density function so it could be used in the model (ISO, 2012).

FEA exported to ANSYS was used to simulate the falling object onto the buntons in a vertical mine shaft. This investigation obtains the mechanical behaviour of a buntion and its damages as a main member of vertical mine shaft structures. The assessment gave a better insight of analysis of geometrical, material, load variations stress interface and strain. The results from this experiment aligns with the historical experience and knowledge of mine shaft structures behaviour over time.

These simulations indicate that a structural member may fail from a major event such as a significant fall of an object. Otherwise, the degradation of members is very slow in a dry environment and where falling objects are prevented. Slow degradation means that the mine shaft structure members can last up to 37 years before it requires replacement. However, humid or wet environment as well as falling objects accelerate the degradation of steel condition from CC1 (100% strength) to less than CC5 (<50% strength) much faster.

The mine life expectancy differs from one shaft to another as it depends on the valuable mineral reserve underground. If a ground survey indicates the most economical estimate of a mine's mineral resources, justifying an extension of the Life of Mine (LoM), it becomes easier to assess the amount of work required to achieve the desired LoM.

### **6.3 CONCLUSION**

The conducted experimental simulation replicating the effects of falling objects within the mine shaft exhibited damages consistent with those observed during routine annual third-party inspections, establishing a robust correlation between simulated outcomes and physical observations. These findings establish the present condition as the foundational benchmark for assessment purposes. In cases where corrosion poses a potential threat, the application of corrosion protection measures becomes imperative. Furthermore, a critical aspect involves regular monitoring of structural elements during weekly shaft inspections, prompting immediate repair actions upon the detection of any indications of material degradation.

The harsh conditions prevailing within the mine shaft environment, compounded by mechanical stressors, significantly hasten the deterioration of both concrete and steel structures. Active inspection management effectively mitigates uncertainties by reducing risks associated with structural integrity. The implementation of an integrated inspection system for mine shafts promises enhancements in decision-making processes, maintenance quality, safety, and reliability, all optimised within an economically feasible framework. Proactive monitoring and management of mine shaft conditions, as facilitated by the condition inspection system, are instrumental in minimising the LCC.

These measures provide a strategic opening to employ RBI and CBM, tailoring maintenance activities to align with specific business risks and opportunities. The accuracy of decision-making processes hinges on the availability of accurate data.

The developed monitoring system plays a pivotal role in projecting pre-emptive remedial actions, thereby effectively managing the LoM shafts. The integration of this monitoring system enhances visibility, facilitates efficient monitoring practices, and optimises the execution of remedial actions

pinpointed during structural inspections. Ultimately, these initiatives are instrumental in managing the overall life of the mine shaft and estimating its remaining operational duration.

#### **6.4 FUTURE RESEARCH RECOMMENDATION**

Recommendation for future research is exploring practical and viable online technology for remote structural monitoring. Current manual analysis of structural conditions against failure risk levels calls for further investigation, particularly in comparing conditions across all structural members. However, integrating online remote condition monitoring sensors, especially in mining shafts due to their harsh conditions, may entail substantial investments in technology development.

This research does not extensively address the specifics of guide alignment checks. In South Africa's gold mines, guides in vertical shafts are inspected for defects and misalignment through regular visual inspections as mandated by the Health and Mining Safety Act (HMSA) regulations. Any defects observed during these inspections are documented and rectified accordingly. However, there is currently no advanced monitoring system in place to continuously measure guide alignment.

The literature on guide systems in mine shafts emphasises their critical role in enhancing the operational efficiency and safety of hoisting mechanisms. Key studies have highlighted the importance of integrating design considerations that account for mechanical properties and dynamic loads, ensuring the stability and longevity of guides under varying operational conditions. The performance of guides is closely tied to the structural health of vertical mine shafts. Continuous advancements in design and monitoring practices are necessary to tackle the dynamic challenges encountered in underground mining environments. Zelenko and Gorbach (2019) emphasize the critical nature of guides in ensuring safe hoisting operations. Their work advocates for implementing real-time monitoring systems to prevent accidents related to guide failures.

Further research is required to explore guide alignment inspection techniques and the effects of integrating inspection systems. Developing monitoring solutions equipped with sensors for real-time guide displacement measurement is crucial, as these systems would empower hoist operators to promptly address potential misalignment hazards. Future studies should also focus on enhancing the design, performance, and inspection methodologies of guides within the context of integrated systems to improve overall mining safety and operational reliability.

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