Automated Tyre Management System for Open Cut Mining Operations

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Thesis

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Declaration of Authorship

I, Samuel Kember, declare that this thesis and its work are my own. Information obtained elsewhere has been correctly acknowledged. My contributions consist of:

- I performed the research required to build an understanding of the context and background surrounding reliability-centred maintenance (RCM)
- I carried out the literature review.
- I conducted a detailed investigation of the existing procedures for monitoring haul truck tyre conditions at the research mine.
- I personally travelled to the mine site on at least three occasions to understand the roles, challenges, responsibilities, and cultural aspects of the workplace.
- I conducted several research papers to inform my industry supervisor, Marcus Valstro, and Corehesion's managing partner, Brad Waldron, about opportunities within the asset monitoring space at mining sites.
- With the support of my industry supervisor, Marcus Valstro, I identified the key problem with current operations and developed a scope of work for the project to be completed at the research mine.
- I carried out analysis and further research to develop detailed design requirements for the system, including methodologies to ensure it met the requirements of key stakeholders.
- I project-managed the entire system design, stakeholder engagement, and presentation. While I did not directly write the software for the system, I worked closely and frequently with software developers at the company to ensure the system design requirements were clear and logical to follow.
- I conducted the analysis and evaluation of potential outcomes following the implementation of the system, assessing whether the system met the thesis objectives.
- I completed the conclusion and developed future work suggestions based on the experience and knowledge gained throughout the thesis.
- I performed all the work required for both case studies.

To the best of my knowledge and belief, this work contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the The University of Sydney or other institute of higher learning, except where due acknowledgement has been made in the text. I acknowledge that Generative-AI tools, including OpenAI's ChatGPT and GitHub's Copilot, assisted in the development of this thesis by aiding in sentence structuring, spell checking, grammatical checking and overall response formatting. However, the research, ideas, critical thought, results and analysis presented in this thesis are entirely my own.

Samuel Kember

October 2024

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

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Abstract

The mining industry is a cornerstone of the global economy, supplying essential raw materials such as coal (thermal and metallurgical), iron, copper, gold, lithium, nickel, cobalt, bauxite, silver and uranium. These raw materials are also the backbone of economies pivoting to a greener and more sustainable footprint. One of the most significant operational costs in mining is the management and maintenance of critical assets, which are vital for ensuring operations are maintained in a cost-effective and safe manner. While substantial technological advancements have been made, many of these solutions are highly capital-intensive and specialised, making them financially viable only for large global corporations with access to the required capital, innovative systems and the expertise to operate and manage them. Research indicates a clear gap in the availability of cost-effective, widely applicable solutions that leverage everyday technology alongside advanced tools to address asset management challenges in mining.

This thesis aims to bridge this gap by developing a solution that utilises everyday technology, integrated with market-ready advanced solutions to enhance the data available to mining operators. The focus of such a system will be on enabling more effective integration of reliability-centred maintenance (RCM) practices. The project presents the design and implementation of a substantial upgrade to an existing software platform that will significantly increase the data collected on the condition of haul truck tyres, a major operational expense in surface mining. By leveraging handheld devices, the existing software infrastructure, and available digital tools (Image recognition data analytics), the proposed system will dramatically improve data availability on tyre conditions. From this, mining operators can make more informed, data-driven decisions, resulting in enhanced safety, reduced downtime, and cost savings. The proposed approach is specifically designed to be scalable and economically viable, providing a competitive solution for asset management in mining.

In recent years, the impact of high inflation on both costs and labour means operators and asset managers must continually seek further operational efficiencies and productivity gains to maintain viable and profitable operations. All operators and owners are striving to minimise the mine's All-In Sustaining Costs (AISC). AISC is the comprehensive measure that evaluates the total cost of producing a unit measure of raw material. It includes all the costs associated with producing the raw material, including operating expenses, sustaining capital expenses and exploration expenses. Each owner and operator of mining operations is continually seeking to drive efficiencies to ensure they are competitively placed on the global cost curve for that raw material.

This system has been iteratively developed at a research mine with the intent of eventual real-world and global implementation. As a result, the focus is not only on meeting client needs but also on ensuring that the process used to deliver these results is economically viable for both the research mine and the software company responsible for developing the solution. The system has been designed to balance practicality with technological advancement, ensuring that the enhancements in data collection and analysis are both effective and affordable, thereby enabling broader adoption and applicability across the mining industry globally. By addressing both the technical and economic requirements, the system is positioned to offer a scalable, cost-efficient solution for asset management in surface mining operations.

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List of Acronyms

SaaS software as a service

AI artifical intelligence

ML machine learning

DOFS Distributed Optical Fiber Sensor

RCM reliability-centered maintenance

P-F Potential failure to Functional failure

PdM Predictive Maintenance

PM Preventive Maintenance

CM Corrective Maintenance

IIoT Industrial Internet of Things

RUL remaining useful life

DT down time

LT logistic time

CBA cost-benefit analysis

RT repair time

DT down time

POD probability of detection

NDT non-destructive testing

MAC Mt Arthur Coal

OTR off the road

LME light mobile equipment

ESIPS Engineering Sydney Industry Placement Scholarship

WHS Work Health and Safety

EAM enterprise asset management

CMMS computerised maintenance management systems

IoT Internet of Things

CAD computer-aided design

TPM total productive maintenance

EV electric vehciles

AGI artifical general intelligence

GPU graphics processing unit

BM business model

BMI business model innovation

ANN artifical neural networks

CNN convolutional neural networks

RNN recurrent neural networks

GAN generative adversarial networks

API application programming interface

OTR Off-The-Road

UAT User Acceptance Testing

IP Image Processing

CV Computer Vision

EMS Electromagnetic spectrum

WBS Work Breakdown Structure

ROI return on investment

BAU business as usual

EVM Earned Value Management

GDP gross domestic product

ATMS Advanced Tyre Monitoring System

PPE Personal Protective Equipment

EMR Electromagnetic Radiation

CCD Charge-Coupled Device

CMOS Complementary Metal-Oxide-Semiconductor

R-CNN Region-based Convolution Neutral Network

TFDS Tyre Fault Detection System

UAV Unmanned Aerial Vehicles

EMEA Europe, the Middle East and Africa

Glossary

damaged valve stem Damaged cause to or around the valve of a tyre. 11

shoulder separation Splits or cracks in the shoulder region of a tyre, which are an indication of internal separation. 11

sidewall bubbles Large bubbles that appear on the sidewall of a tyre. 11

sidewall cuts on rear positions Cuts that occur on the outside of a tyre's sidewall on the back wheels. 11

sidewall cuts on steer positions Cuts that occur on the outside of a tyre's sidewall on the front 2 wheels of the vehicle. 11

tread damage Damage to the rubber tread of tyres. 11

worn-out belts exposed in the tread The tread (rubber outside) of a tyre is worn down to the point the belt (inside structure) of the tyre is visible. 11

Executive Summary

This thesis aims to redefine the current monitoring systems for commonplace assets in heavy industries, particularly mining, through the design and implementation of upgrades to an existing software platform. This platform, the Advanced Tyre Monitoring System (ATMS), enables users to quickly record current asset conditions, track their history, alert key personnel, and receive detailed predictive analysis of the potential operating lifespan of the asset. The impetus for this research was derived from a real-world case study at a major surface mining operation in rural NSW, Australia. The mine had been experiencing increasing problems with asset lifespans falling short of predicted rates and lacked an information-gathering system to diagnose the issue. This highlighted the need for a user-friendly, commercially viable, and practical system that could be quickly integrated into any major heavy industry operation to efficiently gather data and answer key operational questions.

The specific asset lifespan issue addressed in this research concerns haul truck tyres, which are critical and costly assets in mining operations, with each tyre costing up to AUD $80,000. The research mine requires approximately 650 tyres annually or AUD 52 million per annum, a significant operational expense and importance of optimising maintenance and replacement procedures. Historically, these tyres were monitored only during scheduled maintenance downtime, which often proved too infrequent to detect minor issues before they escalated into major failures.

Without real-time monitoring or predictive maintenance systems, early signs of tyre degradation went unnoticed, leaving maintenance teams unable to take proactive measures. This reactive approach led to unnecessary downtime, costly tyre replacements, and increased work health and safety risks. The lack of continuous monitoring and subsequent inability to pinpoint why tyre degradation was occurring at an accelerated rate underscored the need for a more advanced solution to gather data so more informed decisions on mitigation strategies could be made.

The design methodology for implementing the ATMS is divided into two key phases. The first phase focused on developing the monitoring and notification systems, significantly increasing the amount of data gathered on each tyre and streamlining communication between operators and maintenance personnel. This phase was designed to seamlessly integrate into the existing operational structure, ensuring minimal disruption while maximising the impact on tyre monitoring. By enhancing data collection and communication efficiency, the system enables timely responses to potential issues, improving the overall maintenance approach to the assets.

The second phase of the capability upgrade centred on the integration of AI tools and advanced data analysis. This phase aimed to provide decision-makers with clearer, data-driven insights into tyre conditions. By leveraging computer vision (CV) technology, the system offers enhanced analytical maintenance capabilities and reduces the need for human inspectors. This implementation also greatly enhances understanding of tyre degradation patterns, enabling preventative measures to be implemented and further optimising tyre lifespan, thereby reducing operational expenses.

A gradual implementation strategy for both phases was designed to minimise the impact on operations while maximising the ATMS's return on investment (ROI). This phased approach allowed for continuous monitoring and iterative improvements of the system, ensuring that any integration challenges could be addressed with minimal disruption. Additionally, by incorporating feedback from operators and maintenance teams during the rollout, the system was tailored to fit the specific needs of the mine, further enhancing its effectiveness and scalability across different mine sites. This careful, step-by-step deployment ultimately ensured a smooth transition and the long-term sustainability of the system in real-world mining operations.

The thesis also highlights the broader implications of implementing such a system within the mining industry. By leveraging modern digital technologies in tandem with low implementation and operating costs, the ATMS provides a highly cost-effective solution for heavy industry. The design prioritises ease of use, ensuring that operators and maintenance teams can efficiently integrate the system into daily operations without extensive retraining. Additionally, the system's emphasis on delivering accurate and actionable insights further enhances its value, enabling mining companies to significantly improve asset management, reduce operational costs, and improve work health and safety. This approach demonstrates that advanced technology can be accessible and practical, offering immediate and substantial benefits for industries reliant on large-scale equipment and maintenance.

Chapter 1

Introduction

This thesis was conducted over a six-month industry placement at Corehesion Services Pty Ltd. Corehesion is an Australian-born software as a service (SaaS) company specialising in creating bespoke solutions for heavy industry to ensure safety compliance and improve efficiency. Its software platform has primarily been used within the mining industry, with current projects aimed at expanding services into energy production and global shipping industries. These projects will continue to build on Corehesion's expertise in delivering safety and cost-efficiency solutions in heavy industry through software that is purpose-built around clients' requirements.

Asset management and maintenance are essential components of business operations aimed at enhancing cost efficiency and safety [73]. Jung et al. states that the primary aim of this process is to "reduce the risk of equipment failure, extend equipment life, and minimise unplanned outages" [54, p.3391]. This thesis will focus on expanding Corehesion's current service offerings to mining operations by developing a more efficient framework for inspecting truck tyres during normal operations and replacing the current antiquated methodology. The end goal of this project is to increase the operational lifespan of truck tyres by providing operators with more current and timely information about tyre conditions enabling preventative measures to be taken thereby significantly reducing operational costs for mines. This will be achieved by capturing more data from maintenance operations, providing operators with a practical framework to view the data on a timely basis, and laying the groundwork for integrating a market-ready artifical intelligence (AI) driven Computer Vision (CV) tool to aid decision-making.

1.1 Context

Mining is the primary "source of mineral commodities that all countries find essential for maintaining and improving their standards of living" [26, p.10]. Mining can be defined as "the process of extracting useful materials from the earth" [42, p.1] and is an essential part of the modern global economy. The raw materials gathered are used in all industries, including construction, technology, and manufacturing. It supports the development and maintenance of infrastructure, construction, and consumer goods, including transport, technology, and energy requirements for all countries.

There are four main mining methods used across the industry: surface, underground, placer, and in-situ [28]. This thesis will focus on a tyre management system for surface mining due to the high demand for heavy vehicles within this method. However, the system developed could be implemented in maintenance strategies for other types of mining and applications, such as oil leaks or other components that require frequent inspection.

1.1.1 Surface Mining

Surface or open-cut mining is a method used to extract minerals by excavating them from an open pit, as shown in Figures 1.1 and 1.2. This method is preferred when mineral deposits are relatively close to the surface and spread over a large area. Surface mining is usually a more cost-effective method compared to underground mining and is highly efficient at extracting large volumes of low-grade ore, enabling up to 90% recovery of the resource [9]. Therefore, it is the most economically viable method for large-scale mining operations of low-concentration deposits, common with commodities such as gold, copper, iron, and coal [22].

Surface mining has also been found to be safer for workers, as underground mining carries greater potential risks from explosions and wall failures. Australia's surface mining operations have a history of strong safety culture, with fatality rates less than half that of the United States [18]. In general, mining fatalities across the developed world have fallen significantly over the past 20 years in Australia, from 12.4 worker fatalities per 100,000 workers in 2003 to 4.4 in 2015, according to Safe Work Australia [99].

Surface mining also poses environmental challenges, with the creation of large open pits and the need for dumping areas or tailing dams resulting in habitat destruction, soil erosion, and potential contamination of groundwater due to the exposure of sulphides and other hazardous chemicals used to extract raw materials. Regulation and sustainable mining practices are therefore crucial to mitigate these issues by mandating that land be rehabilitated after mining operations are concluded or progressively throughout a mine life.

Figure 1.1 – BHP's Mt Arthur Coal mine

Figure 1.2 – Diagram of a surface mine [55]

Surface Coal Mining

To build a surface mining operation, vegetation and topsoil are first cleared from the area, followed by drilling, rock blasting, and excavation methods used to dig down to the coal deposit. Machines such as draglines, shovels, and trucks remove debris and transport coal to processing facilities. Eighty per cent of the coal produced in Australia comes from open-cut mines, which is relatively high compared to the global average of 40%. Australia currently has approximately 350 open-cut mines, 125 of which are open-cut coal mines [9].

1.1.2 Workplace Health and Safety Risks in Surface Mining

The mining industry "has a reputation for inherent risks and potential health hazards, which are varied and sometimes significantly consequential" [10, p.1]. There are ten main areas of risk involved in surface mining [10]:

1. **Chemical Hazards**: Mining operations can involve exposure to hazardous chemicals such as toxic substances and gases, which can pose serious health risks, including respiratory problems, poisoning, and chemical burns.
2. **Equipment and Machinery Accidents**: Mining vehicles and other machinery used in surface mining can cause serious harm when not operated and maintained correctly.
3. **Heat Stress**: Many mining sites across Australia are located in desert environments that experience high temperatures. Overexposure to heat in environments like this can cause fatigue, distress.
4. **Explosions and Fires**: Explosives and flammable materials are both used extensively in mining operations. These materials create a real risk of explosions and fires on a mining site which, given the large quantities of coal present, could create a large-scale safety and natural disaster risk.
5. **Air Pollution**: Exposure to pollutants common on a mine site, such as coal dust and silica, over prolonged periods can lead to severe respiratory illnesses if not properly monitored and exposure controlled.
6. **Whole Body Vibrations**: Prolonged exposure to excessive vibrations, which are common in heavy machinery such as trucks and excavators, can cause musculoskeletal problems in both the short and long term.
7. **Electrocution**: Breaks or cuts in an electrical system can pose a risk to nearby workers. This, combined with limited visibility in rough terrain or night-shift work, means that workers may not identify an exposed wire until an incident occurs.
8. **UV Exposure**: Mine workers who are outside all day working in an open-pit mine are especially at risk of overexposure to UV radiation. This exposure can lead to skin cancers, eye damage, dehydration, headaches, and nausea.
9. **Manual Handling**: Manual handling of heavy equipment using improper techniques or practices is another major risk that can lead to musculoskeletal disorders in the mining industry.
10. **Noise Exposure**: Mine workers are often exposed to high levels of noise, which, if not properly controlled, can lead to hearing loss and other auditory disorders that have long-term effects on workers' health.

1.1.3 Tyre Incident Risk

This thesis will seek to implement a system that can increase the efficiency of tyre management while simultaneously decreasing the risk of tyre failure, which is a significant part of *Equipment and Machinery Accident* risk. The risk of serious injury or death to operators from tyre mismanagement is a major concern for surface mining operations. There were 82 tyre accident events between 1987 and 2008 in Australia, of which 33% resulted in a fatality, 50% had the potential to cause a fatality, and 9% caused serious injury [71]. Figure 1.3 shows the aftermath of a tyre blowout that resulted in the fatality of the truck driver.

Figure 1.3 – Haultruck tyre incident that resulted in a fatal injury [86]

1.1.4 Tyre Management in Open Cut Mining

Tyre management in surface mining is a critical component of workplace safety and operational efficiency. This work is usually outsourced to third-party contracting companies with a specialist focus on sourcing, maintaining, repairing, and disposing of tyres. Figure 1.4 shows an inspector a MAC carrying out an inspection of a tyre with a sidewall cut while the haul truck is in the maintenance building.

Figure 1.4 – Tyre Inspector performing a routine tyre inspection (Taken at MAC during placement).

The key aspects of tyre management include [72, 58, 88].

1. Selection and Procurement
    - *Right Tyre for the Application*: Choosing the correct tyre based on the specific mine conditions (terrain, load, distances, and temperatures used in) is a crucial consideration. Different tyre compositions and tread patterns can affect performance and tyre longevity.
    - *Quality and Compatibility*: It is important to invest in high-quality tyres from manufacturers with a good history that are known to meet industry standards and are compatible with the specific vehicles and equipment used in the mine.
2. Maintenance and Inspections
    - *Regular Inspections*: Conducting thorough inspections for damage to tyres is essential to prevent failures. Regularly checking air pressure, in particular, is crucial for maintaining tyre integrity.
    - *Scheduled Maintenance*: Implementing a routine maintenance schedule that aligns with the tyre manufacturer's recommendations and real-world usage.
3. Pressure Monitoring and Management
    - *Correct Inflation*: Maintaining the correct tyre pressure is essential for preventing tyre wear and improving fuel efficiency. Underinflation of tyres can lead to increased wear and tear, while overinflation can reduce traction and increase the likelihood of a blowout, which is a serious safety risk.
4. Wear and Damage Control
    - *Rotation and Positioning*: Rotating tyres between different positions on trucks will even out the wear pattern and increase operational lifespan.
    - *Damage Repair*: Implementing procedures that can quickly identify minor damage and repair it before it becomes a major issue can extend tyre life and ensure safe operation.
5. Training and Awareness
    - *Driver Training and Awareness Programs*: Educating vehicle operators on defensive driving techniques to minimise tyre wear and avoid potential hazards can significantly impact tyre lifespan. Running a program to highlight the importance of following safe tyre procedures is also an effective strategy to ensure safe and efficient operation.

6. Retreading and Recycling
   - *Retreading*: Retreading worn tyres can be a cost-effective way to extend the life of a tyre, provided the tyre casing is still in good condition.
7. Data Analysis and Technology
   - *Performance Tracking*: Using data analytics to monitor tyre performance across different operating conditions and adjust maintenance strategies accordingly is an effective way to extend lifespan.
   - *Innovative Technologies*: Exploring the use of advanced technologies (e.g. drone surveillance or the implementation of AI image processing) to inspect tyres in difficult-to-reach areas of the mine can reduce costs and increase efficiency.
8. Safety and Compliance
   - *Compliance with Regulations*: Adhering to all relevant safety and environmental regulations regarding tyre management is mandatory under current Australian Government laws.
   - *Emergency Preparedness*: Having contingency plans in place for tyre-related incidents, including a rapid response team and replacement strategies to minimise downtime, is essential.

Ensuring that these key aspects of tyre management are all addressed is an essential part of surface mining operations, as it not only ensures the safety of all personal but has a significant impact on cost-efficiency of operations.

1.1.5 Research Mine - Mt Arthur Coal

This thesis has been conducted in partnership with BHP's MAC mine, an open-cut energy/thermal coal mine located 5 km south of Muswellbrook in the Hunter Valley. Production commenced at MAC in 2002, it employs a workforce of around 2,000 people, and it is currently the largest coal mine in New South Wales. It has a mining capacity of 20 million tonnes per annum, with 21 unique seams being mined. BHP has scheduled the cessation of mining operations at MAC by the end of the 2030 financial year, as it seeks to move away from coal operations due to its adverse impact on climate change.

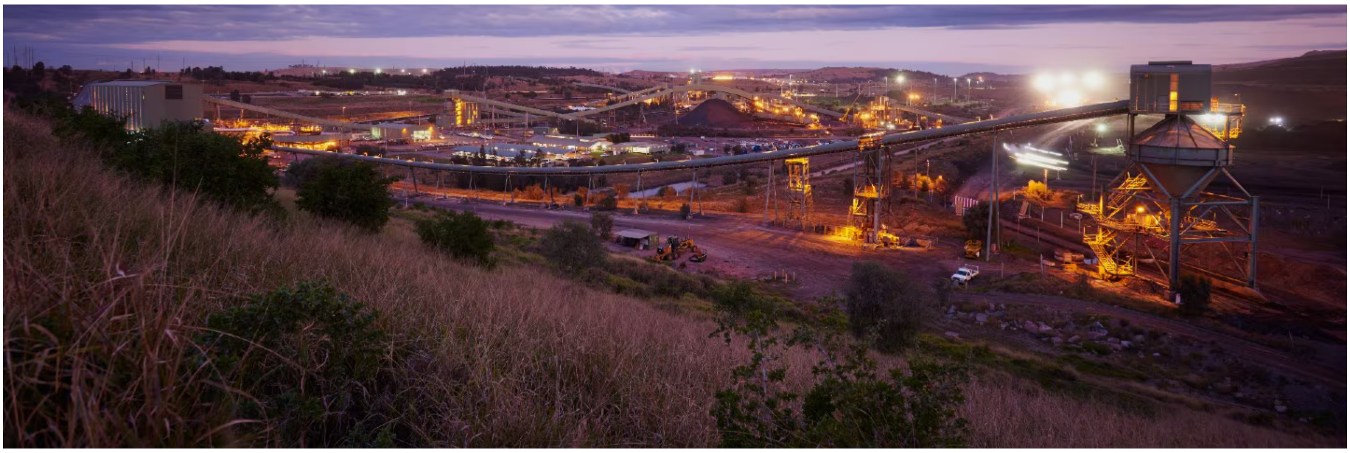

Figure 1.5 – BHP's MAC mine

1.1.6 Truck Operations at Mt Arthur Coal

MAC currently operates 69 T 282 C Liebherr haul trucks (Figure 1.6). Each truck has six tyres (two at the front and four at the rear), with each tyre having an operational lifetime of 4,700 hours.

Figure 1.6 – T 282 C Leibherr Truck

Each truck has a payload capacity of 350 tonnes, with a gross vehicle weight of 600 tonnes when fully loaded, and a maximum speed of 54 km/h [61]. Each of the 69 trucks operates for about 7,300 hours each year (83.3% of the hours in a year). Each of the six tyres on the vehicle is a 50/80R63 Michelin tyre, costing approximately AUD 80,000 apiece. The minor damage repair cost for each tyre is approximately $1,250 per issue, and major damage repair cost is around $5,000 but can increase significantly depending on the damage.

1.2 Motivation

In the last two to three decades, the advent of the digital age has accelerated technological advancements at an unprecedented pace, profoundly transforming all industries, including the mining industry. Despite these significant changes, many areas of the mining industry have been relatively slow to fully harness the potential of new technologies. While there has been notable progress in automating specific mining practices—such as the deployment of self-driving trucks and drone surveillance—strategies for equipment maintenance, in general, have not kept pace with these advancements. This gap underscores the motivation behind creating a thesis that integrates modern technologies into tyre management systems in mining operations, addressing the critical need to enhance operational efficiency, safety, and cost-effectiveness to lower the **ASIC!** (**ASIC!**) for mining operations and improve competitiveness on a global scale, striving to be on the bottom left of the global cost curve.

Modern surface mining operations depend heavily on large, high-value haul trucks, which makes tyre performance and maintenance crucial for operational productivity and safety. Advanced technologies, such as the Internet of Things (IoT), predictive analytics, and real-time monitoring systems, have the potential to revolutionise tyre management. These technologies can provide continuous, precise data on tyre pressure, temperature, and wear, enabling proactive maintenance and significantly reducing the risk of tyre failures, which result in costly downtime and accidents. By implementing such systems, mining operations can improve overall efficiency and safety, ensuring that maintenance strategies evolve in line with technological capabilities.

Furthermore, integrating these advanced technologies supports sustainability initiatives by optimising the lifecycle of tyres, thereby reducing waste and minimising environmental impact. Predictive analytics, for example, can identify potential issues before they become critical, allowing for timely interventions that extend tyre life and enhance resource efficiency. This approach not only aligns with broader sustainability goals but also contributes to substantial cost savings. By leveraging these modern technologies, mining companies can achieve a balance between operational efficiency, safety, and environmental responsibility, fulfilling the industry's demand for technological innovation and sustainable resource management.

This thesis therefore aims to explore and demonstrate the tangible benefits and practical applications of these technologies. It seeks to provide a comprehensive framework for their implementation in tyre management systems within the mining sector and illustrate how modern digital tools can address longstanding maintenance challenges and pave the way for a more efficient and sustainable future in mining operations.

1.3 Problem Statement

The research mine for this project, BHP's MAC, is currently experiencing issues with their haul truck tyres, which are not lasting their full operating lifetime. MAC has been unable to determine the exact cause of this problem due to a lack of passive monitoring of tyres during normal operations. Consequently, tyre management operators cannot identify potential issues with the tyres early enough to take proactive measures to prevent these issues from becoming significant. The current tyre damage tyes include shoulder separation, sidewall bubbles, damaged valve stem, sidewall cuts on steer positions, worn-out belts exposed in the tread, sidewall cuts on rear positions, and tread damage. These issues pose a significant safety risk to all workers within the mine, with unexpected failures potentially having disastrous results for all personnel and equipment involved.

During normal operations, haul truck tyres are inspected every 12 hours by the truck operators in their twice-daily inspection of the vehicle. Any issues found on the tyre's are reported in a report called a 103 form. If a significant issue is detected, the tyre management and maintenance contractor is contacted over a two-way radio to diagnose and provide an assessment of the problem.

The contractor will then either attempt to diagnose the problem over the radio or will have to travel to the truck to make a visual inspection, a round trip that can take 2–3 hours, during which time the truck is not operating. If tyre damage goes unreported, it will only be flagged at the truck's monthly maintenance stop at the workshop, a delay which can result in the issue becoming much more serious. If issues are identified quickly and repair work can be completed while the damage is still considered *minor*, the cost around 25% of a *major* repair. Conversely, if issues are not identified in time, the tyre may need to be scrapped. This represents a significant operating expense that could be avoided with a constant passive monitoring system for the tyres.

Early detection of potential equipment failures is essential for effectively planning maintenance work to minimise downtime. This concept is graphically represented by the Potential failure to Functional failure (P-F) Curve, a reliability engineering and maintenance concept used particularly in industries that involve heavy machinery (mining, manufacturing, and transportation). It illustrates the time between the earliest point at which a potential failure (P) can be detected, and the point at which the equipment fails to perform its intended function (F), as shown in the visual representation in Figure 2.6. The P-F interval is critical for maintenance teams as it provides a window to take corrective actions to prevent failure, thereby avoiding unplanned downtime and associated costs[1].

1.4 Aims and Objectives

This thesis and project focus on creating a tyre management system that clearly communicates key data about tyre issues and degradation to tyre management personnel. By analysing the current system and streamlining the management of this complex issue, the project seeks to provide necessary information about tyre conditions to key stakeholders clearly and concisely. Through this, management personnel will be empowered with the necessary information about tyre condition, overcoming the current system's limitations of incomplete information and excessive bureaucracy, resulting in a meaningful extension of the operational lifespan of the tyres. In fulfilling this aim, the thesis and project will provide both an academic foundation and an industry-tested method for optimising tyre monitoring in a simple, inexpensive, and cost-efficient manner.

[1] This theory is explored in greater detail in Section 2.2

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

i. Evaluate the real-world capabilities of both implemented and theoretical systems for tyre management and explore how reliability-centred maintenance theory can be better incorporated into these systems to enhance cost-efficiency and extend the operational lifespan of tyres.

ii. Explore various tools and research domains that could be integrated into a tyre management system to enhance its effectiveness and efficiency.

iii. Understand in depth the current tyre management method at the research mine, identify the fundamental problems surrounding the current system, and investigate the causes of the issues, methods to prevent them, and reasons why action has not been taken thus far.

iv. Design a system that provides a more efficient, effective, and reliable process for tyre management by:

    a. Increasing the amount of digital information collected on tyres in operation, as well as the frequency of data collection.

    b. Providing a single, easy-to-use, and accessible source for tyre historical data and current condition, with clear notifications for issues as they arise.

    c. Empowering management personnel to take a more proactive approach to extending tyre lifespan and enhancing cost-efficiency through increased data analysis of digitally collected information.

v. Develop the designed system within the research company's current platform and implement it into the research mine to commence real-world testing and operation.

vi. Evaluate the performance of the system and its ability to:

    a. Increase the information available to tyre management personnel.

    b. Increase the digital data collected on tyres across the fleet.

    c. Enable personnel to proactively plan maintenance and replacement more efficiently.

    d. Be quickly integrated into current tyre management systems and begin having a meaningful impact.

1.5 Thesis Outline

The thesis is structured as follows:

Chapter 2: Research and Literature Review

This chapter initially explores the background of the mining industry, with a particular focus on the challenges and opportunities arising from the digital age and its accompanying technological advancements. The field of reliability-centred maintenance is then examined, specifically focusing on optimising maintenance strategies to ensure the reliability, efficiency, and cost-effectiveness of physical assets while aligning with business objectives. The potential role of AI and machine learning (ML) within reliability-centred maintenance is discussed, particularly in relation to collecting large volumes of usable data from machinery, analysing it, and presenting it in an accessible format to key decision-makers on a timely basis. Current methods for gathering and managing data from complex engineering systems are analysed and compared to these advanced potential system uses.

Chapter 3: Methodology

This chapter outlines the current process for tyre management and response employed at the research mine. The procedure is examined to identify critical design considerations that need to be addressed in the development of the new system. The design of the new tyre management system, the ATMS, is then proposed, along with its implementation requirements and timeline. A comprehensive method for enhancing the system, based on an agile project management approach, is outlined. This method ensures the system can be quickly adjusted based on user feedback, optimising it for real-world operations.

Chapter 4: System Implementation and Results

This chapter investigates the outcomes of the research, including a cost-benefit scenario analysis of the potential outcomes from the ATMS implementation at the research mine. It also presents the feedback from the initial presentation to key stakeholders at the mine, and a future implementation plan or framework for the project to be executed when it is most advantageous to Corehesion's business practice.

Chapter 5: Discussion

This chapter provides a reflective analysis of the research outcomes, highlighting both the achievements and challenges encountered throughout the process. It critically assesses the overall impact of the research, including how effectively it addressed the identified gap in the existing body of knowledge. Furthermore, the chapter discusses the broader implications of the findings and how they contribute to advancing the field, as well as potential areas for future exploration. In doing so, it also considers the limitations of the research and offers suggestions for overcoming these in future work.

Chapter 6: Conclusion

This chapter summarises the work conducted throughout the thesis, critically evaluating how effectively the research met its aims and objectives. It also highlights the significance of the contribution made to the broader body of knowledge in this field. Additionally, the chapter explores potential future directions for research, offering a reflection on how subsequent work could build upon the success of the ATMS. This forward-looking discussion emphasises opportunities for further advancements and improvements in both the technological and operational aspects of the system.

Appendix:

To satisfy the requirements of the Engineering Sydney Industry Placement Scholarship (ESIPS), this thesis must include two complete case studies on two units of study which ESIPS formally replaced.

There is also a section which contains seven different reports completed for Corehesion on potential areas of investigation for this project. From these reports, management at Corehesion made a final decision on which thesis topic to pursue towards the end of May with the project work getting underway at the beginning of June.

Also included in the Appendix are; a Work Health and Safety (WHS) report and a practical experience logbook.

The Appendix structure is as follows;

A. Case Study 1 - AMME4710: Computer Vision and Image Processing

B. Case Study 2 - ENGG5205: Professional Practice in Project Management

C. Work Health and Safety Report

D. Potential Thesis Project Scope of Work Investigations

E. Cost-Benefit Analysis Working

F. Practice Experience Logbook

Chapter 2

Research and Literature Review

The following chapter explores key areas of research aimed at enhancing the understanding of academic work conducted in the field, identifying research gaps, and providing deeper insight into relevant topics related to this project. It begins by examining the mining industry's background, with a particular focus on the challenges and opportunities emerging from the digital age. The chapter then discusses reliability-centered maintenance (RCM), a specialised strategy developed for the engineering industry that optimises maintenance to ensure the reliability, efficiency, and cost-effectiveness of physical assets, while aligning with business goals. The potential role of AI and ML within RCM is then explored. A specific investigation of how applications for collecting large volumes of machine data and presenting it to decision-makers is carried out. Current methods for managing data from complex engineering systems are also analysed and compared with advanced approaches.

This chapter will address the following key thesis objectives:

- Evaluate the real-world capabilities of both implemented and theoretical systems for tyre management and explore how RCM theory can be better incorporated into these systems to enhance cost-efficiency and extend the operational lifespan of tyres.
- Explore various tools and research domains that could be integrated into a tyre management system to enhance its effectiveness and efficiency.

2.1 Open-cut Mining Industry Background

The mining industry is currently one of the core pillars of the global economy, providing the raw materials essential for industrial processes, technological advancements, economic growth, and, by extension, continued social development. There are four main mining methods—surface, underground, placer and in-situ [28]. Among these, open-cut mining is particularly notable for its efficiency and cost-effectiveness in extracting resources that are close to the surface and concentrated. This section of the thesis literature review will explore the current position of the mining industry, examine its significance, and discuss the current challenges and potential opportunities it will face in the medium to long term. Through this investigation, a comprehensive understanding of the industry's dynamics will be gained, underscoring the relevance of this thesis' areas of investigation and findings for both the academic field and the industry.

2.1.1 Current Industry Position

As of 2024, the revenue from the top 40 global mining companies was approximately US$845 billion [109], with the estimated value of the global industry ranging between US$1.8-2.3 trillion [33]. The industry significantly contributes to the GDP outcomes of many major economies, including the United States of America, China, the European Union, and Australia. Open-cut mining is the most prevalent method used for mineral extraction, with estimates suggesting that two-thirds of all resources mined come from surface mining [67]. It is mainly used for commodities such as coal, iron ore, gold, and copper.

Technological advancements, including the automation of mining vehicles, digitisation of system processes, and improvements in process and system management, have significantly enhanced productivity, safety, and cost-effectiveness in the industry [92]. Major mining companies, such as BHP, Rio Tinto, and Vale, continue to dominate the global market due to several key factors, including the high capital investment required to enter the market. These companies have successfully leveraged economies of scale, extensive infrastructure, and market position to maintain their competitive edge [92] across the globe.

2.1.2 Importance of the Mining Industry

The importance of the industry can be broken down into the following components [34, 52].

- **Economic Growth:** Mining contributes significantly to its host countries' gross domestic product (GDP) and export revenues. This is evident in Australia, for example, where mining accounts for 14.3% of its GDP and 62.5% of exports [84]. The industry's contributions also extend beyond direct economic output, stimulating growth in other sectors through demand for equipment, services, and infrastructure.
- **Employment:** The sector provides millions of jobs globally, both directly and indirectly. Mining jobs also support local economies, especially in rural areas where mining is typically located, and alternative employment opportunities are limited. The industry employs various levels of skilled workers, from highly specialised engineers and technicians to unskilled labour. In Australia, the mining industry employs approximately 300,400 people as of 2024 [84].
- **Resource Supply:** Essential materials for all industries are sourced from mining, with the industry underpinning all industrial, technological, and social development in the modern global economy [33].
- **Technological Innovation:** Mining is also a key investor and driver of innovation in fields such as geotechnical engineering, environmental science, automation, and data analytics. It has fostered advancements in a wide range of areas that have benefited other sectors.

2.1.3 Challenges Facing the Mining Industry

The mining industry globally is currently facing several significant challenges from various directions, and addressing these issues is a priority for the long-term sustainability of the industry [33, 17, 52].

- **Climate, Social, and Environmental Pressures:** Mining is under severe scrutiny worldwide for its contribution to global greenhouse gas emissions, which range from 4-7% of total emissions [17]. Companies are under increasing pressure from regulators, shareholders, and general populations to decarbonise their operations and demonstrate their contribution to a sustainable future [33]. The social and community impacts of mining operations are also a growing area of focus for stakeholders, with an emphasis on the fair treatment of local communities. Water rights and protection is another significant challenge in this area, particularly in regions struggling with water security, such as the Western United States, Northern Chile, Central Asia, and Eastern Australia.

- **Health and Safety:** Mining is an inherently risky profession, and the health and safety of its employees are given the highest priority. The industry is constantly updating its WHS practices and adopting new approaches, such as digitisation and connectivity, to mitigate risks.
- **Geopolitics:** Geopolitical tensions, particularly the increasing competition between the West and China, the war in Ukraine and the Middle East, as well as the US and EU instability, have all impacted the mining sector. These tensions have led to supply chain risks, increased costs, and significant demand fluctuations.
- **Demand Insecurity:** Fluctuations in commodity prices, uncertain demand, and the threat of product substitution pose challenges to the current mining business model. The transition to renewable energy sources is increasing the demand for minerals required for battery storage and electric devices. Mining companies need to repurpose assets tied to commodities with decreasing demand (e.g., coal), overcome barriers to accessing capital, secure licences to operate, and adapt to evolving demand through scenario modelling and offtake agreements.
- **Constant Innovation and Technological Change:** The rapid pace of technological development presents both an opportunity and a challenge for the industry. Innovations in digital technology are improving productivity, safety, and reducing companies' environmental impact. However, investment in such technology is capital-intensive, with uncertain economic outcomes, but the cost of inaction is greater as competitors gain advantages from such system implementations.
- **Maintenance Skills Shortage:** The mining industry globally is facing a shortage of maintenance skills and talent. This has been exacerbated by the travel restrictions imposed during the COVID-19 pandemic and the industry's perception as unattractive to younger generations [33, 92]. Addressing this skills crisis requires improving working conditions, offering better career development opportunities, and fostering an inclusive and open culture. Remote working and training are also potential avenues for attracting and retaining talent.

2.1.4 Opportunities in the Near Future

Despite the challenges facing the industry, there are also significant opportunities for growth and improvement in the medium to long term. These include [57, 33, 92]:

- **Accelerating Digital Innovation:** Embracing new innovations in the digital space, including advanced data analytics, IoT, AI, and automation, is crucial for mining operations to further streamline systems, enhance safety, improve efficiency, and strengthen competitive edge. Companies that lag behind in the implementation of these systems may risk falling behind their competitors.

- **Increasing Attention to Sustainable Practices:** As environmental responsibility becomes increasingly critical to the mining industry, investment in sustainable practice development has the potential to not only reduce operational costs but also place mining companies at the forefront of technological development in this area.

- **Adapting to Fast-Changing Regulations:** Mining industry regulations, particularly environmental, social responsibility, safety, and labour rights regulations, are rapidly changing in many countries. Ensuring that companies stay ahead of these regulations could give them an edge over competitors that are slow to implement changes and, therefore, incur higher costs.

- **Diversifying Amid Slowing Demand for Traditional Metals:** The demand for traditional materials such as coal is set to decrease in the medium to long term as the transition to renewable energy shifts demand to other areas. This shift presents opportunities for companies to diversify into other minerals as quickly as possible.

- **Capitalising on the Growing Demand for Battery and Electric Materials:** The rise of electric vehciles (EV)s and the electrification of industries will continue to drive strong demand for minerals required for both batteries and other technologies, such as lithium, cobalt, nickel, and manganese. There is an opportunity for mining companies to invest sufficiently in the supply of these materials now to meet future demand and prepare for the potential shortfall in their supply.

2.2 Reliability-Centered Maintenance

RCM, as defined by Nowlan and Heap, is "a scheduled-maintenance programme designed to realise the inherent reliability capabilities of equipment". The reliability of an asset refers to the probability of the asset being able to meet its desired performance standards in yielding output for a specific duration when used under specific conditions [126]. Reliability ($R(t)$) can be mathematically defined as:

$$R(t) = 1 - Probability\ of\ Failure \tag{2.1}$$

Since the mid-1950s, maintenance strategies have changed significantly, due to the rapid increase in both the number and variety of highly complex engineering systems required by modernising industries [78]. These changes have involved a shift away from performing maintenance tasks after equipment failure has occurred to attempting to pre-empt failure and fix issues before they lead to an asset being unable to function correctly [126]. A failure can be defined as an event that results in the inability to complete the required duties and meet the requirements.

RCM focuses on identifying and addressing potential failures of systems before they can cause damage. This is conducted with the aim of minimising unplanned down time (DT) (which is significantly more expensive than planned DT) and optimising the usage of maintenance resources. The core of RCM is the act of balancing the cost of maintenance with the cost of failure. The methodology assesses the consequences of different parts or sub-system failures and then prioritises maintenance tasks based on the weighing of these consequences. For instance, failures that will have a significant operational impact will necessitate proactive tasks to ensure the failure does not occur, thus preventing secondary damage and reducing repair costs. The approach of building a model to achieve this involves detailed analysis of large amounts of data and employing analysis tools such as the P-F curve. This enables asset degradation over time, from a condition of high resistance to failure to low resistance to failure, to be predicted and key points where maintenance should be performed to avoid functional failures identified [78, 14, 126].

Recently, RCM has been transformed by developments in sensor and computational modelling, with real-time data from a vast array of sensors able to be collected and utilised by ML models. This has enabled continuous monitoring and dynamic adjustments of maintenance schedules based on an asset's current performance and condition. Predictive Maintenance (PdM) tools, such as vibration analysis and thermal imaging, have allowed for early detection of wear and tear in areas not accessible by non-destructive testing (NDT), ensuring that timely interventions can take place. These advances, combined with established RCM frameworks, provide a comprehensive approach to maintaining large numbers of assets reliably and cost-effectively for businesses [51, 80].

Maintenance Strategies

Maintenance, as defined by Moubray, involves "ensuring that physical assets continue to do what their users want them to do" [78, p.g. 6]. Maintenance strategy can be classified into one of two major areas: corrective or preventive maintenance. The selection of a maintenance strategy will be conducted based on several factors, including "cost of DT, redundancy, and items' reliability characteristics" [21, p.g. 603].

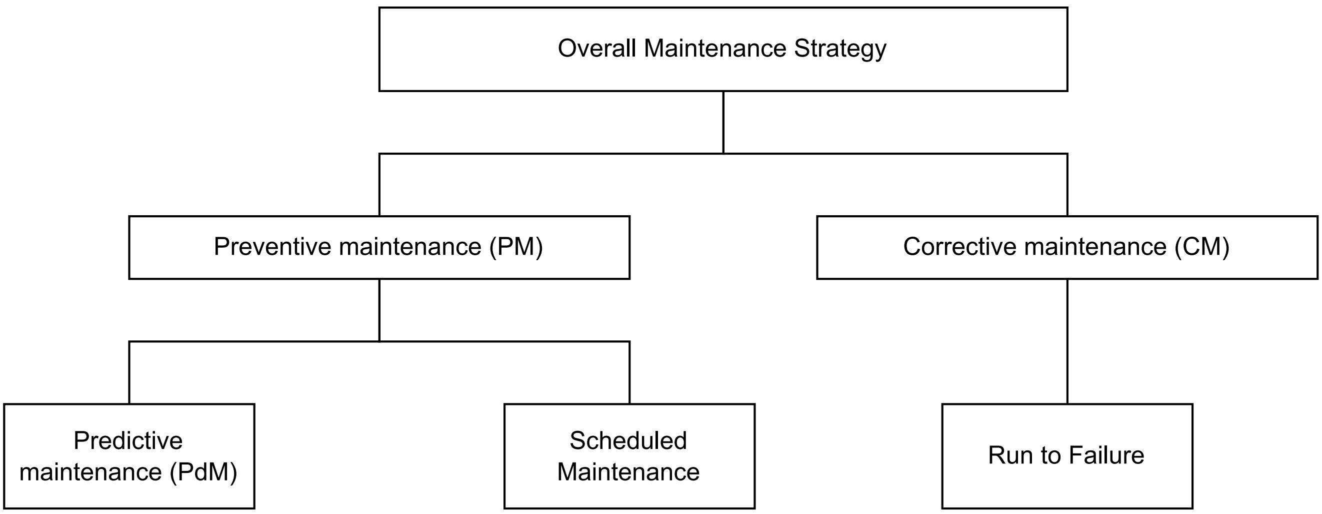

Figure 2.1 – Different maintenance strategies [51]

Preventive Maintenance

Preventive Maintenance (PM), as described by Christer Stenström and Kumar, is "maintenance carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of items" [21, p.g. 603]. PM aims to maintain equipment in optimal working condition by replacing identified worn components and making any adjustments necessary to avoid functional failures.

Predictive Maintenance

PdM, as described by Montero Jimenez et al., "focuses on the organisation of maintenance actions according to the actual health state of the system, aiming at giving a more precise indication of when a maintenance intervention will be necessary" [76, p.g. 539]. It employs condition-monitoring tools and techniques to identify early signs of potential failure, enabling maintenance operators to plan interventions accurately. This use of real-time data and trend analysis to predict optimal maintenance timing enhances asset reliability, cost efficiency, and safety [51, 80].

Corrective Maintenance

Corrective Maintenance (CM), as described by Christer Stenström and Kumar, is maintenance "carried out after a fault has been recognised; it is intended to put the failed item back into a state in which it can perform its required function" [21, p.g. 603]. CM is a reactive maintenance approach where maintenance work is only initiated when equipment experiences functional failure (e.g. malfunctions or breaks down) and addresses issues as they arise.

For an organisation, finding the most efficient ratio between PM and CM is a complicated process that is specific to its operating environment. There is a significant lack of research in balancing these two strategies; however, a generally accepted balance in most industries is an 80/20 split between PM and CM, which follows the Pareto principle [120]. The Pareto principle, first postulated by Vilfredo Pareto in 1906, illustrates the fact that 80% of the problems in a system stem from 20% of the causes.

2.2.1 History of RCM

Up until the 1950s, the maintenance of machinery was primarily considered a craft, acquired through extensive experience, with minimal focus on systematic prioritisation or developing effective strategies beyond the expertise of maintenance professionals. However, as engineering systems became increasingly complex in the post-war era, maintenance costs associated with these systems began to rise sharply, along with a growing demand for a large number of highly skilled and knowledgeable technicians [82, 14].

By the late 1950s, escalating costs within maintenance departments created a financial incentive for industries to overhaul their maintenance strategies and investigate new methods of operation. The airline industry led this shift due to the increasing complexity of aeroplanes and the critical emphasis on safety. Initial studies on industry operating data contradicted many fundamental assumptions underpinning traditional maintenance practices and deviated from established industry norms [30, 14].

One of the first major assumptions to be questioned was the theory of a direct cause-and-effect relationship between operational reliability and scheduled maintenance. This principle posited that because mechanical parts wear out, the reliability of any equipment was directly related to its operational age, implying that more frequent overhauls would better protect systems against failure. However, studies disproved this belief by showing that the reliability of many systems was not solely dependent on their operational age [82, 30, 14]. In aircraft maintenance, it was initially assumed that all reliability issues directly impacted operational safety. The studies revealed, however, that many types of failures could not be prevented, regardless of the intensity of maintenance activities. This realisation, coupled with the increasing complexity of technology, necessitated a shift in focus from merely preventing failures to ensuring that failures did not compromise operational safety or integrity [82, 14].

Out of this necessity for a fundamental change in maintenance approaches, RCM was developed. RCM, as defined by Moubray, is "*a process used to determine the maintenance requirements of any physical asset in its operating context*" [78, p. 7]. This systematic approach to maintenance strategy for large-scale industrial applications focuses on maintaining system functionality rather than merely preventing equipment failures. RCM was originally proposed and developed by Nowlan and

Heap in their 1978 work "Reliability-centered maintenance" [82], who developed the theory within the aviation industry for United Airlines. Since the 1970s, RCM has been adapted to most heavy industries, including manufacturing, power generation, transportation and mining. This section provides a comprehensive examination of RCM, encompassing its historical development, key principles, implementation methodologies, the P-F curve, and its impact on organisational performance.

RCM was first developed in the United States for their commercial aviation industry due to the demand for greater efficiency in the maintenance strategy of airline operations. The seminal work completed by Nowlan and Heap [82] provided the foundational framework that refocused operations from reactive to preventive maintenance. This work emphasised building a detailed understanding of a system's function and identifying potential failures to devise maintenance strategies optimised for reliability, safety and cost efficiency.

Further works, such as those by Moubray, Siddiqui and Ben-Daya, and Darragi et al., adapted the initial work of Nowlan and Heap to other non-aviation industries, expanding the application of RCM. Since the onset of the Industrial Revolution in the late 18th century, engineering systems have been subject to continual evaluation and have witnessed an exponential increase in complexity. This surge is attributable to technological advancements and evolving industrial demands. According to Selbe, this growing complexity shows no signs of abating, as "the capabilities of our current engineered systems are expanding exponentially, pushing the boundaries of what was previously deemed achievable" [101, p.g. 39].

2.2.2 Development of Complexity within Engineering Systems

Since the onset of the First Industrial Revolution in the second half of the 18th century, engineering systems have been subject to continual evaluation and have witnessed an exponential increase in complexity. This surge can be attributed to technological advancements and evolving industrial demands. According to Selbe, this growing complexity shows no signs of abating, as "the capabilities of our current engineered systems are multiplying exponentially as the complexity of these technologies push the limits of what was previously considered possible" [101, p.g. 39]. This section will explore key developments in the growing complexity of engineering systems, tracing their evolution from the onset of the Industrial Revolution to the introduction of smart systems, the IoT, and the emergence of AI and ML. This development can be separated into four distinct Industrial Revolutions, as highlighted by Figure 2.2.

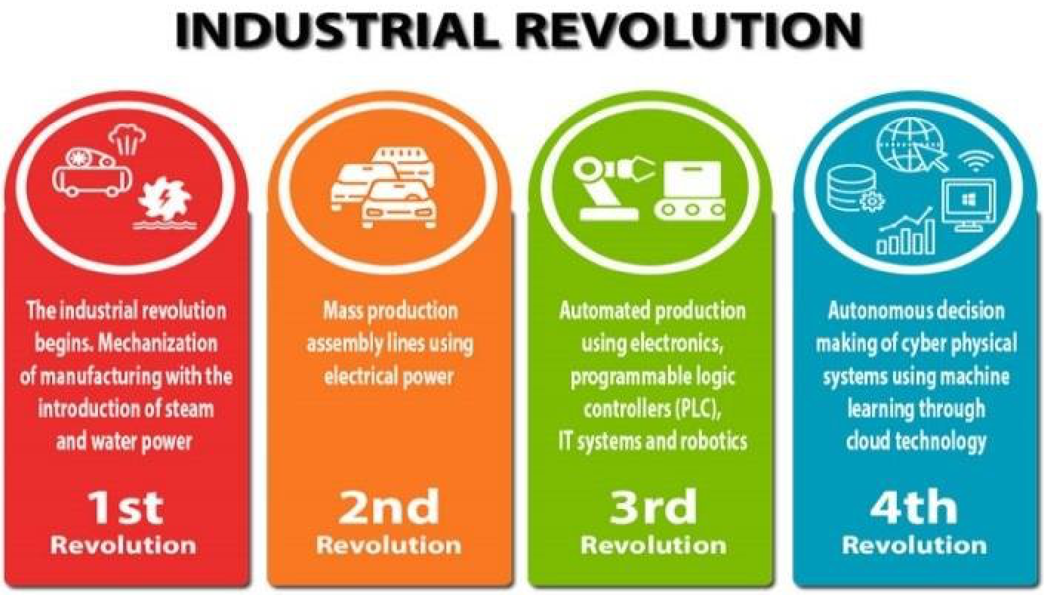

Figure 2.2 – The four Industrial Revolutions [53]

The First Industrial Revolution: The Birth of Modern Engineering

During the second half of the 18th century, the First Industrial Revolution occurred, beginning with groundbreaking technological developments such as steam power in Britain. This shift introduced widespread use of machinery in industry, transforming society from agriculture-based to industrial. Steam power replaced human, hydraulic, and animal labour, and powerful machines took the place of manual tools and simple mechanisms, leading to the consolidation of home-based, scattered workshops into large-scale factories. The transition from manual labour to mechanised production significantly increased productivity and efficiency in major industries.

Key innovations of this era that facilitated this change included [32, 23]:

- **Steam Engines:** The development of the steam engine by James Watt and others revolutionised transportation and the manufacturing of goods, as well as providing a reliable and powerful source of energy for various applications.

- **Mechanisation:** The introduction of machinery, such as the power loom and spinning jenny, replaced manual labour, leading to the establishment of large factories and the widespread mass production of everyday goods.

The advent of complex engineering systems led to the creation of a specialised engineering field focused on the repair and maintenance of these systems when they malfunctioned. Historically, maintenance was generally carried out by operators trained not only in the operation but also in the basic upkeep of their equipment. However, as the need for technical expertise among average factory workers diminished, this responsibility was transferred to trained engineers who understood the intricacies of the systems. At this stage, reliability engineering was in its nascent stages, with maintenance practices primarily reactive, addressing issues as they arose rather than implementing any preventative strategies [32].

The Second Industrial Revolution: Mechanisation and Electrification

The Second Industrial Revolution, which began in the late 1860s and continued until the early 20th century (1860s–1914), ushered in significant advancements in industrial development with the introduction of electric power, steel production, automobiles, and aircraft. This era significantly enhanced the industrial structure, scale, and general living standards, while adding layers of complexity to the engineering systems that underpinned it [74].

Key innovations from this era included [32, 74]:

- **Electrification:** The widespread adoption of electricity in both industry and homes facilitated the development of complex electrical systems such as power generation and distribution networks, necessitating new engineering approaches to manage electrical power safely and efficiently.

- **Automobiles and Aviation:** The growth of personal transportation, specifically through automobiles and aviation, posed sophisticated engineering challenges. The development of the internal combustion engine, which incorporates thousands of moving parts within a compact space, demanded advancements in design, manufacturing, and maintenance techniques.

During the Second Industrial Revolution, reliability engineering began to emerge as a distinct discipline, separate from the broader development of engineering systems. The increasing demand for more reliable and safe electrical and mechanical systems led to the development of systematic maintenance practices and the initial use of statistical methods to predict performance and enhance reliability.

The Third Industrial Revolution: Electronics and Information Technology

The Third Industrial Revolution, which began in the mid-20th century following the conclusion of WWII, was characterised by the rise of electronics, information technology, and automation, all of which significantly increased the complexity of engineering systems. This revolution marked an unprecedented shift in the management of information, placing it at the centre of the economy, in contrast to power, which was the cornerstone of the first and second revolutions [38].

Key innovations from this era included [38, 32]:

- **WWII Innovations:** The technological demands of the Second World War, followed by Cold War competition, led to rapid advancements in cutting-edge technology, including radar, jet engines, and early computing systems. These innovations laid the groundwork for today's modern electronic, control, and transportation systems, which are significantly more complex than earlier engineering advancements.
- **Transistors and Integrated Circuits:** The invention of the transistor and the subsequent development of integrated circuits sparked the electronics revolution, enabling the miniaturisation of electrical components and increasing their reliability.
- **Computing and Information Technology:** By the end of the Third Industrial Revolution, the proliferation of computers and the advent of the internet transformed engineering practices. Increasingly complex software systems and the invention of tools such as computer-aided design (CAD) enabled more sophisticated designs of individual components, a higher degree of integration between different subsystems, and enhanced analysis and simulation of systems.

This revolution necessitated significant advancements in the field of reliability engineering. The integration of computing power enabled more sophisticated analysis, modelling, and simulation techniques, while improvements in data collection and analysis tools enhanced predictive maintenance strategies. During this period, RCM as an engineering concept was first proposed and developed [1], and the focus on RCM and total productive maintenance (TPM) [2] became more prevalent [38].

The Fourth Industrial Revolution: Cyber-Physical Systems and IoT

The Fourth Industrial Revolution, which we are currently experiencing (beginning in the early 2010s), is characterised by the convergence of physical and digital technologies. As noted by Schwab, the World Economic Forum Founder and Executive Chairman, in his 2016 book titled *The Fourth Industrial Revolution*, "We are witnessing profound shifts across all industries, marked by the emergence of new business models, the disruption of incumbents, and the reshaping of production, consumption, transportation, and delivery systems" [100, p.g. 7]. This revolution has been marked by the advent of cyber-physical systems, the IoT, AI, and a significant increase in the complexity of engineering systems [90, 100].

Key innovations from this era include [90, 100, 91]:

- **IoT and Connectivity:** The IoT can now connect a vast array of devices, systems, and subsystems, enabling real-time data collection, processing, and analysis. This large-scale connectivity has led to the development of smart grids, intelligent transportation systems, advanced manufacturing processes, and more.
- **AI and ML:** The integration of AI and ML into engineering systems has enabled the development of advanced predictive maintenance, autonomous systems, and significant advancements in data analytics. These technologies require complex algorithms and substantial computational power, further adding to the complexity of any engineering system.
- **Cyber-Physical Systems:** The convergence of the physical and digital worlds in cyber-physical systems has facilitated the creation of intricate networks of sensors, actuators, and control systems. These are used in highly advanced engineering ecosystems such as smart cities, autonomous vehicles, and sophisticated robotics.

[1] See Section 2.2.1

[2] According to Chan et al., "TPM is a methodology that aims to increase the availability of existing equipment, thereby reducing the need for further capital investment" [19, p.g. 71]

In this latest industrial revolution, reliability engineering has evolved to incorporate a suite of advanced technologies, including IoT, AI, and ML. These technologies now enable continuous monitoring and real-time analytics of all systems, allowing for far more accurate predictions of equipment failure and more effective maintenance strategies. The focus is now on developing engineering systems that are not only reliable but also adaptable and resilient to changing conditions [100, 91].

The escalating complexity of engineering systems across the three previous Industrial Revolutions, as well as the current one, reflects the impact of rapid technological advancements in this field. It also highlights the increasingly crucial role

2.2.3 The Evolution of Maintenance

Since the 1930s, the evolution of maintenance can be split into four generations, with each successive generation redefining how maintenance is viewed given increased expectations, regulations, and safety standards. These generations highlight the shift from reactive to proactive maintenance strategies that have occurred over the last 90 years.

The First Generation

The first generation of maintenance strategy, referred to as reactive or "breakdown" maintenance, was prevalent until the 1950s, including both the build-up to and execution of World War II. During this period, the industry was not particularly mechanised, and therefore DT was not as consequential to operational effectiveness. As a result, preventing equipment failure was not a high priority, with most equipment at the time being relatively simple and over-designed. Consequently, the equipment was reliable and easy to repair, with no need for systematic maintenance beyond basic servicing, lubrication, and cleaning. The focus of maintenance was on restoring the functionality of machines as quickly as possible to minimise DT. Skill requirements for maintenance workers were also lower [78].

The Second Generation

During WWII, wartime investment in technology, combined with wartime pressures for increased production with limited industrial manpower, resulted in increased mechanisation of industries. By the 1950s, industry was beginning to depend on an ever-increasing number of new and complex machinery that substituted labour at lower cost and greater efficiency. As this dependence grew, equipment DT became a larger concern, leading to the development of PM theory, which hypothesised that preventing equipment failures through smaller, frequent repairs would be more efficient.

In the 1950s and 1960s, this consisted mainly of equipment overhauls aimed at reducing the likelihood of failures by performing regular inspections, servicing, and part replacement. While PM was an improvement on a reactive approach to maintenance, it was often costly and inefficient. Components were frequently replaced while still in operational condition, and unnecessary maintenance actions were performed to maintain schedules. With the cost of maintenance continuing to rise relative to other operational costs, and businesses having increasing amounts of capital tied up in fixed assets, the industry began to invest significantly in *maintenance planning and control systems*. These specialised teams focused on cost-effective methods of maintaining the operational integrity of machinery while maximising the life of assets [78, 51].

The Third Generation

The third generation of RCM, which spans from the mid-1970s until the early 2000s, saw major changes as maintenance strategies became increasingly important across industries. These changes can be classified under the following three categories: *new expectations*, *new research*, and *new techniques* [78, 51].

New Expectations
As investing in better maintenance strategies became an efficient way to reduce operational costs and increase productivity, there were growing expectations about what could be delivered. These included [78]:

- **Reduced downtime:** The effects of downtime became increasingly aggravated by the shift to just-in-time systems. This change led to increased demands on maintenance strategies to decrease asset downtime and schedule it more effectively across industries.

- **Increased safety:** With increasing oversight from regulatory bodies and decreasing acceptance of workplace injuries as a normal part of operation, maintenance strategies had to adjust their methodology to ensure the safety of equipment was prioritised.
- **Cost of maintenance:** In the 30 years from the first to third generation, the cost of maintenance in absolute terms and as a percentage of overall operation costs had risen significantly. In some industries, it had become the highest operating expenditure, and thus cost control became a high priority for businesses.
- **Increased reliability and availability:** The growth of mechanisation and automation during this period also resulted in reliability and availability becoming key issues across sectors such as healthcare, data processing, and telecommunications.

New Research

New research during this period changed many basic beliefs in the industry about age and failure. It dispelled the assumed connection between the operating age of assets and the likelihood of failure. The first generation's view of failure was based on the simple understanding that as assets aged, they were more likely to fail. The second generation introduced the concept of "infant mortality" as a major failure point (Figure 2.3 and 2.4).

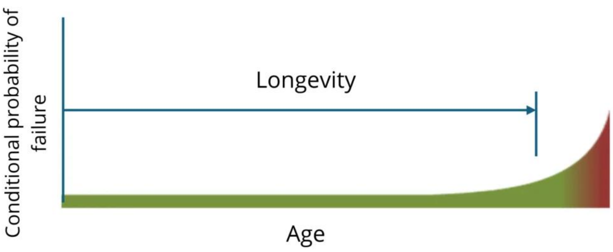

Figure 2.3 – 1st Generation failure pattern [48]

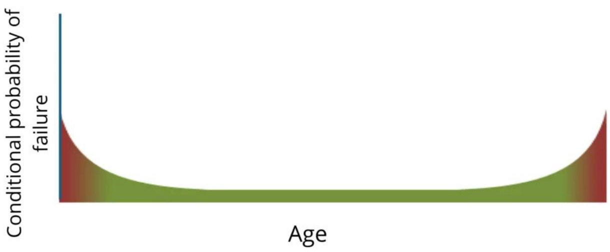

Figure 2.4 – 2nd Generation failure pattern [48]

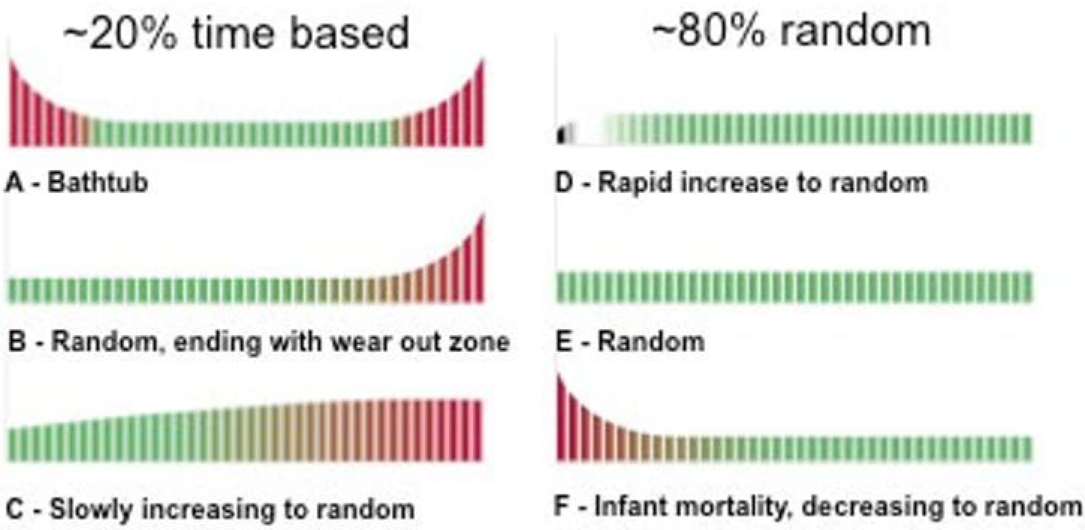

Figure 2.5 – 3rd Generation failure patterns [119]

Third-generation research revealed that six different failure patterns occur in practice, each with differing probabilities (Figure 2.5). Each failure pattern requires a different method of management to prevent functional failure. However, failures can be categorised as either random (80

New Techniques

During the third-generation period, there was explosive growth in concepts, techniques, and technologies applicable to reliability maintenance. Integration of RCM with other management systems, such as enterprise asset management (EAM) and computerised maintenance management systems (CMMS), created a more holistic approach to asset management by connecting individual maintenance strategies to broader organisational goals and operations.

The Fourth Generation

The fourth generation, often referred to as advanced RCM, has incorporated significant advancements in information technology tools, such as the IoT, AI, and ML, to further enhance maintenance strategies. This generation has been characterised by the following developments [91]:

IoT Integration: Utilising sensors and IoT-connected devices allows for continuous monitoring of the condition of equipment and predicting failures with high accuracy. This technological shift has enabled real-time data acquisition and processing, enhancing the predictive capabilities of maintenance programs.

AI and ML: Applying AI and ML algorithms to analyse large datasets generated by IoT devices helps identify patterns that precede failures (potential failure recognition). These technologies refine predictive maintenance schedules and optimise maintenance tasks based on actual equipment conditions rather than predefined schedules, leading to better cost efficiencies.

Decision Support Systems: Advanced decision support systems have been developed to assist maintenance managers in making informed decisions by providing insights derived from integrating data with other business intelligence resources.

Sustainability and Energy Efficiency: Maintenance strategies now incorporate sustainability goals, focusing not only on maintaining equipment reliability but also on reducing environmental impact and improving energy efficiency.

2.2.4 Recent Advancements in RCM and Future Trends

Within the past decade, significant advancements in the capabilities and reductions in the cost of advanced sensor technologies have greatly increased the application of real-time monitoring within advanced engineering systems. Within this period, extensive studies have been conducted into using prognostic methods based on the increasing amount of sensor information on components to determine their remaining useful life (RUL) [102]. Utilising prognostic information has been shown to increase the efficiency of maintenance planning, resulting in more information being used to make decisions for single-component systems [124, 126]. However, as modern engineering systems become increasingly complex, along with dynamic operational environments and a growing number of inter-dependencies between subsystems, maintenance optimisation models built on single-component systems are no longer an effective tool [102].

2.2.5 RCM Process and Principles

RCM Basic Questions

The RCM process, according to Moubray, revolves around seven core questions about the asset or system that is under review [78, p.g. 7].

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

RCM Process Steps

A typical RCM process will broadly include the following 5 steps, which aim to identify and manage potential failures with the end goal of preserving system function.

1. **Function Identification**: This step identifies and documents the functions of individual components of a system (both primary and secondary functions), performance standards, and operational requirements. This understanding is crucial in establishing the responsibilities of each component, its limits, and the impact of its failure [82, 14].
2. **Failure Mode Identification**: Once a complete understanding of a system is compiled, potential areas of failure, called *failure modes*, are then identified. This involves determining how a specific component or subsystem may fail or be unable to perform its intended function

completely. Failure modes can occur due to several reasons, including but not limited to operational wear and tear, environmental conditions, design flaws, unforeseen stresses, etc. [82].

3. **Failure Effect Analysis**: Once potential failures are identified and categorised, the next step is to investigate the effect of the failure modes on the operational integrity of an engineering system. This includes effects on system performance, safety, and operational efficiency. The goal of this step is to understand how a failure mode will impact the system and what potential measures can be implemented to mitigate these effects [30].

4. **Failure Management Strategy**: An appropriate maintenance strategy for managing a system is developed in this step. The maintenance tasks outlined in this strategy will include preventative maintenance, predictive maintenance, and corrective actions. The development process will aim to balance operational effectiveness, safety, and cost to ensure all resources are utilised as efficiently as possible while mitigating risk [82].

5. **Implementation and Continuous Review**: Finally, after the implementation of a strategy, a continuous monitoring process and review system should be set up to ensure that implemented maintenance strategies remain effective and can be adjusted in real-time based on current performance data and changing conditions [30].

Key Principles of RCM

RCM is underpinned by several key principles aimed at optimising the efficiency, reliability, and safety of assets. These principles follow the primary goal of RCM, which is to preserve system functionality and thereby ensure that assets perform their intended operations within design parameters [30, 82].

1. **Preserve System Function**: The primary goal of RCM is to preserve system functionality, even in the face of potential individual component or subsystem failures. This means that an asset can continue to perform its intended operational role within specified design parameters [82].

2. **Identify Failure Modes**: A critical aspect of RCM is identifying all possible paths to system failure in terms of its functional requirements. Understanding these failure modes is key to designing and developing an effective maintenance strategy [82].

3. **Analyse Failure Effects**: Assessing the consequences of component or subsystem failures ensures that maintenance actions are prioritised appropriately based on their impact on system performance and safety. This principle ensures failures are triaged according to their potential impact [14].

4. **Prioritise Based on Criticality**: Maintenance actions must be prioritised according to the criticality of the failure mode in relation to system function. This ensures resources are focused on the most significant risks, making maintenance efforts, budgets, and time as effective as possible [14].

5. **Select Effective Maintenance Tasks**: It is essential to select maintenance tasks that effectively address a failure mode while being cost-efficient. This ensures that maintenance tasks provide the highest possible value based on the inputs [30].

6. **Use Condition-Based Monitoring**: Implementing condition-based monitoring allows for real-time tracking of a system's health. This facilitates the use of predictive maintenance techniques, enabling maintenance interventions to be scheduled before a failure occurs [14].

7. **Ensure Continuous Improvement**: Continuous evaluation and improvement of maintenance strategies is vital to adapt to changing conditions and new data. This ensures maintenance practices remain effective over time [82].

8. **Focus on Safety and Compliance**: All maintenance practices must adhere to safety and regulatory standards. These requirements must be integrated into the design stage of maintenance strategies. Procedures must be in place to ensure ongoing compliance with current regulations [14].

2.2.6 The P-F Curve and its role in Reliability Centred Maintenance

The P-F Curve is a well-documented concept from the reliability engineering field, serving as a model for understanding and managing asset degradation. Since its inception, it has been adapted to various industries (primarily involving heavy machinery) and combined with modern predictive maintenance techniques and technologies. As a result, it has evolved into a broad framework that integrates various maintenance and reliability engineering concepts, which can complicate its application in maintenance strategy [51].

Definition

The P-F Curve is a graphical representation used to identify the point at which a potential failure can be detected or identified (P) and the point at which the failure becomes evident (F). The P-F Interval is the time difference between these two points, indicating the number of operational hours the machine can continue to operate after detection before a functional failure occurs. The P-F interval is critical for planning maintenance activities, as it provides a window to take corrective actions before a potential failure has an operational impact [51, 83].

The P-F Curve graphically represents a part's degradation over its operational lifespan (X axis), from the point of high "Resistance to Failure" to low (Y axis). See Figure 2.6. It is important to note that the Y axis measures an item's resistance to any possible failure. With increasing age, the part becomes less able to resist failure when stressed, until the point it fails to perform its role to the required specifications [51].

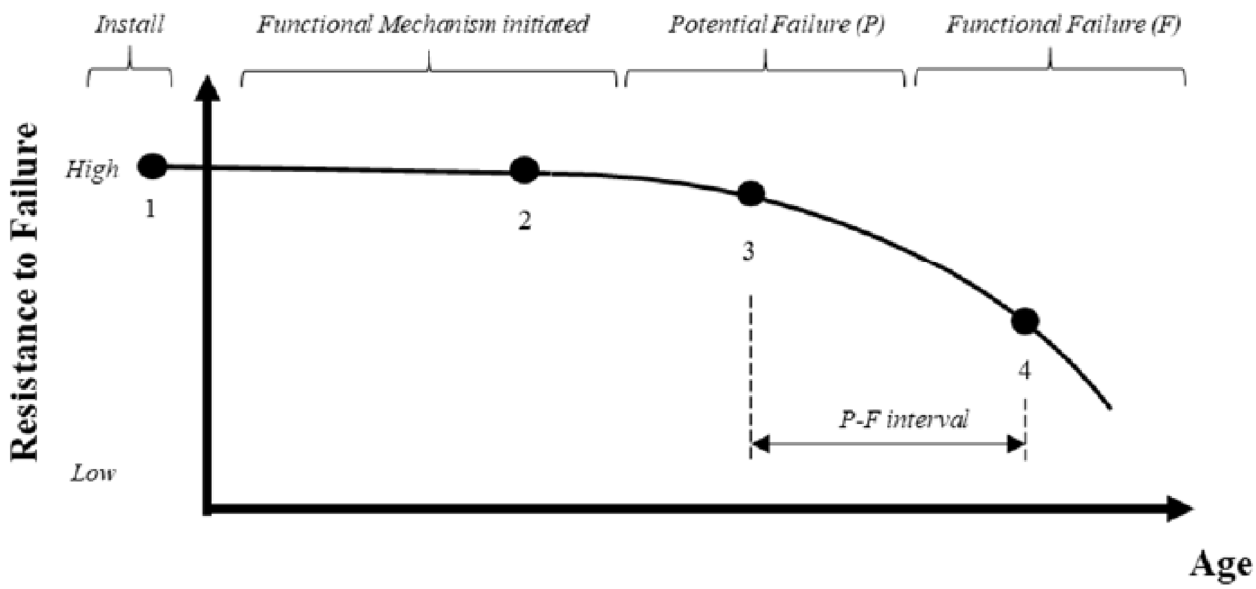

Figure 2.6 – PF Curve with a P-F Interval [51]

In the context of reliability maintenance, a failure, as described by Nowlan and Heap, is "an unsatisfactory condition" [82, p. 12], implying that while the part may not be broken, it is in such a condition as to cause sub-optimal operating conditions within a system. From this understanding, a definition of a Potential Failure can be established as an "identifiable physical condition which indicates a functional failure is imminent" [82, p. 13]. A Functional failure, as defined by Nowlan and Heap, "is the inability of an item (or equipment containing it) to meet a specified performance standard" [82, p. 12].

Detection of Failures

In evaluating the potential failures within items, accurate detection and consistent reporting are essential first steps. Detection can be broken down into two main areas [82];

1. The operator/sensing equipment must be in a position to detect a potential failure. This refers to physical location, timing, and access to the correct inspection equipment.
2. The operator/sensing equipment must have the training and capability to recognise either a potential or functional failure in an item.

Role of P-F Curve in RCM

RCM utilises the P-F Curve to ascertain the optimal timing for maintenance intervention on a particular subsystem. By analysing both an asset's overall position on the **P-F Curve!** (**P-F Curve!**) and each of its subsystems' positions, maintenance teams can effectively plan predictive and preventive tasks to prevent functional failure. This results in enhanced asset reliability and reduced downtime [80, 14].

Importance of the P-F Curve in Maintenance Strategy

Predictive Maintenance: The P-F interval is crucial in predictive maintenance, where continuous monitoring of equipment conditions is done using various data gathering and analytics tools. The goal is to detect signs of degradation early and predict when a failure might occur, based on real-time data.

Cost Efficiency: By effectively utilising the P-F interval, organisations can optimise their maintenance schedules, reducing unnecessary routine checks and focusing resources only when there is a likely need. This approach can significantly lower maintenance costs and extend the lifespan of equipment.

Safety and Reliability: Maintaining equipment within the P-F interval enhances the safety and reliability of operations. This is particularly important in industries where equipment failures can pose serious safety risks and lead to significant operational disruptions.

Techniques for Determining P-F Interval

Condition Monitoring: Techniques such as vibration analysis, thermography, and acoustic monitoring help detect anomalies in machinery that may indicate an impending failure.

Data Analysis: Advanced data analytics, including machine learning models, are used to analyse historical and real-time data to predict the P-F interval more accurately.

Failure Modes and Effects Analysis (FMEA): This systematic approach helps identify potential failure modes in a system and their causes and effects, supporting the determination of critical P-F intervals.

Modern Advancements in P-F Curve Applications

In the last decade, advancements in data analytics and ML have enhanced the applicability of the P-F Curve. Utilising modern monitoring methods, which enable continuous updating of an asset's curve based on real-time data, has significantly increased the potential application of this theory [51, 83]. As stated by Josebeck and Gowtham, "an efficient maintenance program is one which is continuously being optimised by using new performance data" [51, p.g. 3]. Historically, continuously monitoring assets and plotting new curves based on updated data would not have been cost-effective for operations; however, with the rise of Industrial Internet of Things (IIoT), small, cheap sensor equipment can monitor asset performance and report back instantaneously. Leveraging this data, usually collected from a fleet of similar assets, can then be used to remove initial variability inherent in all designs and establish a reliable baseline P-F Curve with an interval that should work in most operating conditions [51, 30].

ML Framework A framework for implementing a ML system for a P-F Curve is given in Figure 2.7. The 'parameters' used in the model are "detectable-defining-characteristics" [51, p.g. 3] of a potential failure mode. The 'inputs' are the current operating conditions of the asset. The P-F interval predicted by the ML algorithm can then be used to modify the inputs (F_b), e.g. changing when maintenance tasks occur, the priority of different work orders, or a change in the amount/frequency of data collected. Based on this information, additional parameters (F_c) that will influence a failure mode can be added to the model. The outcome for different maintenance actions can also be fed back into the P-F interval generated to validate the model using (F_a).

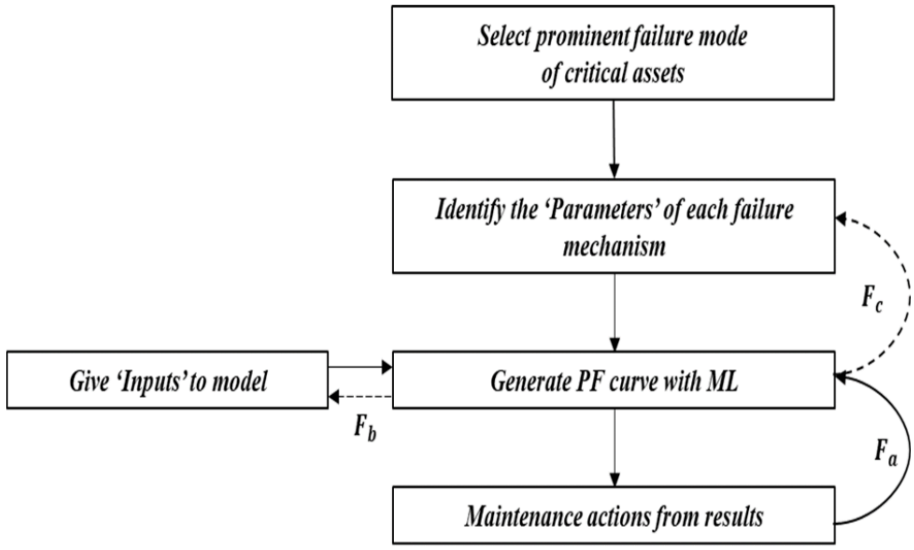

Figure 2.7 – P-F Curve plotting Machine learning framework [51]

Utilising ML to generate a P-F Curve effectively removes the problems historically associated with this method, which included; curves not being updated regularly enough, curves not fully capturing failure modes, or curves not capturing enough information to represent a system accurately [51].

Dynamic P-F Curves: ML algorithms can analyse the increasing amounts of operational data available from modern assets to continuously refine their P-F Curve, providing more accurate predictions of potential failure occurrences. This dynamic approach allows maintenance teams to plan tasks with up-to-date information, reducing the risk of unplanned downtime [51, 30].

Multivariate P-F Curves: P-F Curves that incorporate multiple parameters such as temperature, load, and usage patterns enable operators to gain a more comprehensive understanding of asset degradation. This approach provides insights into complex failure modes that require modelling multiple inputs accurately, thereby enhancing model accuracy [51]. As seen in Figure 2.8, the use of a multivariate regression P-F Curve approach can better predict the accurate **P-F Curve!** of an asset. Combining data collected from different failure modes can establish a more accurate P-F Curve for the asset.

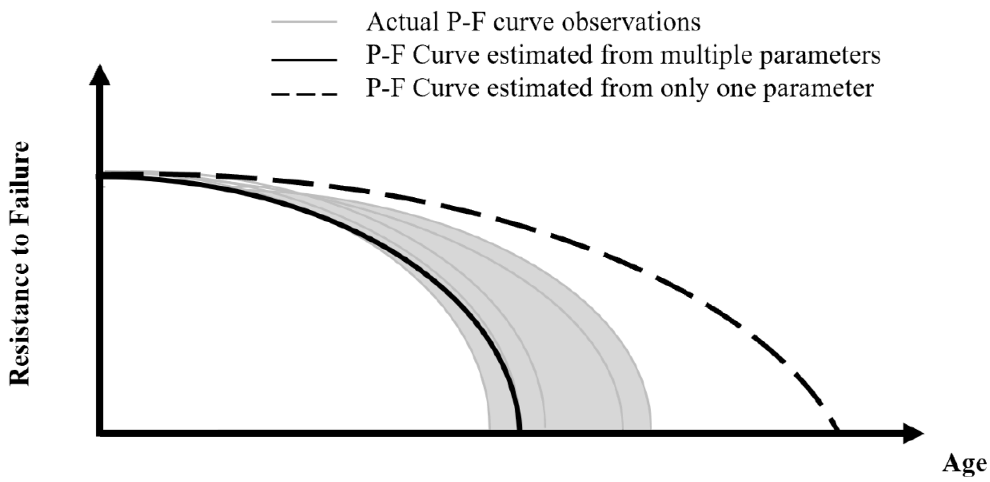

Figure 2.8 – Multivariate Regression used in a P-F Curve [51]

Potential Issues with Implementing Machine Learning for P-F Curves

During the development of ML algorithms to build P-F Curves, Josebeck and Gowtham suggests that developers keep in mind the following aspects, which if not seriously addressed, could significantly affect the outcome of the system.

- *Choice of failure mode and parameter:* When determining failure modes and parameters, criticality analysis methods should be implemented to identify the correct dominant failure mechanisms of an asset.
- *Data integrity:* Ensure that the data used to train the ML model is gathered correctly and has not been corrupted.
- *Using the correct algorithm:* Maintenance operators need to decide what type of algorithm is used (classification, regression, etc.).
- *Integrating with the Maintenance Program:* Unless the ML algorithm is integrated into the decision-making chain used by an operation, its effectiveness will be limited. Alerts raised or actions suggested from the P-F interval analysis must be implemented by the maintenance team.

2.2.7 RCM Cost-Benefit Analysis

Christer Stenström and Kumar, in their 2015 article "Preventive and Corrective Maintenance - Cost Comparison and Cost-Benefit Analysis," outlined the following method to determine the cost of both PM and CM maintenance. They then described how to conduct a cost-benefit analysis of PM to determine the balance between PM and CM for an organisation.

CM Cost

To calculate the cost of CM over a given time interval, the following data must be incorporated: service/production loss, logistic time (LT), repair time (RT), and materials. Christer Stenström and Kumar, in calculating the CM cost, assumed that finding/noticing a failure was at zero cost.

$$C_{CM} = \sum_{i=1}^{n} (n_{P,i} C_P 2t_{LT,i} + t_{RT,i} + C_{M,i} + t_{DT,i} C_{DT}) \tag{2.2}$$

where n is the number of functional failures; n_p is the maintenance team size (personnel required); t_{LT} is the LT for travelling/moving the asset one way; t_{RT} is the RT for the asset; t_{DT} is the service time lost due to the failure; C_P is the monetary cost for personnel; C_M is the cost of materials; and C_{DT} is the cost of production loss due to DT.

PM Cost

Similar to CM, the cost of PM over a given time interval can be calculated by considering the same data.

$$C_{PM} = C_P \left(\sum_{i=1}^{m} n_{P,i} t_{PM,i} + \sum_{j=1}^{k} n_{P,j} [t_{AT,j} + 2t_{LT,j}] \right) + C_{PMM} + C_{PMDT} \tag{2.3}$$

where m is the number of inspections carried out and potential failures repaired; k is the number of trips taken between the workshop and the item's location in the field; t_{PM} is the amount of active PM time; t_{AT} is the preparation and administrative time; C_{PMM} is the cost of materials for PM; and C_{PMDT} is the cost of production lost due to DT.

Cost-Benefit Analysis

A cost-benefit analysis (CBA) is, according to Christer Stenström and Kumar, "a decision-making procedure for comparing costs and benefits of activities, like projects and policies. [Its objective] is to support decision-making and make it more rational and thus, to have more efficient allocation of resources" [21, p.g. 605]. Using a B/C (benefit-cost) ratio, the value of PM can be calculated to determine whether the investment in the process is worthwhile.

$$B/C = \frac{B_{PM}}{C_{PM}} = \frac{\alpha\beta\bar{C_F}}{\bar{C_I} + \alpha\bar{C_R}} \tag{2.4}$$

where B_{PM} is the benefit from PM; $\bar{C_F}$ is the mean cost of the functional failure; $\bar{C_I}$ is the mean cost of inspections carried out; $\bar{C_R}$ is the mean cost of potential failure repairs conducted; α is the probability of detection (POD) of a potential failure with $\alpha \in [0, 1]$; and β is the potential-to-functional failure likelihood with $\beta \in [0, 1]$.

The mean cost of functional failure ($\bar{C_F}$), the mean cost of inspections ($\bar{C_I}$), and the mean cost of potential failure repairs $\bar{C_R}$ can be determined from the following equations.

$$\bar{C_I} = \frac{1}{m_I}\sum_{i=1}^{m_I} c_{I,i} = \frac{1}{m_I}C_{PMI} \tag{2.5}$$

$$\bar{C_R} = \frac{1}{m_R}\sum_{i=1}^{m_R} c_{R,i} = \frac{1}{m_R}C_{PMR} \tag{2.6}$$

$$\bar{C_F} = \frac{1}{n}\sum_{i=1}^{n} c_{F,i} = \frac{1}{n}C_{CM} \tag{2.7}$$

where c_I is the cost of inspecting an item; c_R is the cost of potential failure repairs of an item; c_F is the cost of functional failure repairs of an item; m_I is the number of inspections; and m_R is the number of potential failures.

The POD can be calculated by using the number of potential failures and the number of inspections. These inspections are classified as NDT, with inspections commonly carried out in the form of visual inspections. The α represents the fraction of items (parts, sub-systems, or systems) inspected that do not meet the functional requirement level of the asset.

$$\alpha = \frac{m_R}{M_I} \tag{2.8}$$

2.2.8 RCM Implementation Strategy

The method of effectively integrating an RCM strategy into an existing operation can be broken down into two main phases: the implementation process phase and maintaining/updating processes over the program lifetime [30].

Implementation Phase

The implementation phase of an RCM strategy will typically consist of four main steps [30]:

1. **Planning for RCM:** The process begins with understanding the goals of the system implementation and selecting an approach and subsequent technical methods that best suit the pursuit of those goals. In this step, technical and administrative procedures are established, and adequate resources required to pursue the selected approach must be obtained.
2. **RCM technical work:** Apply the different technical approaches selected in the first step. These can include, but are not limited to, collecting and analysing asset data, establishing data collection and storage systems, identifying required maintenance tasks, developing technical results through system analysis (e.g., P-F curve development), and documentation.
3. **Technical review of RCM results:** Based on a comprehensive review of the processes built, updates and modifications are identified and applied. All necessary changes to procedures and other activities are carried out.
4. **RCM results implementation:** Based on the final results from the implementation phase and using efficient administrative procedures (which are essential to effective RCM implementation), the system is launched. The success of the process and its accuracy in mapping out maintenance tasks are closely related to how this final stage is executed. It is important to ensure adequate training of personnel, redundancy planning for systems, and that all documentation is carried out to a high standard to give the system every chance of success.

Maintaining/Updating Phase

The second phase of implementing an RCM strategy is building a consistent structure that can maintain the program and make updates whenever necessary. The main objectives of this phase are [30]:

- Ensure design changes and procedures are fully applied to the preventive maintenance program.
- Collect experience from systems and operators and make changes based on their recommendations (assuming these recommendations are valid and effective).
- Maintain documentation.

To achieve these objectives, some essential points in the implementation of phase two are [30]:

- Implement periodic monitoring of the maintenance experience from all levels of the organisation to review the RCM strategy's effectiveness.
- Maintain all RCM analyses conducted in control documents so they can be referred back to.
- Produce an annual report on the maintenance strategy for review.

2.3 Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) are pivotal fields in modern technology, driving advancements across various industries. Strong defines AI as "intelligence exhibited by an artificial entity to solve complex problems" [110, p.g. 64]. AI is "a broad area of computer science that explores how to make machines function more like a human brain" [2, p.g. 1], or to put it more simply, it is the development of computer systems that can perform tasks typically reserved for humans due to the intelligence required.

On the other hand, ML, as defined by Jo, is "the computation paradigm where the capacity for solving the given problem is built by previous examples" [50, p.g. 3]. It is the process of solving real problems by learning from previously trained examples. This section delves deeply into the fundamental theories and principles underpinning AI and ML, exploring how these technologies operate and investigating the current industry and research understanding of the topics. This investigation aims to determine both how these technologies can be applied to mining practices and the subsequent gaps in the literature within this application area.

2.3.1 History of Artificial General Intelligence

The concept of Artifical general intelligence (AGI), introduced in the 1950s, was the root of modern-day AI. AGI, as described by [85], "refers to the ability of a machine to perform any intellectual task that a human can do" [85, p.g. 1]. However, during this time period, due to limits in computational power and other technologies, the dream of AGI could not be realised.

Initially, due to the complexity of human intelligence and the vast amounts of data processing required to replicate it, research focused on developing narrow AI, which is designed to perform specific tasks. These developments can be seen in the rise of ML in the 1990s, a clear subfield of AI research. From the ML field came the development of deep learning in the 2010s, a process that utilises neural networks to process complex data and make decisions that appear 'intelligent'. This development had a major impact on AI research, as did the introduction of graphics processing unit (GPU)s, which provided the computational power to train large-scale neural networks. Deep learning algorithms, inspired by the functioning and structure of the human brain, can analyse data and extract meaningful insights. They also form the basis for tasks such as natural language processing, image recognition, and speech synthesis [85, 64, 68].

Currently, following the introduction of Chat-GPT3 in November 2022, AI has begun to be seen as a revolutionary tool within the wider community. Investment in AI startups is at an all-time high, and there is a growing emphasis on the development of general-AI, which aims to create systems with human-like cognitive abilities.

2.3.2 Artificial Intelligence: An Overview

AI is a broad field of research and development encompassing various subfields and approaches which aim to create systems that are capable of performing tasks that typically require human intelligence and time to complete. AI can be broadly categorised into three distinct levels [64, 85]:

1. **Narrow AI:** Also known as 'weak AI', is designed and trained to perform specific tasks due to the development of algorithms and large datasets. Current narrow AI system examples include Apple's Siri, Amazon's Alexa, and Google Assistant. Limitations of this form of AI lie

in its inability to generalise knowledge across different areas or domains, and it can sometimes produce erroneous results due to queries being outside its scope of operation.

2. **General AI:** Also known as 'strong AI', represents the concept of systems that possess the ability to understand, learn, and apply knowledge across a broad range of tasks, akin to human cognitive capabilities. This level of AI aims to replicate human-level intelligence and reasoning beyond the narrow specific domains of narrow AI. While the development of General AI is currently underway across the world, no system has yet been able to develop an operational model that fits the criteria. OpenAI's Chat-GPT-4, Meta's Llama3.1, and Google's Gemini are examples of systems that are coming close to this level of intelligence. Applications for such systems are vast, from research and development in a multitude of fields to automation and implementation across all industries to aid workers in increasing productivity.

3. **Superintelligent AI:** This is a hypothetical form of AI that can surpass human intelligence and capabilities in every field. A system like this would possess a greater understanding and ability to solve complex problems than a human. This level is still the subject of ongoing research and ethical debates across the world.

According to Mulla, "AI programming focuses on three cognitive skills: learning, reasoning, and self-correction" [79, p.g. 1] [64].

- **Learning:** This is the process of acquiring data and developing algorithms that define how the system will turn the data into actionable information.
- **Reasoning Processes:** Developing the capability for the system to choose the right algorithm to reach the desired outcome in each instance.
- **Self-Correction:** The ability for the system to continually update and improve its defining algorithms. This allows the system to learn from its errors and ensure that its accuracy increases over time.

2.3.3 Machine Learning: An Overview

Machine Learning is a subset of AI and computer science that, according to IBM, "focuses on using data and algorithms to enable AI to imitate the way that humans learn, gradually improving its accuracy" [47, p.g. 1].

According to [15], the learning system of a ML algorithm can be broken into three main parts [47]:

1. **A Decision Process:** A 'recipe' of calculations and/or other steps that are taken with the data to determine the kind of pattern the algorithm is looking to find.
2. **An Error Function:** A method to measure how accurate the guesses of the decision process are by comparing its output to known examples. It determines whether the decision process made the right choice. If it did not, it provides a quantifiable measurement of 'how off' the decision was.
3. **An Updating or Optimisation Process:** The algorithm looks at the decisions it missed or areas where it failed to perform optimally and updates the decision process accordingly, so it performs better next time.

There are many types of machine-learning models; however, they can be classified into four main subtypes [15, 68, 47]:

1. **Supervised Learning:** The model is trained on a pre-labelled dataset to allow the algorithm to compare its output with each example's answer to assess accuracy.
2. **Unsupervised Learning:** The model is given a raw dataset, and the algorithm identifies its own patterns and relationships within the data without outside input from users.
3. **Semi-supervised Learning:** The datasets provided contain both raw and structured data, guiding the algorithm without giving it all the answers. In this way, the model is able to make independent conclusions while still being guided by the labelled data.
4. **Reinforcement Learning:** The dataset uses a "rewards/punishment" system, offering feedback to the algorithm in a way that allows it to learn from its own experiences.

Common Machine Learning Algorithms

There are a number of ML algorithms that are commonly used by modern companies. Each algorithm can have many different applications depending on how it is set up and the task it is required to do [15, 47].

- **Neural Networks:** Neural networks simulate the way the human brain works, with a huge number of linked processing nodes. Neural networks are good at recognising patterns and play an important role in applications including natural language translation, image recognition, speech recognition, and image creation.
- **Linear Regression:** This algorithm is used to predict numerical values based on a linear relationship between different variables. For example, the technique could be used to predict house prices based on historical data for the area.
- **Logistic Regression:** This supervised learning algorithm makes predictions for categorical response variables, such as "yes/no" answers to questions. It can be used for applications such as classifying spam and quality control on a production line.
- **Clustering:** Using unsupervised learning, clustering algorithms can identify patterns in data so that it can be grouped. Computers can help data scientists by identifying differences between data items that humans may have overlooked.
- **Decision Trees:** Decision trees can be used for both predicting numerical values (regression) and classifying data into categories. Decision trees use a branching sequence of linked decisions that can be represented with a tree diagram. One of the advantages of decision trees is that they are easy to validate and audit, unlike the black box of a neural network.
- **Random Forests:** In a random forest, the machine learning algorithm predicts a value or category by combining the results from a number of decision trees.

2.3.4 Business AI Implementation Strategy

To most effectively take advantage of AI, businesses should first develop an implementation strategy with subject matter experts. This strategy will define how AI will be integrated into an organisation and provide a framework for all future development. Without such a strategy, organisations could miss out on fully taking advantage of the potential benefits of AI or implement systems that do not effectively operate with current business practices and existing infrastructure [37, 95].

Steps for Building a Successful AI Strategy

Based on IBM's experience and expertise in this area, they suggest the following steps for implementing a successful AI strategy [37, 15].

1. **Explore the Technology:** Develop an understanding of various AI technologies, including generative AI, ML, natural language processing, computer vision, etc. Research how these can be applied to relevant industries and the benefits that can be gained.

2. **Assess and Discover:** Understand the organisation the system will be implemented into, its priorities and capabilities. Focus on its IT department's strengths, weaknesses, and expertise.

3. **Define Clear Objectives:** Clearly define the issues the organisation needs to solve and identify metrics that will be used to measure this performance.

4. **Identify Potential Partners and Vendors:** Find companies in the AI and ML space that have a history of working within the industry of investigation. Create a list of potential tools, suppliers, and partnerships that could be beneficial and prioritise procurement based on the implementation timeline.

5. **Build a Roadmap:** Develop a roadmap that focuses on early successes that will create value quickly and address practical needs. Determine the tools and support required based on what is critical to the project, including:

    - *Data:* Make a data strategy that outlines whether new or existing data will be required to fuel the solution and establish a governance framework.

- *Algorithms:* Determine who will deploy algorithms and design, develop, and test models, and how they will accomplish this.
- *Infrastructure:* Identify where the system will be hosted and how it will be scaled.
- *Talent and Outsourcing:* Assess the readiness of the business and identify skill gaps within the organisation that need to be filled.

6. **Present the Strategy:** Present the strategy to key stakeholders and gather feedback. Focus on how it aligns with business objectives and clearly communicate the benefits, costs, and expected outcomes.
7. **Begin Training and Encourage Learning:** Start upskilling employees or hire individuals required for the implementation.
8. **Establish Ethical Guidelines:** Understand the ethical considerations for AI implementation and develop guidelines on the company's position.
9. **Assess and Adapt:** Ensure to regularly assess the efficiency and usefulness of the system and stay up to date with any new developments in the space, including products. Continue to adapt based on these developments.

Integrating AI as a method for innovating an operation's business model was investigated by Reim et al. in their 2020 work entitled "*Implementation of Artificial Intelligence (AI): A Roadmap for Business Model Innovation*". This work suggested an implementation method using the four key steps outlined below (see Figure 2.9).

1. **Understand AI and organisational capabilities:** Understanding AI's characteristics will be the foundation for implementation within a business. This is particularly important for upper management so they can produce a conceptual framework for how AI can be used within their business model (BM). This step should also include questions such as: Do we need to further develop or refine current capabilities? Where would be the most impactful position to implement AI in our current operations?

2. **Understand the current BM, potential for business model innovation (BMI), and business ecosystem role:** Clearly understand how the current BM delivers value to customers, including all processes, key roles, and value creation within the business. From this understanding, potential areas for BMI can be identified, focusing on increasing the value creation of the business's product.

3. **Develop and refine capabilities needed to implement AI:** Understand the business's current ability to implement AI, including employee skill levels, IT department expertise, and management's ability to understand and take advantage of the value added by BMI. Decide which AI strategy the firm would like to take based on its skill level: either as a first developer in the industry (developing a new in-house method of implementation) or as a first follower (focusing on using off-the-shelf products tailored to current business needs). Evaluating surrounding firms can aid in developing both technical and strategic solutions in this area.

4. **Reach organisational acceptance and develop internal competencies:** Work with the organisation to ensure acceptance at all levels of the business during the implementation phase. This can be achieved through initiatives such as executive pilot projects, the foundation of AI teams, and organisation-wide AI training. These programs mitigate the risk associated with misunderstanding the technology and help to build trust and widespread use of the system.

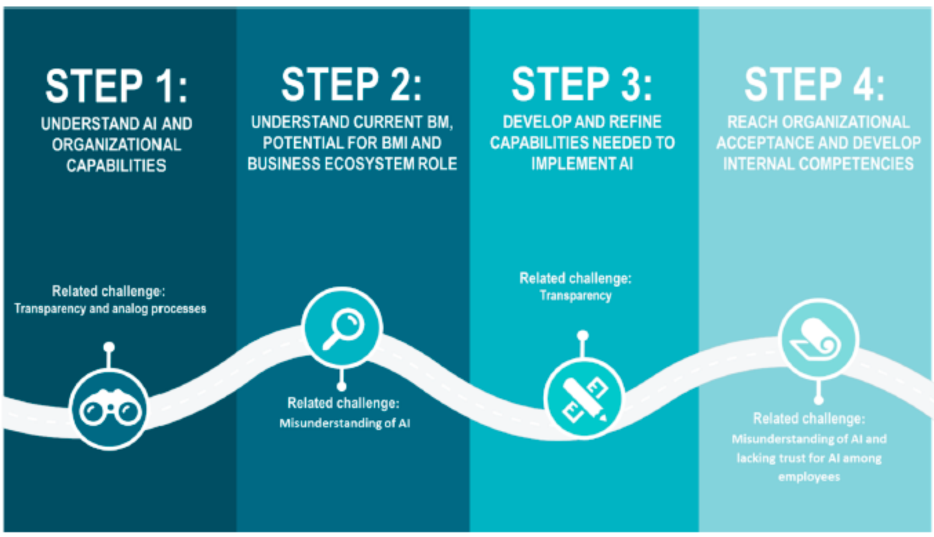

Figure 2.9 – Roadmap for AI Business Model Implementation [95]

Both methodologies focus on understanding a business's requirements and using a common-sense, practical approach to AI within a business model. They also highlight the need for training personnel on how to effectively make use of the new technology.

2.3.5 Image Recognition and Current Market Tools

According to Yascar, image recognition is "the ability of software to identify objects, places, people, writing, and actions in digital images. Computers can use machine vision technologies in combination with a camera and AI software to achieve image recognition" [123, p.g. 1]. Image recognition technology has become widely used in various areas, including text recognition, object classification, people flow monitoring, and illegal photo identification [122]. This section will investigate image recognition technology, including research into theoretical foundations and identification of current on-market practical solutions for companies looking to implement image recognition into their business model. The aim is to understand how image recognition works and identify the right tool to use within a tyre management system.

The general process for image recognition involves image pre-processing, image feature extraction, and image classification. Image pre-processing focuses on improving the accuracy of image recognition by enhancing useful information within an image and removing noise and interference. Image feature extraction transforms an image from what is classed as a 'non-image' description (numerical representation, vector description, etc.) into a low-dimensional feature description. Image classification is performed based on the features extracted from the image, and the image is recognised based on the classification decision [60].

Theoretical Foundations of Image Recognition

Within image recognition, there are two main categories: traditional image recognition algorithms based on image processing and new image recognition algorithms based on AI. Traditional image recognition algorithms take a long time and cannot achieve real-time processing or high levels of accuracy. However, the advent of AI-based image recognition has allowed for fast, simple, and efficient systems to be developed to learn more advanced imagery [122].

AI image recognition relies heavily on deep learning, a branch of ML derived from artifical neural networks (ANN), which attempts to simulate the pattern of passing and processing of information between neurons in a biological brain. Supervised and unsupervised learning are the two main categories of deep learning (classification is based on whether data is labelled or not). Supervised learning includes convolutional neural networks (CNN) and recurrent neural networks (RNN), while a common unsupervised learning model is generative adversarial networks (GAN) [60].

Convolutional neural networks

CNNs are one of the most widely used models in image recognition. Their advantage lies mainly in avoiding a large amount of feature extraction work in pre-processing, thereby simplifying the steps within this section. The model, according to Li, "is based on the assumption of local correlation and feature repetition of the image" [60, p.g. 994], or in other words, the assumption that a pixel is more correlated with its neighbour than with others further away. This results in avoiding a large number of parameters that are usually necessary for full connectivity [20].

Recurrent neural networks

RNNs are specially designed for either time-series data or sequential data problems. Unlike traditional neural networks, RNNs introduce the concept of temporal recurrence in which signals do not immediately vanish after travelling between neurons. In RNNs, the input of a hidden layer neuron in the network contains the output of the neuron in the previous layer and also the output of the hidden layer neuron generated from the prior input. Essentially, this means that the network has a memory function that can process sequential data, as in this type of data, the previous data point has a significant influence on the later one [123, 60].

Generative adversarial networks

GANs are a type of unsupervised model first proposed by Goodfellow et al. in 2014. GANs consist of two models, a generative model G and a discriminative model D, which use a game approach to optimise the models as they compete with each other. The real sample data is captured using the G model, and new data samples are generated from it. The D model is then a binary classifier that estimates the probabilities of the samples inputted into it, which are from the training samples. Unlike traditional generative algorithms, GANs only use backpropagation, which is much more efficient compared with earlier Markov chain models. Therefore, GANs can be applied in a wide range of areas within image processing as a result [60, 43].

Current Market Tools

Given that this thesis is focusing on the implementation of a market-ready solution for tyre management, investigating the current tools available is an important step. This section will look at the current industry leaders to determine which is the most viable solution to implement. The three platforms investigated will be Google's Cloud Vision AI and Microsoft's Azure AI Cognitive Services. Both platforms can be accessed through application programming interface (API)s [3] and can therefore be seamlessly integrated into an existing software platform.

Google Cloud Vision AI

Google Cloud Vision AI offers a number of computer vision products that could be suitable for this task, including:

- *Cloud Vision API:* A quick and easily integrated product for basic vision features.
- *Visual Inspection AI:* Used for automating visual inspection tasks in manufacturing and industrial settings (Little to no additional expertise required).
- *Vertex AI Vision:* Building and deploying custom models for specific needs (Additional expertise required).

Visual Inspection AI

This product, according to Google, is a "purpose-built, deep learning algorithm-based model for high-precision manufacturing inspections."

[3] An API, according to Goodwin, "is a set of rules or protocols that enables software applications to communicate with each other to exchange data, features, and functionality" [44, p.g. 1]

Its suggested use cases include:

- Manufacturing inspection tasks, addressing a wide range of use cases across automotive, electronics, semiconductor, and industrial sectors.
- Welding seam inspection.

Microsoft's Azure Custom Vision

Azure Cognitive Services offers a suite of APIs for different services, including image analysis, spatial analysis, optical character recognition, and facial recognition [69], and allows for customisable vision models based on requirements.

2.4 Data Collection and Management in the Mining Industry

Data collection and management have always been integral parts of the mining industry, significantly influencing operational efficiency, safety, and environmental sustainability. With the advent of the 4th Industrial Revolution (see Section 2.2.2) and advancements in digital technologies, including IoT, AI, and ML, the mining sector is undergoing a significant transformation in how data is collected, processed, and utilised. This section will explore the importance of data in the mining industry, various data collection methods, challenges in data management, and future trends and opportunities. The aim is to understand in-depth the strategies and technologies used within the industry to identify gaps in current operations and research.

2.4.1 Importance of Data in the Mining Industry

Data plays a crucial role in the mining industry for several reasons [3, 118]:

1. **Operational Efficiency:** Data-driven insights allow for real-time monitoring and increased optimisation of operations, reducing downtime and enhancing productivity. Effective data management can significantly improve the efficiency of mining processes, enabling better planning, execution, and resource allocation.

2. **Safety Improvements:** Continuous data collection through sensors and monitoring systems that enable live data updating helps detect potentially hazardous conditions, aiding in accident prevention and ensuring worker safety. The integration of data from various sources and its collation in a central network enhances the predictive capabilities of safety systems, allowing for proactive measures to mitigate risks.

3. **Sustainability:** Accurate data on the current condition of mineral deposits and environmental conditions aid in efficient resource extraction while simultaneously minimising the mine's environmental impact. Sustainable practices in mining are supported by widespread data collection and analysis, ensuring onsite engineers and specialists can comply with environmental regulations and reduce the ecological footprint of mining activities.

4. **Regulatory Compliance:** Comprehensive data management and extensive collection can be used to ensure adherence to environmental regulations and reporting requirements. Regulatory bodies have increasingly demanded more reporting on the industry's compliance, which has necessitated more detailed and widespread data gathering across operations as well as management systems to ensure compliance is maintained.

2.4.2 Challenges in Data Management

Despite the huge potential for increased data collection and efficient management within mining operations, its implementation and development still come with significant challenges for the industry [75, 3, 16]:

1. **Data Integration:** Integrating data sourced from a wide range of gathering methods, including geological surveys, remote sensing, and sensor networks, is a highly complex task. Current mining systems usually stop short of full integration due to the capital cost and time required for minimal return on investment. However, with the advent of advanced AI, full integration at economically viable costs is now a more realistic possibility. Operations that achieve this quickly will gain a competitive advantage in terms of efficiency, safety, and cost-effectiveness.

2. **Data Volume and Velocity:** The vast amounts of data generated on a modern mine site require robust storage and processing solutions. Due to the sheer volume and high velocity of

data, scalable and efficient data management infrastructures are necessary. A challenge also arises when accounting for various systems (e.g., different haul truck companies having different data storage requirements) that must be integrated into the storage system.

3. **Data Quality:** Ensuring data accuracy, completeness, and consistency is critical for data management systems to provide reliable analysis and decision-making. Poor data quality can lead to erroneous conclusions and inefficient decisions. Integrating systems to rigorously validate data, while time-consuming, will pay off with long-term reliability and cost-effectiveness.

4. **Regulatory Compliance:** Managing data required for compliance with regulatory requirements involves regular audits and reporting on gathering and storage methods. Compliance with increasingly complex environmental and safety regulations necessitates well-documented and planned data management practices to ensure transparency and accountability.

2.4.3 Recent Technological Developments in Data Management

Within the past 20-30 years, as the 4th Industrial Revolution has begun to impact all industries within the global economy, data management has been one of the most heavily influenced areas. Several newly developed technologies have the potential to significantly improve data management practices and capabilities within the mining industry [94, 31, 16, 75, 3];

1. **Big Data Analytics:** Tools for processing and analysing large datasets uncover patterns, trends, and insights, supporting predictive maintenance and resource optimisation. Over the last 2-3 decades, the development of accessible data management tools, such as Microsoft's SQL Server, has led to a significant leap in companies' ability to manage billions of data points.

2. **Cloud Computing:** Cloud-based platforms provide scalable and flexible storage for large data sets at relatively low costs, as well as processing solutions. Cloud-based operations also facilitate remote access and real-time analysis by teams across the world, offering cost-effective and scalable solutions for managing large volumes of mining data and supporting real-time data processing and analysis.

3. **Internet of Things (IoT):** IoT devices collect real-time data from equipment and the environment, uploading this data directly to central data management facilities either onsite or in operations centres through cloud computing. This massive increase in available information on assets and conditions at mining sites can enhance operational efficiency and safety. IoT technologies enable the seamless integration of various data sources, providing a comprehensive view of mining operations and enhancing predictive maintenance capabilities.

4. **Machine Learning (ML) and Artificial Intelligence (AI):** These technologies can be integrated with the massive amounts of data gathered to analyse it in real-time, allowing predictions of equipment failure, optimisation of resource extraction, and improvements in strategic decision-making (see Section 2.3).

2.5 Summary of Findings

2.5.1 Open-cut Mining Industry Background

The open-cut mining industry is a critical source of the raw materials required for the modern global economy and contributes significantly to GDP and employment in economies such as the United States, China, the European Union, and Australia. As of 2024, the global mining industry is valued between US$1.8-2.3 trillion, with the top 40 global mining companies earning US$845 billion in revenue. Open-cut mining remains the dominant method of mineral extraction and is responsible for two-thirds of global production. Leading companies such as BHP, Rio Tinto, and Vale have been able to maintain a competitive advantage in the industry through economies of scale, high capital investment, and technological advancements, including automation and digitisation, which have resulted in improved productivity, safety, and cost-effectiveness of operations. In Australia, mining accounts for 14.3% of GDP, 62.5% of exports, and employs approximately 300,000 people nationwide. It is a key driver of innovation in fields such as geotechnical engineering, environmental science, automation, and data analytics.

The industry is currently facing several challenges, including environmental and social pressures, increased scrutiny from regulators on health and safety, geopolitical tensions, demand fluctuations, and a global shortage of skilled workers in key roles. Additionally, mining's contribution to global emissions is increasingly under scrutiny, with companies—especially publicly traded ones—facing mounting pressure from regulators and society to decarbonise operations and adopt more sustainable practices. Technological development, although offering many potential benefits, requires heavy investment with uncertain returns.Despite the challenges, the industry has numerous opportunities for growth. Accelerating the adoption of digital technologies such as IoT, AI, and automation can lead to more streamlined operations, improved safety for workers, and enhanced cost efficiency. The transition to renewable energy sources has also increased demand for minerals used in battery storage and electric vehicles, offering the potential for diversification. By capitalising on these trends and embracing technological advancements, mining companies can position themselves for long-term success.

2.5.2 Reliability-Centered Maintenance

This section of the chapter provided a comprehensive overview of RCM, tracing its evolution and development as a result of the increasing complexity of engineering systems to recent advancements and future trends of the theory based on technological development. Key principles, including the P-F Curve, were analysed, as well as a comprehensive method for building a cost-benefit analysis to determine whether implementing RCM is cost-effective. This section concluded with a basic implementation strategy derived from existing literature.

A significant observation made in this section was the lack of clear research or literature focusing on the implementation of lower-cost, practical solutions for integrating RCM practices into industry. While there was extensive discussion surrounding the use of a wide array of sensing technologies that require high capital investment, there was a notable absence of exploration into systems that leverage affordable everyday technologies, accessible to industries with more constrained budgets or a less highly skilled workforce. This represents a crucial gap in current research, which this thesis aims to address by providing insights and solutions that could make RCM adoption more feasible for organisations with limited resources.

2.5.3 Artificial Intelligence and Machine Learning

This section investigates AI and ML with the aim of building a foundational understanding of the different types of models available, the major differences between them, and the on-market tools available to industry that could be leveraged in a low-cost implementation strategy for the maintenance of basic engineering systems. The section explored key differences between various AI levels and highlighted the advancements made from the mid-20th century until the present, including major breakthroughs. This was followed by a detailed investigation into AI's potential to transform industries, with the aim of understanding how it could possibly integrate into existing infrastructure within maintenance practices across the mining industry. Following this, an in-depth investigation of ML models was carried out, aiming to develop an understanding of how they work and how they could be leveraged in industry.

The section then pivoted to examine current on-market practical tools for companies looking to implement AI without the resources to develop their own. An implementation strategy for this process was researched, and a considerable gap in the literature was identified for small companies looking to take advantage of AI tools without the large IT departments common in bigger organisations. This section concluded with the theoretical foundations of AI-driven image recognition and on-market tools for its practical implementation into an existing SaaS platform.

2.5.4 Data Collection and Management in the Mining Industry

This section explored the literature on the current uses of data management systems in the mining industry. It then examined the challenges associated with data management in today's environment, where the exponential growth in sensor technology and the volume of data generated have made managing this data significantly more complex. Following this, recent technological advancements in data management practices were thoroughly explored to identify gaps in the industry's current capabilities.

As with other research gaps identified in earlier sections, although there has been extensive investigation into highly complex systems, there is a lack of research into low-cost, simple-to-implement data management solutions using technologies from off-the-shelf providers.

2.5.5 Gap in Current Literature

From the extensive research undertaken for this project, the key gap identified in the literature was how to effectively implement RCM concepts into a practical, cost-effective, and user-friendly delivery method that enables its widespread adoption in the maintenance of commonplace tools within the mining industry. This thesis specifically investigates how to address this issue for a mining site aiming to increase tyre lifespan. However, the system design and application explored will be applicable across a wide range of industrial sectors. Addressing this gap is critical because, while RCM is a proven and extensively researched methodology for optimising reliability and efficiency, its adoption is often hindered by the complexity and high cost of its integration. Bridging this gap between theoretical frameworks and practical, on-site applications is a key area of research that is currently lacking and would provide substantial benefits to the mining industry. By making the RCM framework more accessible and adaptable, the industry can improve the maintenance and reliability of critical equipment, leading to enhanced operational efficiency and reduced costs.

Additionally, there is a notable lack of research into how new technologies such as AI, ML, and advanced data management systems can be effectively leveraged by small to medium-sized companies using off-the-shelf solutions. While much of the focus has been on complex and costly systems, the scalability and adaptability of these technologies for smaller operations with limited resources remains underexplored. This is a critical area for further investigation, as the ability to harness these advancements in a simplified and affordable manner would democratise access to cutting-edge maintenance strategies like RCM across various industries. By addressing this gap, the research aims to provide a comprehensive approach that combines RCM principles with emerging technologies to develop practical, scalable solutions for a broader range of applications.

Chapter 3

Methodology

This chapter will detail the current process for tyre management and response systems used at the research mine for this project. This process was investigated to identify the problem outlined in Section 1.3 and to enable the design of a new system that addresses the core issues while fitting within the existing system architecture. Following this extensive evaluation of the current process, the new tyre management system design and the implementation requirements are outlined. The rollout of the new system design is planned in two separate stages to allow for an agile project management strategy[1] allowing for changes to be made as feedback is received from system users.

The two phases of implementation are detailed in Section 3.2 and are as follows:

1. **Phase 1**: This will focus on developing a method that ensures the current condition of problem tyres is visible to tyre inspection personnel. This will revolve around a digital form that operators will fill out every time they stop for refuelling at fuel depot stops (every 6-8 hours). Operators will be able to provide a detailed account of issues and are required to upload specific images of each tyre, which can be viewed by tyre inspection personnel.

2. **Phase 2**: This will shift the focus of the system from simply conveying information to tyre inspectors, to analysing tyre history data to provide more comprehensive information about each tyre. This will include a data analysis dashboard for system operators, enabling a better understanding of tyre operating life and highlighting areas for improvement in tyre lifespan.

[1] "Agile project management is an iterative approach to managing software development projects that focuses on continuous releases and incorporating customer feedback with every iteration" [8, p. 1] (see Section B for more details).

This chapter will address the following key thesis objectives:

- Develop an in-depth understanding of the current tyre management method at the research mine, identifying the fundamental problems with the current system and investigating the causes of these issues, methods to prevent them, and reasons why action has not been taken thus far.
- Design a system that provides a more efficient, effective, and reliable process for tyre management by:
  a. Increasing the amount and frequency of digital information collected on tyres in operation.
  b. Providing a single, easy-to-use, and accessible source for tyre historical data and current condition, with clear notifications for issues as they arise.
  c. Empowering management personnel to take a more proactive approach to extending tyre lifespan and enhancing cost efficiency through increased data analysis of digitally collected information.

3.1 Existing Tyre Management System at the Research Mine

The research and literature review conducted on the potential application of RCM demonstrated the clear benefits of creating a system that integrates data gathered from various components of the tyre management process. To begin framing how such a system would function, it was essential to first develop a comprehensive understanding of the existing methodology, procedures, and the roles of key personnel. To achieve this, an online meeting followed by an in-person meeting and site tour was organised with the research mine's tyre contractor. Both meetings were crucial for gathering detailed insights necessary for designing the methodology, complementing the research already undertaken.

The onsite visit was conducted to observe tyre inspection procedures in action at the workshop. This firsthand experience provided a valuable understanding of the operational environment, allowing for better alignment between the proposed system and the practical realities of both the working environment and the tyre management team. Through these interactions, it became clear that understanding how the tyre contractors operate, their mandate, the sources of information they rely upon, as well as their work culture and key responsibilities, were critical considerations. These factors, significantly influence the design decisions and overall end-user experience, ultimately determining the effectiveness and usability of the ATMS design and implementation.

At the research mine, as is common across the industry, equipment maintenance costs are estimated to account for between 30-50% of the mine's annual operating budget [96]. Within this budget, tyres are typically the second largest cost, and it will be assumed that this is the case for the research mine [65]. Therefore, understanding the causes of tyre degradation and implementing systems that provide operators with higher levels of information about current tyre degradation is essential for preserving and extending the useful life of Off-The-Road (OTR) tyres.

3.1.1 Current Strategies to Minimise Tyre Degradation

Currently, the research mine has several proactive strategies aimed at reducing OTR tyre degradation and extending useful lifespan. These methods are designed to address the most significant factors that contribute to tyre degradation: road conditions, load management, and operational best practices. The main strategies currently implemented are:

Optimisation of Haul Roads

The condition of haul roads used by haul trucks is one of the most significant contributors to tyre wear in the research mine's operations. Poorly maintained roads with factors such as uneven surfaces, sharp rocks, deep mud, or excessive dust can cause rapid and/or uneven tyre wear. To address these issues, the research mine focuses on:

- **Regular Grading and Levelling:** Haul roads across the mine are regularly graded and compacted to reduce the impact of potholes and undulations. The gravelling ensures that haul trucks can maintain grip, while the compacting reduces the shock and impact forces exerted on tyres, contributing to slower wear rates.

- **Dust and Mud Control:** Excessive dust during dry periods or mud during particularly wet periods leads to poor traction and, therefore, slippage, which causes uneven wear across the tyres. The mine uses water sprayers to suppress dust and gravels its haul roads to increase traction, ensuring a more stable road surface and significantly reducing the likelihood of slippages.
- **Road Design:** The mine plans the layout of its haul roads to reduce steep grades, optimise curve angles, and avoid sharp turns where possible. These design considerations reduce the potential for tyre issues such as sidewall cuts, which occur when a truck impacts the side of a haul road and uneven wear.

Load and Speed Regulation

The load and speed of haul trucks during operation are two factors that can accelerate tyre wear if improperly managed. At the research mine, there are stringent controls in place to ensure both of these factors are kept within predetermined limits.

- **Load Management:** Overloading the tyres of haul trucks increases tyre pressures beyond their optimal level, leading to excessive heat build-up during operation. This heat accelerates degradation as it weakens the tyre compound. The mine uses sensors on the trucks to monitor their load, and operators ensure that haul trucks are not overloaded.
- **Speed Control:** Excessive speed leads to increased tyre degradation, particularly when trucks are loaded. The mine has designated speed limit zones, determined based on terrain, road conditions, and vehicle load. These zones are monitored, and the variable speed limits are strictly enforced.

Tyre Rotation

Tyre rotation is a method by which mines can increase the service lifespan of tyres by ensuring they degrade evenly. Due to the uneven nature of loading a haul truck, tyres in specific positions wear faster than others, making tyre rotation essential to balance this uneven wear. Figure 3.1 demonstrates the numbering system for the 6 tyres on a haul truck, with the cabin positioned above tyre 2.

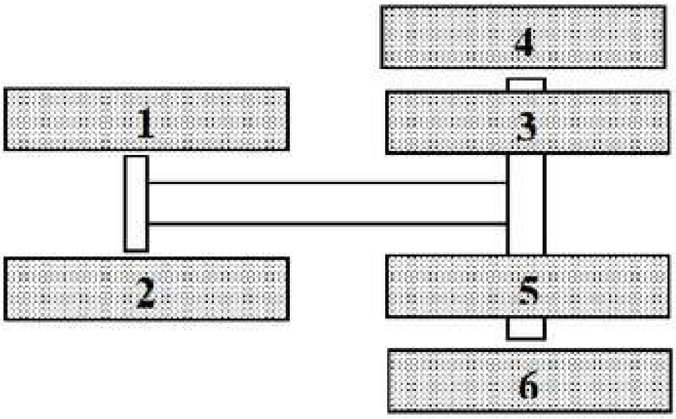

Figure 3.1 – Tyre Position Numbers of a Haul Truck

Every month, haul trucks undergo routine maintenance. During this time, the tyres are inspected and potentially rotated based on the current wear trend of each tyre's position.

Tyre Inspections

Tyre inspections are a fundamental part of the research mine's preventive maintenance strategy and aim to ensure early detection of damage or wear on tyres before they fail. Inspections are conducted visually and are either:

- **Routine Visual Inspections:** tyres are quickly inspected for any obvious damage, including sidewall cuts, shoulder separation, bead bubbles, or obvious tread damage. These visual inspections are conducted by the haul truck operator every 12 hours as part of their routine vehicle inspection and recorded in a form called a 103.
- **Detailed Inspections:** The mine contracts a tyre inspection company to conduct regular, in-depth inspections of the tyres. These inspections are scheduled weekly and include checking tread depth, performing rim checks, and inspecting the sidewalls.

3.1.2 Tyre Monitoring

Tyre monitoring at the research mine can be split into two separate areas; actions taken by haul truck operators in normal operations and inspections carried out by tyre experts once a month.

Day-to-Day Inspections

Operators are required to check their vehicles every 12 hours and fill out a form called a 103 which is a record of the current condition of the machinery as well as any issues identified. During these stops, operators are meant to inspect the vehicle tyres for damage or other issues. Currently, whenever damage to a tyre is noted by an operator, it is categorised by the operator using three different levels:

- **L1 (Green)**: Assess the condition of your tyres. If there is no serious damage, if the damage has been previously inspected (and marked with paint), or if there is an information tag in the cab – return to work.
- **L2 (Amber)**: Less serious damage. Return to work and plan inspections for an opportune time (i.e. when there is a crib, fuelling, or blast delay).
- **L3 (Red)**: Tyres require immediate attention – call dispatch and arrange for Otraco inspection immediately.
  - Separation of the tyre
  - Sidewall bubbles
  - Wire exposed in the tread or in the sidewall
  - Damaged or leaking valve stem
  - Wheel nuts or bolts missing

This categorisation is based solely on the operator's discretion while in the field and unless damage is reported, it can go unnoticed. The research mine does basic training with its haul truck operators to better educate them on what issues look like and when to elevate a situation. An example of training slides the research mine provides to its truck operations can be seen in Figure 3.4.

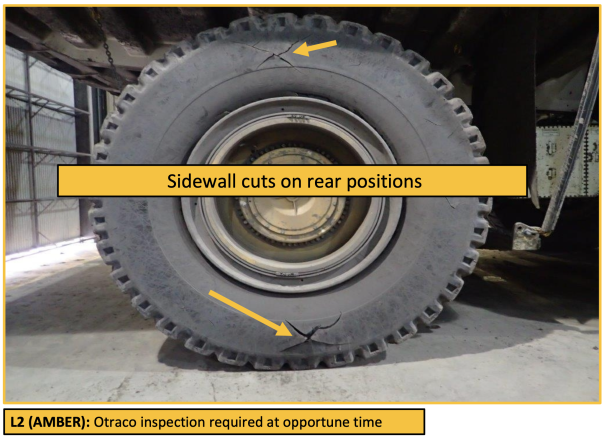

Figure 3.2 – Category Amber Damage

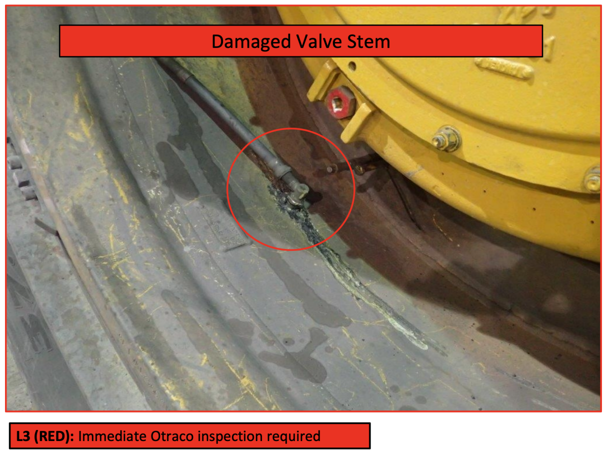

Figure 3.3 – Category Red Damage

Figure 3.4 – Excerpts from MAC Tyre Awareness Guide (MAC-STE-GDE-003)

Tyre Contracting Company

The research mine largely relies on a tyre contracting company called Otraco [2] to manage its tyre maintenance strategy. Otraco is responsible for conducting repairs and replacements of tyres, monitoring their condition, and strategically planning the deployment of tyres on each haul truck (e.g., position). Otraco makes these decisions based on observations and data gathered from in-person inspections conducted on each tyre by an Otraco contractor. Each tyre on a haul truck is currently meant to be inspected once a week for signs of damage and general wear and tear. However, given that the haul trucks operate 24/7 when not undergoing maintenance, it is difficult to find time to perform these inspections in a way that does not reduce the operating time of the haul trucks which is a vital concern for the mines' operations.

[2] Otraco is a major supplier for OTR and light mobile equipment (LME) tyre management across Australia, Chile, and Southern Africa.

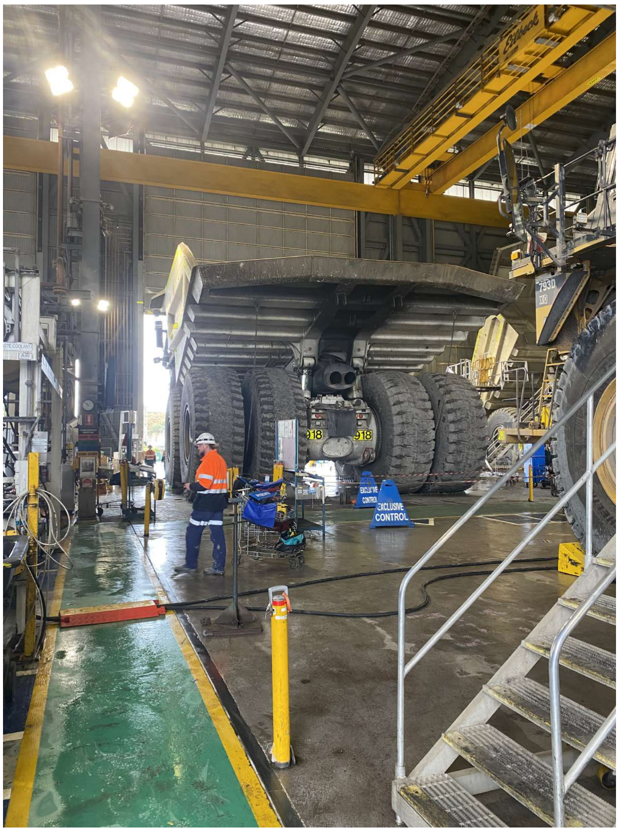

Figure 3.5 – Haul Truck Workshop at MAC

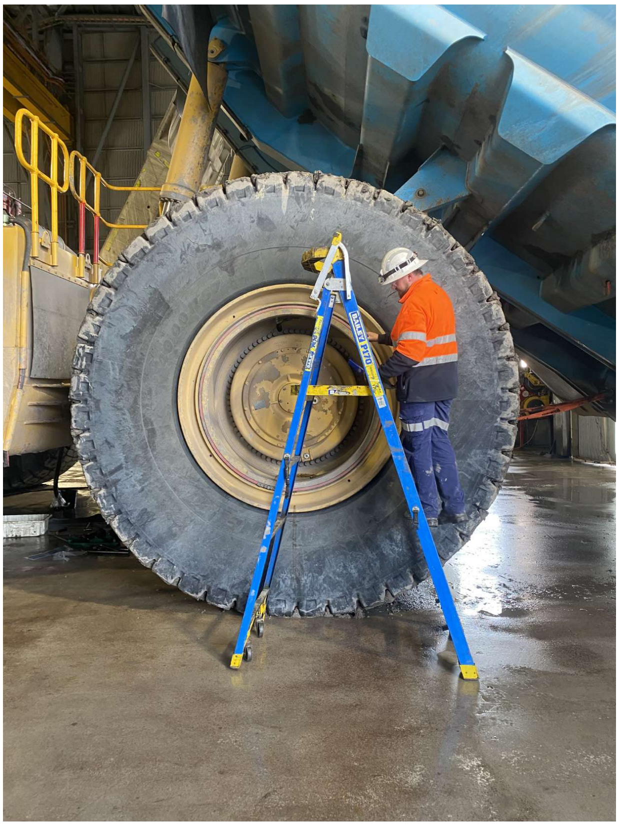

Figure 3.6 – Otraco Contractor inspecting the tread of a haul truck tyre

In current operations, Otraco contractors typically inspect the tyres when the trucks are in the workshop for their routine monthly maintenance, as shown in Figure 3.5 and 3.6. However, detecting issues at this stage can often be too late, as minor problems may have already developed into major issues. With thorough inspections occurring only once a month and inspections being the primary method of gathering data to assess the effectiveness of measures aimed at increasing a tyre's service life, there is currently a significant gap in the tyre management process at the research mine.

Detailed Inspection Procedure

When conducting an inspection, an Otraco contractor completes the *OT-OP-OBP24 Performing a Tyre Field Survey* form, either electronically or on paper. This form guides the contractor through each step of the inspection process, which includes the following:

- Health and Safety
- PPE (Personal Protective Equipment)
- Tools & Equipment
- Required Qualifications
- Job Preparation
- Damaged or Leaking Valve Procedure
- Tyre Pressure Checks
- Tyre Temperature Checks
- Tread Depth Measurement
  - With Chains
  - Without Chains
- Heel & Toe Wear
- General Tyre Condition Report
- Inspection of Wheels and Rims

The Tyre Field Survey, the front page of which is shown in Figure 3.7, stipulates that inspections must be carried out in a tyre workshop. Given that trucks only enter this environment once a month, this presents a significant challenge in maintaining up-to-date data on the tyres in operation.

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OBP REVISION NUMBER: 9	TASK LOCATION: Tyre Workshop
OBP APPLICABLE TO: Includes checking and adjusting tyre inflation pressures, PT check procedure, measuring tyre tread depths, measuring Heel & Toe wear, and additional tyre and wheel/rim in-service inspections.	
REVISION DETAILS: Biennial review.	
APPROVAL DATE: 04/08/2022	NEXT REVIEW DATE: 04/08/2024

Figure 3.7 – OT-OP-OBP24 Tyre Field Survey Report

3.1.3 Common Tyre Issues

The most common issues identified during these inspections fall into two key areas:

1. General Tyre Condition
2. Wheel and Rim Damage

If left unaddressed, these issues can worsen over time, leading to further damage and potential structural weakening of the tyre. Since the current system operates on monthly tyre inspections, problems may only be detected when significant repairs are needed, or the tyre requires replacement—even though the issue may have been minor in the beginning.

General Tyre Condition

When inspecting the tyres for general condition, an Otraco contractor will identify any issues using the identification system outlined in Figure 3.8 and 3.10. This system provides a detailed checklist that describes the various potential issues that could arise with the tyres, such as cuts, cracks, sidewall damage, or abnormal wear patterns. It also recommends appropriate actions for each identified issue, helping to prioritise maintenance efforts. Depending on the severity of the problem and the availability of resources, these actions may either be addressed immediately or scheduled for a future date.

13. INSPECTION OF TYRES IN SERVICE

Perform an inspection of all tyres on the vehicle to ensure that the tyre is safe for continued operation.
If the tyre/s being inspected show any of the conditions identified in the table below, perform the 'recommended action to take', (depending on the severity level of the tyre condition identified).
Note - The tyre conditions identified below are common conditions, however others may exist. Always perform a JHA to assess any additional conditions experienced or if other alternative actions need to be taken.

Condition 1		Severity	Recommended action to take
Tyre is completely deflated or low on pressure		**Level 1** Tyre has a pressure loss **no greater than 20%** of its recommended cold inflation pressure.	Inspect the tyre for damage or leaks, if none found, adjust the pressure of the tyre as per Sections 8 & 9 of this OBP.
		Level 2 Tyre has a pressure loss of **20% or more** of its recommended cold inflation pressure.	Remove vehicle from service. Send to tyre workshop for removal and inspection.
		Level 3 Tyre in a dual wheel assembly is completely deflated with zero psi/kPa.	Remove vehicle from service. Send to tyre workshop for removal and replacement.
		Level 4 Tyre (single wheel configuration) is completely deflated with zero psi/kPa.	Perform an in-pit wheel change.
Condition 2		**Severity**	**Recommended action to take**
Cuts or splits in tread or sidewall area.		**Level 1** Steel belts or nylon body plies are not visible.	Keep in service. Mark and monitor. Record on tyre inspection sheet.
		Level 2 Steel belts or nylon body plies are visible.	Remove vehicle from service. Send to tyre workshop for removal and replacement.
Condition 3		**Severity**	**Recommended action to take**
Worn-out tyres.		**Level 1** 100% worn, or first belt exposed.	Schedule in for tyre removal within 24hrs.
		Level 2 Third belt layer is exposed.	Remove vehicle from service. Send to tyre workshop for removal and replacement.

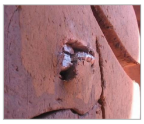
Condition 4		Severity	Recommended action to take
Rocks embedded in tread.		**Level 1** Upon removal of rock, damage is minor and does not extend to steel or nylon belts.	Keep in service. Mark and monitor. Record on tyre inspection sheet.
		Level 2 Upon removal of rock, damage extends to steel or nylon belts.	Remove vehicle from service. Send to tyre workshop for removal and replacement.
Note – Perform a personal hazard assessment before removing rocks from tread. Inspect size and depth of injury.			
Condition 5		**Severity**	**Recommended action to take**
Separations in the tread area.		**Level 1** Separation over a small area, not greater than one tread lug.	Keep in service. Mark and monitor. Record on inspection sheet.
		Level 2 Separation over a large area, greater than one tread lug. Constantly puffing dust. Repeated callouts from mine production to inspect.	Remove vehicle from service. Send to tyre workshop for removal and replacement.
Condition 6		**Severity**	**Recommended action to take**
Bubbles in the bead/flange or sidewall area.		**Level 1** Bubble in the bead/flange area.	Remove vehicle from service. Send to tyre workshop for full deflation and drilling. Assess for continued operation or removal.
		**Level 2** Bubble in shoulder/sidewall area.	Refer to OBP070 – 'Deflation of an Earthmover Tyre using a Tyre Spike' procedure.
Condition 7		**Severity**	**Recommended action to take**
Signs of leaking air i.e. tyre sealant leakage.		**Level 1** Tyre leaking, air pressure reducing.	Steer or single wheel – perform an in-pit wheel change or assess for movement to tyre workshop.
			Dual wheel – Remove truck from service. Send to tyre workshop for removal and replacement.

Figure 3.8 – OT-OP-OBP24 Inspection of Tyres Section - Part 1

Condition 8		Severity	Recommended action to take
Rocks stuck between the dual wheels.		**Level 1** Rock stuck between dual wheels.	Refer to OBP078 - 'Removing rocks stuck between dual wheel assemblies' procedure.
Condition 9		**Severity**	**Recommended action to take**
Tyre with a heat separation or the smell of hot rubber is evident.		**Level 1** A heat separation has been identified and the smell of hot rubber is evident.	Remove truck from service. Refer to *OT-OP-OBP87* Identify & Manage Hazardous Tyres for further details, if necessary.
Condition 10		**Severity**	**Recommended action to take**
Failing or failed tyre repairs.		**Level 1** Repair failed, tyre deflating or fully deflated.	Remove truck from service. Send to tyre workshop for removal and replacement.
		Level 2 Repair bulging, tyre still fully inflated.	Approach, if safe to do so. Deflate tyre immediately, send to tyre workshop for removal and replacement.
Condition 11		**Severity**	**Recommended action to take**
Indications of impact with objects.		**Level 1** Minor contact, no signs of further damage.	Keep in service. Mark and monitor. Record on inspection sheet.
		Level 2 Signs of, or potential for, deformation forming.	Remove truck from service. Send to tyre workshop for removal and replacement.

13.1 Record any faults or concerns identified during the visual inspection in the relevant sections of the Field Survey sheet.

It is important that a thorough visual inspection of the tyre/s condition is performed in order to reduce the likelihood of tyre failure and potential injury to personnel and damage to equipment.

Perform a thorough visual inspection of the tyre/s. If a tyre is deemed to be not safe for continued operation, take the correct course of action to rectify the situation.

Figure 3.9 – OT-OP-OBP24 Inspection of Tyres Section - Part 2

For minor issues that are not deemed critical, the repairs can be deferred and included in the next maintenance window, while major concerns that impact safety or tyre performance require immediate attention to prevent further damage or potential failure during operations. This structured approach helps streamline the tyre management process and ensures that issues are tracked, mitigated, and managed efficiently over time.

For issues that are identified but are in either the monitoring or planned action at a later date stage, white paint is used to mark them so as to indicate they have been noticed and recorded. An example of this on one of the tyres from the research mine can be seen in Figure 3.10.

Figure 3.10 – White Markings indicating tyre issue has been recorded

Wheel and Rim Damage

After completing the tyre inspection, the contractor will also check for issues with the wheels and rims, using a similar identification system as outlined in Figure 3.11. This system ensures that any potential problems with the wheels and rims are identified and addressed promptly to prevent further damage or operational hazards.

14. INSPECTION OF WHEELS AND RIMS IN SERVICE

Perform an inspection of all the associated wheel/rim components to ensure that they are safe for continued operation. If the wheel/rim components being inspected show any of the conditions identified in the table below, perform the 'recommended action to take', (depending on the severity level of the condition identified).

Note - The wheel/rim conditions identified below are common conditions, however others may exist. Always perform a JHA to assess any additional conditions experienced or if other alternative actions to need to be taken.

Condition 1		Severity	Recommended action to take
Signs of leaking air i.e. tyre sealant leakage.		Level 1 Leaking from valve extension.	Refer to Section 6 of this OBP.
		Level 2 Leaking from rim.	Remove truck from service. Deflate tyre. Perform in-pit wheel change, or assess further for sending vehicle to tyre workshop for removal and replacement.

Condition 2		Severity	Recommended action to take
Loose wheel or loose wheel fasteners.		Level 1 Some fasteners are loose but wheel is not damaged or visibly loose.	Replace or re-tighten fasteners at current location. Assess if vehicle is required to return to tyre workshop for wheel removal and inspection.
		Level 2 Wheel is visibly loose and fasteners are loose or missing. Damage is visible.	Remove truck from service. Prepare for wheel change in pit. Report event as required.

Condition 3		Severity	Recommended action to take
Loose cleats or slipping (spun) wheel.		Level 1 Some fasteners are loose but wheel is not damaged or visibly loose.	Replace or re-tighten fasteners at current location. Assess if vehicle is required to return to tyre workshop for wheel removal and inspection.
		Level 2 Wheel is visibly loose and cleats/fasteners are loose or missing. Damage is visible.	Remove truck from service. Prepare for wheel change in pit. Report event as required.

Condition 4		Severity	Recommended action to take
Missing or broken wheel fasteners.		Level 1 Wheel fasteners are missing or broken.	Refer to OEM recommendations. Replace missing or broken fasteners at current location or move vehicle to tyre workshop if safe to do so.

Condition 5		Severity	Recommended action to take
Crack in rim gutter section.		Level 1 Cracks are visible in rim gutter section. Potential for imminent failure.	Cordon off area. Deflate tyre without entering line of fire.

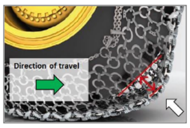
Condition 6		Severity	Recommended action to take
Cracks or damage to rim components.		Level 1 Cracked or damaged rim components are visible.	Assess if damage has potential to cause further hazards. Send to tyre workshop for removal and replacement, or keep in service.

Condition 7		Severity	Recommended action to take
Missing valve caps.		Level 1 Valve caps are missing from valves.	Install new valve caps immediately.

Condition 8		Severity	Recommended action to take
Unsecured valve extensions.		Level 1 Valve extensions are unsecured and becoming damaged.	Secure valve extensions immediately as per OEM recommendation or site policy.

Condition 9		Severity	Recommended action to take
Missing lock ring retainers (outer facing lock rings i.e. pos 1, 2, 3 & 6).		Level 1 Two-piece or hinged lock ring and the tyre is **still inflated.**	Replace or repair retainer at current location, or - Escort-follow the vehicle to the tyre workshop for repairs.
		Level 2 One-piece lock ring and the tyre is **still inflated.**	
		Level 3 One-piece lock ring and the tyre is **completely deflated.**	Do not move vehicle. Install retainer at current location.
		Level 4 Two-piece or hinged type lock ring and the tyre is **completely deflated.** Rear wheel.	

Condition 10		Severity	Recommended action to take
Missing or damaged tyre chain components.		Level 1 Tread chain components damaged or missing.	Replace or repair chain components at current location, or send to tyre workshop if safe to do so.
		Level 2 Tension chain damaged.	Replace or repair chain components at current location.

Condition 11		Severity	Recommended action to take
Loose tyre chain - excess chain 'bag'.		Level 1 The distance between the tyre and the centre of the chain (in the 'bag area') exceeds the manufacturer's recommendations. *(Refer to the manufacturer's data for the specific tyre sizes' maximum allowable measurements).*	Re-tension the tyre chain immediately at a safe location (in-pit or workshop).

Condition 12		Severity	Recommended action to take
Tyre chain is not centred on tyre - 'walking off'.		Level 1 Tyre chain is not sitting centrally on the tyre. *Circumference of the tensioning chain should be at equal distances from the rim flange.*	Re-centre the tyre chain on the tyre immediately.

Condition 13		Severity	Recommended action to take
Damaged or worn rock ejector.		Level 1 Rock ejector is rubbing heavily against tyre sidewall.	Remove truck from service. Send truck to tyre workshop for removal and repair/replacement.
		Level 2 Rock ejector has potential to penetrate tyre and cause burst.	Remove truck from service. Request that rock ejector is removed at the current location. Send truck to tyre workshop for new or repaired rock ejector to be fitted.

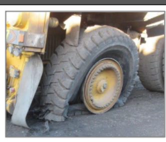
Condition 14		Severity	Recommended action to take
Vehicle suffers a tyre burst during operation.		Level 1 A sudden tyre burst during vehicle operation has caused the demountable rim and rim components to impact the road surface.	Perform a tyre and rim change at the current location. Replace all wheel fasteners (nuts and studs).

Figure 3.11 – OT-OP-OBP24 Inspection of Wheels and Rims

This checklist outlines common issues that can occur in the wheel and rim areas, including rim cracking, valve damage, missing, loose, or broken wheel fasteners, and chain damage (if chains are used). Similar to the tyre section, it also provides recommendations for actions to be taken based on the severity of the identified issue.

3.1.4 Cost Implications of Tyre Management

At the research mine, the cost of tyre maintenance and management is one of the most significant in the operational cost budget. For this project, we are specifically interested in the cost associated with directly sourcing and maintaining the haul truck tyres across the year. The following figures were sourced from the research mine and reflect the economic part of the tyre management ecosystem.

Category	**Figure**
Number of T 282 C Liebherr haul trucks	69
Number of tyres per truck	6
Cost of Replacement tyre	$80,000
Operating hours per year	7,300
Minor Damage repair	$1,250
Major Damage repair	$\approx \$5,000$
Average Life of Tyre (hours)	4,700
Average number of Minor repairs per tyre	6
Average number of Major repairs per tyre	2

Table 3.1 – Key Figures of Tyre Management at MAC

From the figures given in Table 4.1 we can calculate the following estimated numbers for the research mine. It is important to note that these figures are approximate, as completely accurate data was not made available to the project either because it is not completely recorded or this project was not conducted with the research mine directly. Despite this limitation, based on information gathered from various sources at the research mine, these figures present a conservative estimate, as they do not account for other operational systems and costs needed to support the direct management and maintenance operations.

Category	Figure
Number of tyres used / Year	643
Cost of Replacement Tyres / Year	$52m
Cost of Minor Damage repairs per tyre	$7,500
Cost of Major Damage repairs per tyre	$\approx \$10,000$
Total Tyre Repair Cost per tyre	$17,500
Total Cost of Replacement and repairs / year	$63.375m

Table 3.2 – Key Calculated Figures for research MAC

3.1.5 Limitations of the Current Tyre Management System

While the existing tyre management system at the research mine provides a structured approach to maintaining and extending the life of OTR tyres, several key limitations have a significant effect on its overall effectiveness. These limitations stem from both operational challenges and gaps in data collection, as outlined below:

1. Infrequent and Reactive Inspections One of the most significant limitations is the infrequency of detailed tyre inspections. As detailed in Section 3.1.2, Otraco contractors primarily inspect tyres during routine monthly maintenance, with additional inspections conducted only when problems occur with trucks during operation that require their attention. This reliance on a monthly inspection cycle leaves a large window where tyre conditions may worsen, particularly with heavy use. Minor issues, such as small cracks or uneven wear, can escalate into more serious problems before being detected, resulting in more expensive repairs or tyre replacements. This reactive approach, where repairs are often triggered by the detection of major damage, does not provide a proactive system that could prevent damage in the first place.

2. Limited Real-Time Data Collection Another limitation is the reliance on manual inspections and data collection. While tyre inspections are carried out by trained personnel, much of the data is manually recorded, leading to potential errors, incomplete records, or delays in data processing. The lack of, continuous monitoring systems leaves tyre condition assessments largely dependent on periodic physical inspections but unqualified individuals, increasing the risk of undetected issues between inspections.

3. Lack of Comprehensive Digital Record-Keeping As noted in the cost analysis, accurate data on tyre repairs and replacements is not comprehensively recorded by current mine systems. This lack of complete and accurate data limits the ability to make data-driven decisions regarding tyre management. Without detailed records of tyre repairs, failures, and operational conditions, it is difficult to optimise maintenance schedules, predict failures, or assess the long-term cost-effectiveness of current practices. The reliance on estimates for both the frequency of tyre repairs and associated costs means that the mine may be missing opportunities for cost savings or performance improvements that could be identified through better data collection and analysis.

5. Limited Training for Haul Truck Operators Another challenge is the variability in how haul truck operators assess tyre conditions. Although operators are required to perform day-to-day inspections, their ability to accurately identify issues depends on their level of training and experience. Currently, the research mine conducts basic training for its operators, but there may be inconsistencies in how damage is reported or categorised. Without consistent, standardised reporting across all operators, minor issues could be missed, and serious problems may go unreported until they escalate.

7. Delayed Decision-Making in Tyre Maintenance Finally, the current system often delays decision-making regarding tyre repairs or replacements. Decisions are typically based on visual inspections and operator discretion, which can be subjective. While the Otraco contractors play a critical role in ensuring tyres are maintained, they are often only called to inspect tyres when major issues arise, rather than when preventive maintenance could be performed. This reactive system can result in higher long-term costs due to more frequent tyre replacements and more extensive repairs than would be necessary with a more proactive system.

3.1.6 Summary of Existing Process

The current tyre monitoring/management system in practice at the research mine is laid out in Figure 3.12, which is a process diagram of the system.

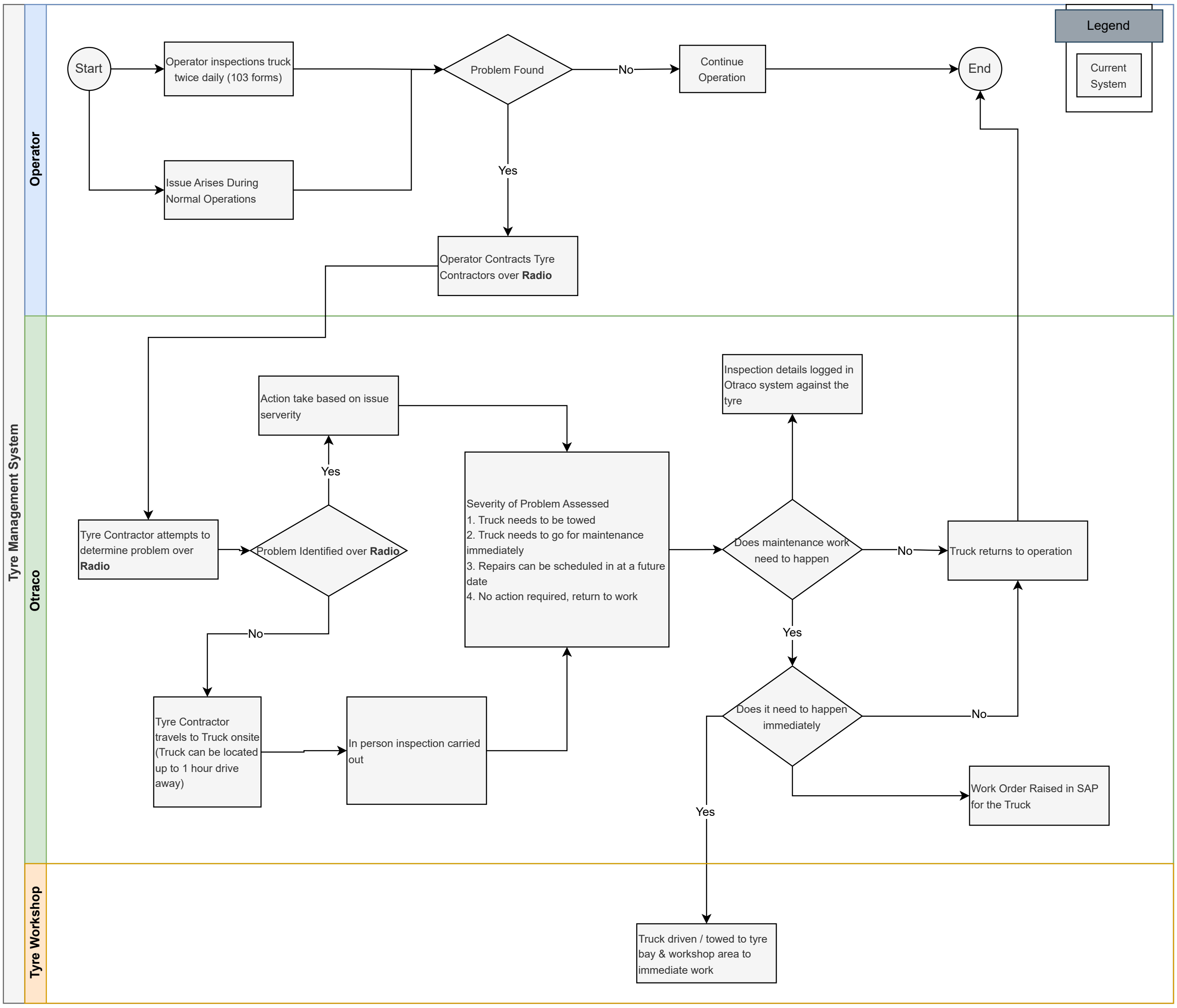


Figure 3.12 – Process Diagram of Existing Tyre Management System at MAC

This process diagram details how problems are identified and acted upon, including the actions of the haul truck operators, Otraco contractors, and the tyre repair workshop. Note that this process diagram only includes the information flow when problems are identified in the field. As explained above, Otraco contractors also inspect the tyres approximately once a month when haul trucks are in the workshop for maintenance. If problems are identified by haul truck operators during their twice-daily inspections or when a problem occurs, Otraco contractors are then contacted via radio. They will then either attempt to diagnose the problem verbally or come out to inspect the vehicle (a 1-3 hour round trip). Once the problem is determined, a decision will be made based on the problem assessment.

3.2 Proposed System Design

Following a comprehensive investigation and analysis of the research mine's current operations and practices, a new system design, the ATMS, has been proposed. This design aims to integrate Corehesion's platform and capabilities into the existing management structure, enhancing operational capacities while minimising disruption and the need for extensive retraining.

Design Considerations Based on Limitations

Based on this thesis' analysis of the current system implemented at the research mine, with a focus on its limitations, it was determined that the key capability gaps lie in the frequency and accuracy of data collection, as well as data accessibility. Furthermore, the absence of consistent digital record-keeping, analysis of available data, and data management systems to channel useful information to operators for informed decision-making is a significant limitation.

To address these limitations, the first phase of the system design prioritises improving the frequency and precision of data collection on tyre conditions. Following this, a structured method for recording data and making it readily accessible on a platform familiar to end-users will be introduced. This will ensure that all relevant information is logged in a centralised location and available for review.

The second phase will build on the increased data collection from the first phase to integrate Industry 4.0 systems (AI image recognition) from Corehesion's current service provider (Microsoft). This solution will allow for a rapid expansion in data analysis based on enhanced monitoring in a cost-effective manner, streamlining operations and increasing the efficiency of front-line operators.

The new system will be designed with usability, cost-efficiency, and practical operational impact in mind. Given Corehesion's widespread use at the research mine, training will be minimal, and there will be limited requirements for additional infrastructure.

Testing Process at Corehesion

Corehesion's testing process is designed to ensure the accuracy, reliability, and performance of its platform in capturing and managing data. The methodology is structured into two critical stages: software testing and extensive User Acceptance Testing (UAT).

During the software testing phase, new features and functionalities undergo thorough evaluation for performance, accuracy, and integration. This phase ensures that each work item developed aligns with the technical specifications outlined in Corehesion's development methodology. The goal is to identify and resolve any technical issues before progressing to the next stage.

Once the software testing phase is complete, UAT is conducted to ensure the system meets the business requirements as defined by the business analysts. This phase is crucial for verifying that the platform delivers real value to the end users and integrates smoothly with the business processes it is designed to support. Corehesion places great emphasis on UAT to ensure the platform is intuitive and functional for its users.

3.2.1 Phase 1

Objective: Integrate the Corehesion platform into the tyre management structure to enhance data collection through visually recorded inspections every 6-8 hours at Haul Trucks fuel depos and streamline reporting to Otraco contractors. This phase will establish a strong foundation for accurate and reliable data gathering, facilitate automated data logging, and create a centralised digital record-keeping platform.

Phase Steps

1. **Corehesion Platform Capability Upgrade:**
    - Several changes to Corehesion's current platform will be required to allow it to perform the inspections and send through notifications for Phase 1 (See Figure **??**.)
    - A Restructure Corehesion's Work Items and Assets will be required to be able to handle "Parent assets", video/image uploads and well as a reformatting of the notification system to allow for both Urgent and Daily communication dumps.
2. **Corehesion Platform Integration with Tyre Management Process:**
    - The Corehesion platform is currently already deployed onsite for a variety of other applications. However it will be needed to be integrated into the Tyre management process.
    - The deployment of equipment to the fuel depos (Ipads) will also be required to carry out the imaging.
3. **Training and System Rollout:**
    - Train all relevant personnel on using the Corehesion platform for conducting inspections, capturing images, and logging data accurately.
    - Begin initial deployment on a subset of trucks to test the system's functionality and gather feedback for refinement.
4. **Testing and Validation:**
    - Run the Corehesion platform in parallel with existing manual processes to validate data accuracy and efficiency.
    - Implement iterative improvements based on feedback and ensure smooth integration with the mine's operations.

System Design

The system design for Phase 1 is centred around the initial integration of the Corehesion platform. This phase aims to streamline data collection, improve record-keeping, and introduce regular visual inspections every 6-8 hours by haul truck operators or maintenance personnel at the refuelling depos. The Corehesion platform will serve as the central hub for logging and managing the data collected from inspections.

Visual inspections are designed to be simple but effective, ensuring that tyre conditions are consistently monitored and logged in a centralised repository. The design leverages existing infrastructure to minimise disruption and costs, while still improving overall data accuracy and availability. Furthermore, the system is scalable, allowing for future expansions in the number of haul trucks or inspection points.

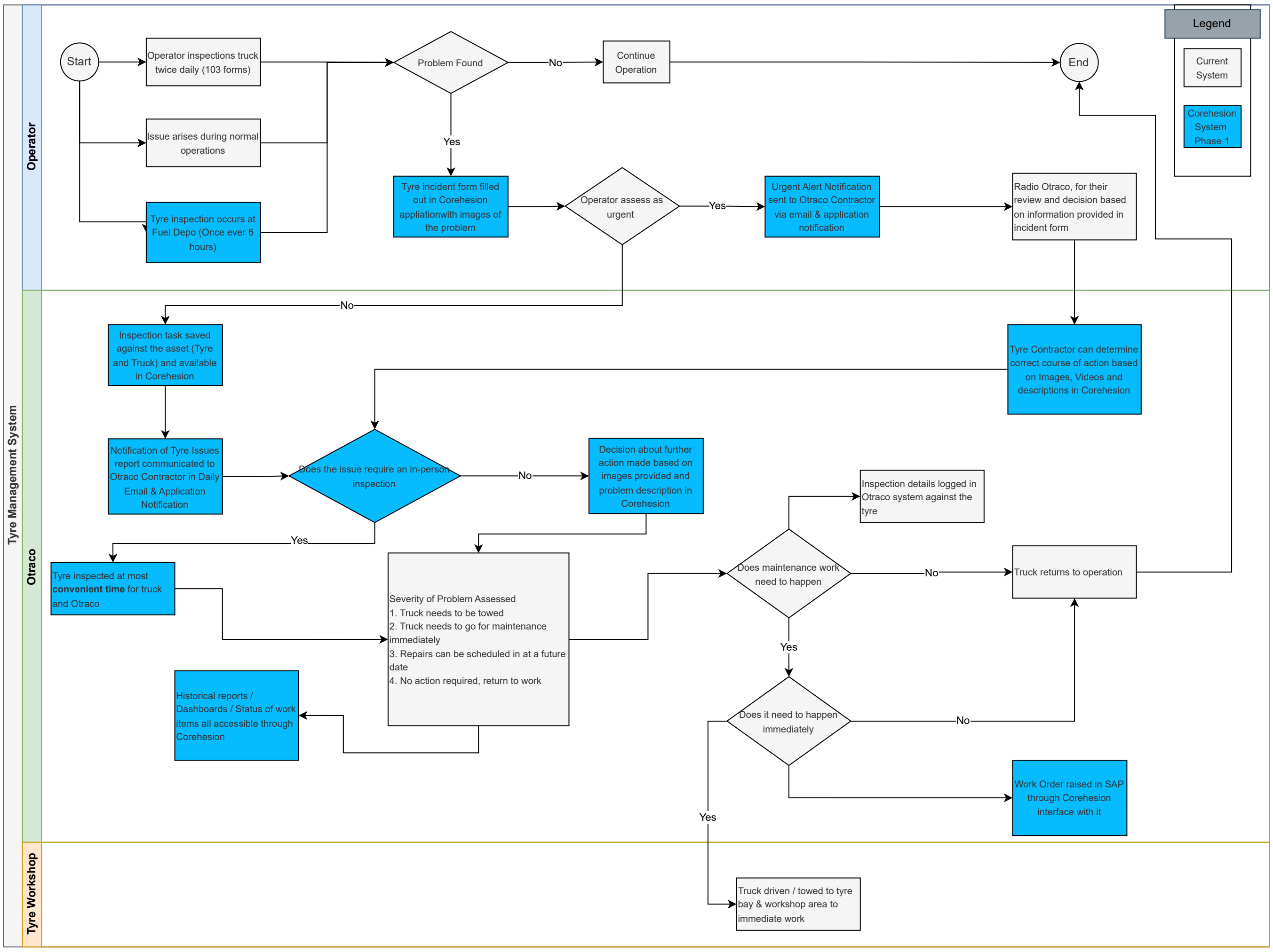


Figure 3.13 – Process Diagram of Phase 1 Tyre Management System Design

Workflow and Work Items

The required updates to the Corehesion system for Phase 1 are listed below the Work Items Table (Table 3.3). Corehesion uses a Kanban board for all its software development and these work items will be fed into that development board for the project. These updates are relatively minor, as the system will leverage Corehesion's extensive software already in place, including its asset management, forms, and notification functions. All of these features are already available and configurable within the system.

Story Number	Business Requirement
1001	A new area where historical data for an asset can be uploaded.
1002	Ability to have an asset have a parent asset (e.g. A tyre is its own asset, but has a parent asset which is a truck).
1003	Ability to manage the relationship between assets in a central. location - This means that you are able to 'inspect' a truck and upload information to all 6 of its tyres.
1004	Historical information on asset available with the inclusion of pictures.
1005	Ability to take images/videos and upload them to an asset (e.g. a tyre) - This will be a type of form instruction.
1006	Ability to raise an Urgent Problem/alert for an asset (the addition of a new feature on the main asset page when managing).
1007	In the new 'Urgent Problem' feature, place to upload an image or video of the issue.
1008	From a parent asset (Truck), incorporate the ability to raise a Work Order in SAP while in the asset.
1009	A historical dashboard within an asset developed to show: • Current condition as last reported by the operator. • History of work completed on it (including all related assets e.g. tyres). • Next scheduled inspection/work item.
1010	Notification system to bundle any "issues" reported from assets to the correct operator (e.g. tyre management operator). This will act as a Daily Log or Daily Update. When issues are reported from the new inspection feature, if they are not serious, they will be reported together at the beginning of every day (8am notification).

Table 3.3 – Phase 1 Work Items

Figure 3.14 illustrates the workflow for developing these work items. Upon completion, each work item will be tested using Corehesion's current testing system.

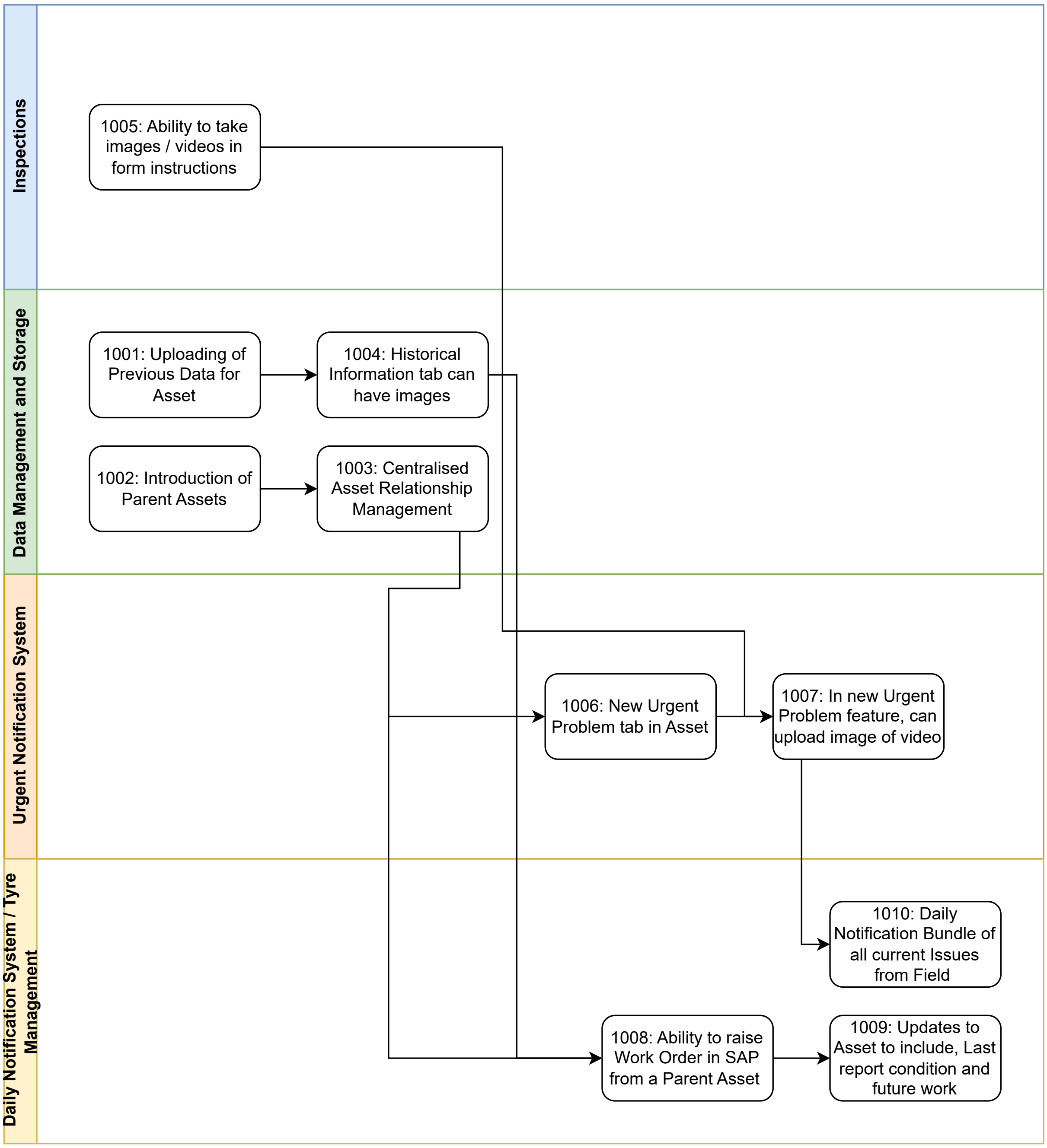


Figure 3.14 – Workflow Diagram for Phase 1

Release Method

Phase 1 will be released in a controlled manner, beginning with a pilot program on a small subset of haul trucks and inspections carried out at one fuel depot. This phased rollout will enable the collection of feedback and the identification of any necessary adjustments. Once the pilot program has demonstrated success, the system will be deployed across the mine's entire fleet. This feedback loop from the initial pilot program will ensure that the software developed is intuitive to use and integrates smoothly with the mine's existing practices.

Training will be provided to all personnel involved in the inspection process, including the haul truck operators, fuel depot attendants, and Otraco tyre management operators, ensuring a smooth transition to the new system. Continuous monitoring will occur during and after the rollout to identify any potential issues, with updates applied as necessary to maintain optimal performance.

3.2.2 Phase 2

Objective: Enhance the Corehesion platform by incorporating AI-based image recognition Microsoft Azure Custom Vision to automatically identify tyre issues during inspections. This system will work to automate workflows and optimise decision-making processes to further improve operational efficiency and response times to increase tyre lifespan.

1. **Integration of Custom Vision:**
   - Custom Vision will be integrated in the back-end with Corehesion's current platform. This will allow the platform to use the technology from Forms.
   - Integrate the training of Custom Vision into the Asset Tyres within Corehesion.
2. **Automated Decision-Making and Workflow Optimisation:**
   - Upgrade the workflow within Corehesion to allow Custom Vision to make decisions about the current condition of tyres before passing information on through notifications to Otraco Employees.

3. **Advanced Analytics and Performance Evaluation:**
   - Incorporate reporting based on the image analysis provided by Custom Vision.
   - Increase Corehesion's platform's ability to display large amounts of data efficiently for end users.

4. **Post-Implementation Review and Continuous Improvement:**
   - Conduct a post-implementation review to assess the effectiveness of the new system (Phase 1 and 2), document lessons learned, and plan for continuous improvements.
   - Explore opportunities to integrate additional features or expand Custom Vision's capabilities within Corehesion's platform based on operational needs.

System Design

In Phase 2, the system design builds upon the existing Corehesion platform by incorporating Microsoft Azure's Custom Vision recognition system to automatically detect tyre issues. The integration of this platform will allow for more accurate and faster identification of potential problems, such as wear or damage, without requiring manual interpretation of inspection data.

The system's AI models will process images collected during inspections, which occur every 6-8 hours at the fuel depots, and automatically flag any issues for review by Otraco operators. This not only improves the speed of decision-making but also ensures greater accuracy and consistency in identifying tyre-related problems. The system is designed to be scalable, allowing it to be expanded for use in other maintenance areas beyond tyres.

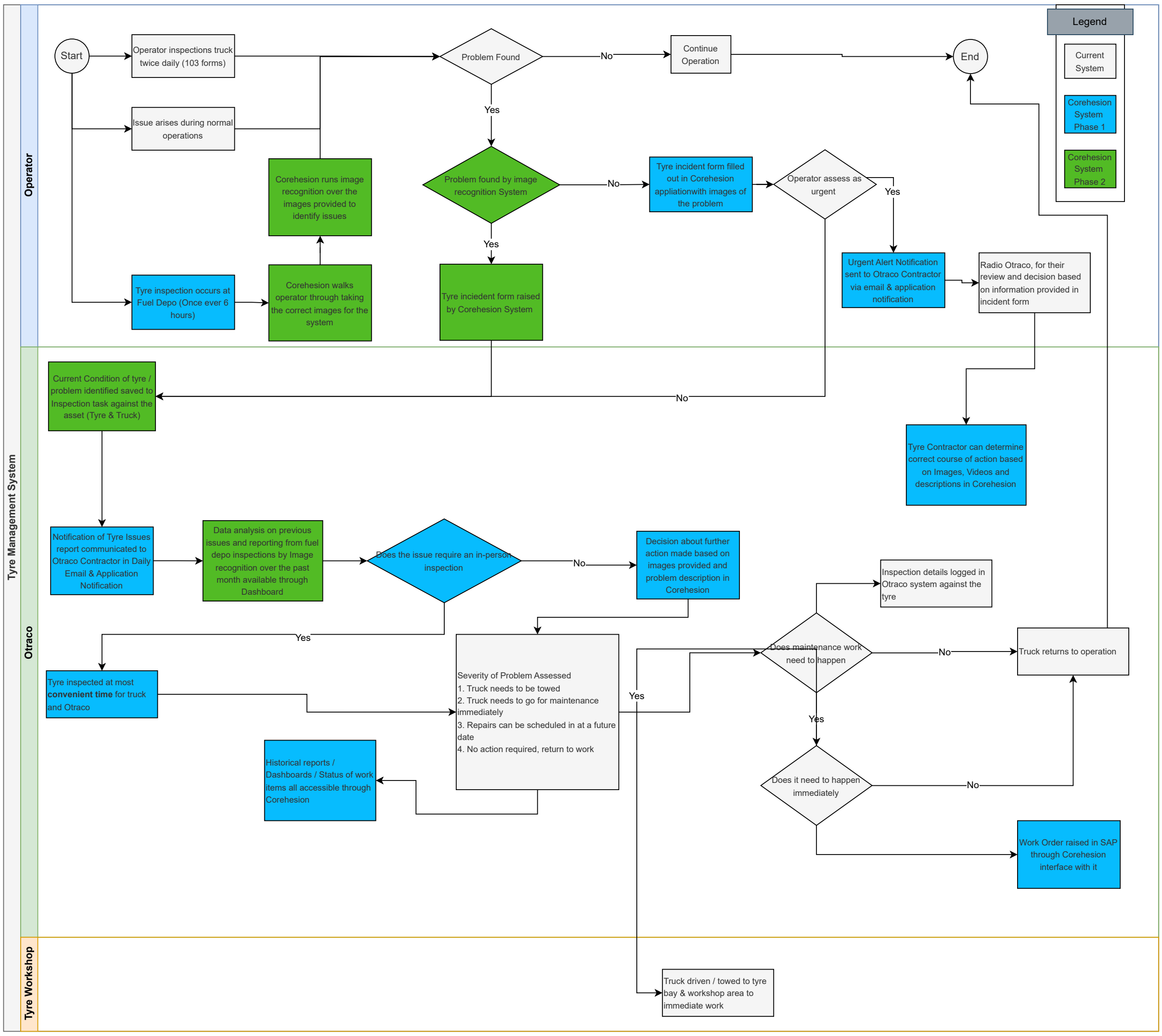


Figure 3.15 – Process Diagram of Phase 2 Tyre Management System Design

Workflow

The required updates to the Corehesion system for Phase 1 are listed below in the Work Items Table (Table 3.4). While there are fewer updates compared to Phase 1 in terms of Work Items, this work will take much longer to implement as it is more involved. However, once set up, this will give the Corehesion platform much greater capabilities than previously, as it will be integrated with Microsoft's suite of service offerings.

Story Number	Name
2001	Form Instruction 'Take Image' can be used to guide a user to take a specific photo
2002	Custom Vision integrated into Corehesion platform, allowing it to run through Corehesion's desktop and mobile applications
2003	Custom Vision can be trained within the Corehesion platform. • A training area will be available within each 'type' of asset (e.g. Tyres), where images can be uploaded to train the AI Vision model. • The training area will be linked to the tyres described in the Form Instructions set up in Corehesion.
2004	Incident forms for daily review by operators can be created from information analysed in Custom Vision
2005	Notification system update to allow urgent alerts from AI image processing to be sent
2006	Historical data dashboard updated to include reporting from analysis performed by Azure, including a general prediction of remaining useful life

Table 3.4 – Phase 2 Work Items

Figure 3.16 demonstrates the workflow for developing the Phase 2 Work Items.

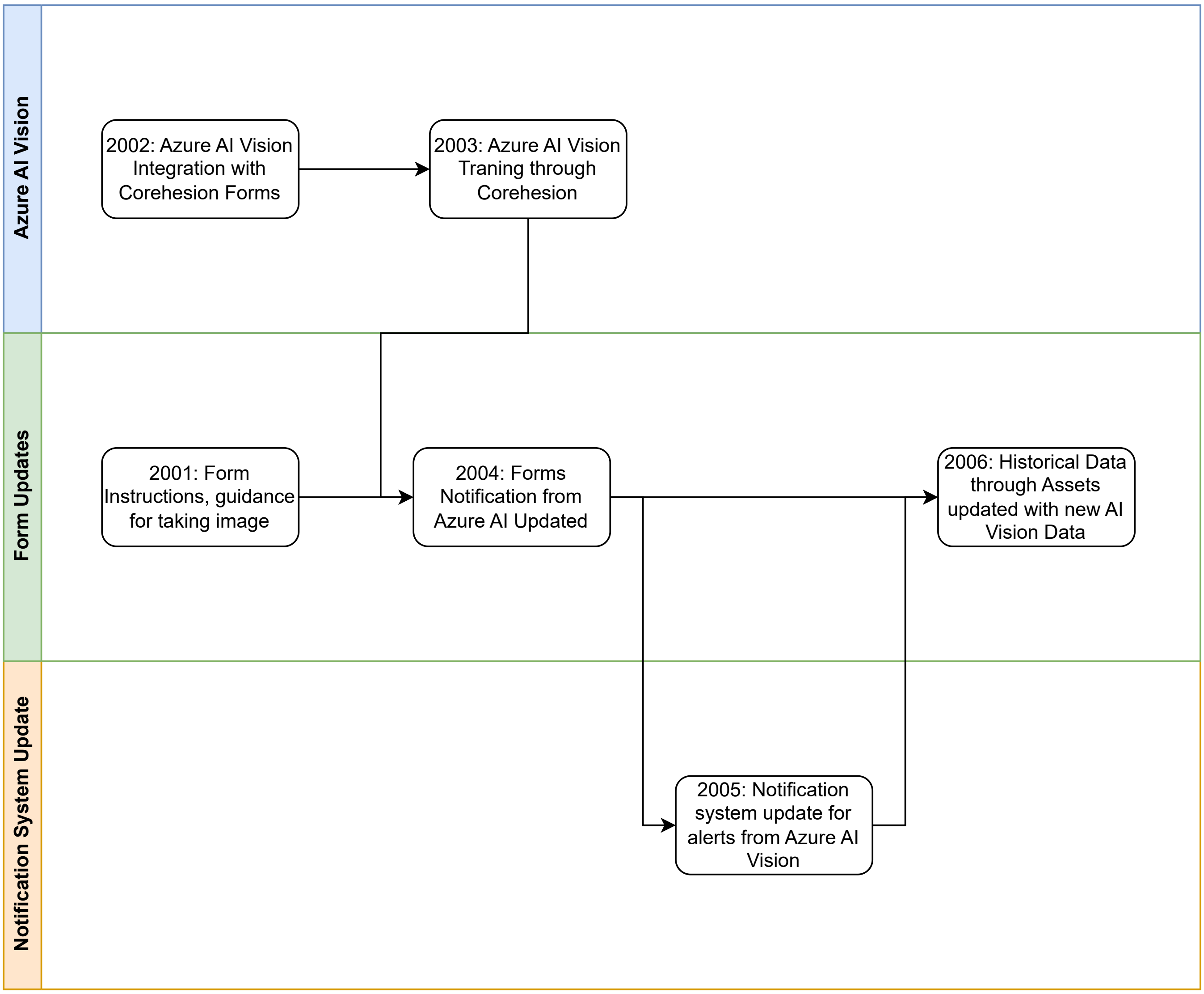


Figure 3.16 – Workflow Diagram for Phase 2

Release Method

Similar to Phase 1, the release of Phase 2 will begin with a limited deployment, focusing on a small number of trucks to ensure the AI's performance and accuracy. Based on the success of this initial rollout, the system will be fully deployed across all haul trucks and maintenance facilities.

Comprehensive training will be provided to ensure that all personnel understand how to interact with the AI-enhanced system. However, for the Corehesion platform, minimal training will be required as it will operate in a similar way for frontline users. Regular performance evaluations will be conducted, and any necessary updates will be applied to further optimise the system's functionality.

3.3 System Optimisation Strategy

The following section outlines the steps taken to ensure that the ATMS, designed in collaboration with key stakeholders at the research mine, aligns with the operational requirements. The stages of optimisation are based on Corehesion's current model:

- Identifying issues within the existing operating methodology
- Customising business requirements based on a tailored solution developed to address those issues
- Developing software that adheres closely to these requirements
- Conducting extensive UAT to ensure the system functions in a way that meets client needs
- Incorporating client feedback in a continuous loop following the initial implementation, through both close relationships with clients and a helpline.

3.3.1 Agile Development

Corehesion utilises agile development across their entire product development process which promotes flexibility in approach and allows for rapid adaptation to changes. Through iterative cycles, the team can continuously evaluate system performance based on user feedback and internal reviews, make incremental improvements, and adjust features to meet evolving needs. This ensures that the system remains aligned with the operational goals of clients and that feedback can be adapted into the system quickly and effectively. A more extensive definition of agile development can be found in Section B.5.1

In the context of this thesis project, agile development will facilitate the integration of user feedback from pilot programs and initial rollouts allowing the team to prioritise functionality based on real-world use cases. This continuous feedback loop reduces the risk of deploying features that may not be utilised or optimised for the actual working conditions in the research mine. This is an important consideration as ensuring that this project has real-world application is the key to this development.

Agile development will also support faster delivery of system updates, enabling the tyre management system to evolve and address emerging challenges more efficiently. With shorter development cycles and frequent testing, issues can be identified and resolved swiftly, ensuring the system's continuous improvement without major disruptions to ongoing operations.

3.3.2 User Acceptance Testing

UAT is a critical component of system development and optimisation at Corehesion. It is conducted by both software testers within the company and end users, and it validates the functionality of the system in a real-world environment. By involving testers who have an intimate knowledge of the system and end users who will need to use it every day, the development team can gather valuable insights into areas that need improvement and those that simply require more training for better understanding. It also ensures that any issues not apparent during initial testing phases are identified and resolved.

For the proposed system, Corehesion will conduct its usual testing during software development, after which the system will be piloted with Otraco operators and a small number of haul truck drivers to assess how easily operators and maintenance personnel can interact with the system, from capturing inspection data to navigating the automated workflows. Ensuring the system is intuitive and efficient for users will increase its adoption rate and reduce the need for extensive training, which is crucial for maintaining operational efficiency.

UAT therefore provides a final layer of verification that the system meets the specific needs of its users, minimising the likelihood of post-deployment adjustments. This testing phase is essential to ensuring the system's reliability and usability before a full-scale rollout, particularly in environments with stringent operational demands, such as mining.

3.3.3 Performance Monitoring and Data Analytics

Following the implementation of the new system at the research mine, continuous performance monitoring will be carried out to ensure that it continues to operate as intended. Corehesion maintains close contact with its client's cost implementation as a way of quality control. This reduces the need for a dedicated in-house team to focus on this area and instead means that problems identified by the client are quickly acted upon. Clients inform Corehesion about an issue through either a helpline, which is manned by a Corehesion software tester, or through Corehesion business analysts' presence on-site at its various sites.

Performance monitoring from a system-specific approach will be conducted on a number of levels. The accuracy of the AI vision model will be monitored by the system, with a quality control process in place in the first rollout of Phase 2 that allows Otraco operators to double-check the assessments. This information will be fed back into the model for further improvements. Data analysis of the information collected in the historical section of each asset can also be used to ensure that tyres are indeed getting an increased average lifespan (which is the key aim of the project). This historical information can also be used to then inform management at the research mine about tyre order requirements for the next year, something that needs to be done some time in advance due to supply chain issues that are still prevalent. This data-driven approach will help maintain the system's reliability and ensures that any future enhancements are grounded in concrete performance data about the project's current success.

3.3.4 System Scalability

Corehesion designs all its software to be transferable, not only between mining operations but across different industry applications in general. It is currently used by the mining, energy generation, and international shipping industries, with plans to expand into other industrial sectors. This program, while focused on tyres, has the potential to be scaled to other machinery components that experience regular wear and tear and would benefit from increased monitoring. Therefore, ensuring that the system and Corehesion's infrastructure are designed to scale efficiently will prevent performance degradation as the system expands.

The integration of Microsoft's suite of service offerings, starting with Custom Vision for this project, will significantly expand what Corehesion can offer its customers through its platforms.

3.3.5 Cost Efficiency and Resource Management

Optimising the tyre management system also involves ensuring cost efficiency, both in terms of upfront investments and long-term operational costs. By leveraging Corehesion's existing platform for the majority of the system, this has minimised the need for expensive software development, meaning it can be implemented without significant capital outlay.

At the core of this project is optimising resource management with the system aiming to improve the allocation of mine's resources by reducing man hours required and increasing tyre lifespan. The data collection from tasks already performed (refuelling the trucks) and extra reporting will reduce manual effort in the long term, freeing up tyre management staff for more critical tasks while also lowering operational costs.

3.3.6 Integration with Other Mining Systems and Platforms

Given that the research mine already utilises Corehesion for some of its site and asset management, the full integration of the platform will be much more seamless. Efforts in this design have been made to ensure that the system is able to work well with current operating systems, including communicating with SAP and outputting information in a way that is compatible with Otraco's tools.

By enabling cross-system communication, the system will eventually be able to leverage data collected from other areas in the mine (e.g., crew schedules, planned operating routines/sites, etc.), which it can use to enhance its own functionality. An example of this would be incorporating real-time vehicle data to optimise inspection schedules. The integration will also further facilitate better resource allocation and coordination between departments across the mine by creating a single source of information on the platform. Through this centralisation of data, decision-makers could gain a more comprehensive view of the mine's operations, allowing for more informed decisions regarding equipment maintenance and overall operational strategy.

3.4 Potential Limitations

While the proposed system offers significant improvements to the current operations at the research mine, there are some limitations that must be considered during this planning phase of the project.

One of the primary challenges will be ensuring that the data collected from images, videos, and survey forms from operators is accurate and usable. This issue could be a significant concern early in the system roll-out when there may still be confusion about how to operate it. Ensuring that good-quality pictures of tyres are taken and that any issues are flagged appropriately, especially in Phase 1, will be a key area of potential failure. To mitigate this issue, we will ensure that the training provided to operators is clear and useful, with regular check-ups occurring early in the program.

Another major potential limitation is the accuracy of Microsoft Azure's Custom Vision CV system. The challenges of using image recognition for this system have been explored more thoroughly in Chapter A. While the potential of this technology is great, a significant amount of training data will be required. This highlights the benefit of the roll-out plan being divided into two separate phases, as the images collected during Phase 1 can then be used to train the platform for Phase 2.

The final major limitation identified during this planning phase is the cost of implementation and ongoing maintenance, particularly for Custom Vision, which may be higher than initially anticipated. Microsoft charges per API request for this service, and this could potentially increase the project's costs. Similarly, the cost of developing the system's new capabilities, particularly the more complex aspects of Phase 2, could result in budget overruns or delays in full system deployment, especially if unexpected technical challenges arise during the integration process. The agile development method and effective controls that Corehesion has in place should mitigate these risks as much as possible. From that point, it becomes a judgment call based on the information available when the issues arise.

Chapter 4

System Implementation and Results

This chapter explores how the ATMS, designed and outlined in Chapter 3, was implemented at the research mine throughout my project. Despite delays in the project's commencement and the longer-term timelines of both MAC and Corehesion, the project had progressed through the initial pitch and user feedback stages by the time I departed Corehesion. Therefore, this chapter will focus on the initial stakeholder impressions and feedback from the design presentation, the established groundwork carried out for the future continuation of the project, and scenario analysis of potential cost savings from the system. Additionally, this chapter will explore the potential areas of scalability for the system beyond tyre monitoring and maintenance management.

This chapter will address the following key thesis objectives:

- Develop the designed system within the research company's current platform and implement it into the research mine to commence real-world testing and operation.
- Evaluate the performance of the system and its ability to:
  a. Increase the information available to tyre management personnel.
  b. Increase the digital data collected on tyres across the fleet.
  c. Enable personnel to proactively plan maintenance and replacement more efficiently.
  d. Be quickly integrated into current tyre management systems and begin having a meaningful impact.

4.1 Cost Benefit Scenario Analysis

The following section will investigate the system's potential impact after implementation on the tyre lifespan of the average haul truck and, by extension, MAC's bottom line. While the project has only reached the initial presentation to stakeholders phase, the projections offered here are based on a comprehensive understanding of the data and current maintenance practices. This has been built up from both onsite visits with Otraco's tyre management team and working with Corehesion's business analysts on the problem. These figures, though projections, are grounded in realistic expectations and consider both direct and indirect benefits of improved tyre management. A reduction in the frequency of tyre repairs, in particular the major damage repairs, would not only reduce downtime (DT) but also lead to significant cost savings in the long run. Increased monitoring will also enhance safety conditions for operators and increase overall fleet efficiency. The following scenarios, which could potentially occur from increased monitoring by the Corehesion Platform, will be investigated.

1. **Realistic:** The average lifespan of each tyre increases to 4,900 hours—a 4.26% increase—and the tyres require one fewer major repair and 2 fewer minor repairs per lifespan. This is expected as issues are detected earlier through more frequent monitoring, allowing for more proactive maintenance and thereby reducing repair requirements.

2. **Optimistic:** The average lifespan of each tyre increases to 5,170 hours—a 10% increase—and the tyres require one fewer major repair and four fewer minor repairs per lifespan. This scenario assumes optimal conditions, where the platform enables large-scale early detection of issues and has a significant impact on both major and minor tyre damage repairs through timely interventions.

3. **Conservative:** The average lifespan of each tyre increases to only 4,800 hours—a 2.13% increase—and there is only one fewer minor repair required over the tyre's lifespan. This scenario accounts for minimal improvements, where increased monitoring leads to early detection of minor issues but has a limited impact on the overall reduction of repairs and little effect on tyre lifespan.

Below is the information from Chapter 3 given by the research mine on current operations [1].

Category	Figure
Number of tyres used / Year	643
Cost of Replacement Tyres / Year	$51.44m
Cost of Minor Damage repairs per tyre	$7,500
Cost of Major Damage repairs per tyre	$\approx \$5,000$
Total Tyre Repair Cost per tyre	$17,500
Total Cost of Replacement and repairs / year	$62.69m

Table 4.1 – Key Calculated Figures for research MAC

4.1.1 Scenario 1: Realistic

In this scenario, it is assumed that the system has a moderate impact on tyre lifespan and maintenance requirements. This is a realistic expectation for a new system that requires time to integrate into the operational workflow of the mine. As operators become accustomed to the system and data is collected from the working environment, improvements on top of these figures could be achievable.

Category	Figure
Number of tyres used / Year	617
Cost of Replacement Tyres / Year	$49.34m
Total Tyre Repair Cost per tyre	$10,000
Total Cost of Replacement and repairs / year	$55.51m
Reduction in Total Cost from Current Operations	$7.18m

Table 4.2 – Scenario 1, Key Figures

In this situation, the increase in tyre lifespan of 200 hours per tyre has led to 26 fewer tyres being required by MAC per year, which corresponds to $2.1m in cost reduction per year. The reduction in per-tyre repair costs from $17,500 to $10,000 also represents significant savings across the year. In total, this scenario saw a reduction in operational costs of approximately $7m.

[1] For the full working of the following scenario analysis see Appendix E

4.1.2 Scenario 2: Optimistic

This scenario assumes that the system achieves optimal performance and has an immediate and sizeable impact on operations. It is expected that the monitoring system improves both tyre lifespan and maintenance, with a strong positive impact on efficiency. Early detection of issues allows for timely interventions, resulting in fewer replacements and lower repair costs.

Category	**Figure**
Number of tyres used / Year	585
Cost of Replacement Tyres / Year	$46.77m
Total Tyre Repair Cost per tyre	$7,500
Total Cost of Replacement and repairs / year	$51.15m
Reduction in Total Cost from Current Operations	$11.54m

Table 4.3 – Scenario 2, Key Figures

In this situation, the increase in tyre lifespan of 10% (470 hours) resulted in 58 fewer tyres being required each year, leading to $4.67m in cost reductions per year. The reduction in maintenance requirements lowered the maintenance cost per tyre by $10,000, resulting in a total operational cost reduction of approximately $11.5m.

4.1.3 Scenario 3: Conservative

This scenario considers a much more conservative outcome, where the monitoring system has a minimal impact on operations. In this case, while the system provides some benefits, the reduction in both tyre usage and repair costs is less pronounced.

Category	Figure
Number of tyres used / Year	630
Cost of Replacement Tyres / Year	$50.37m
Total Tyre Repair Cost per tyre	$16,250
Total Cost of Replacement and repairs / year	$60.60m
Reduction in Total Cost from Current Operations	$2.09m

Table 4.4 – Scenario 3, Key Figures

In this situation, the increase in tyre lifespan of 100 hours resulted in 13 fewer tyres being required each year, leading to $1.07m in cost reductions per year. The reduction in maintenance requirements lowered the maintenance cost per tyre by $1,250, resulting in a total operational cost reduction of approximately $2m.

4.1.4 Comparison and Projections

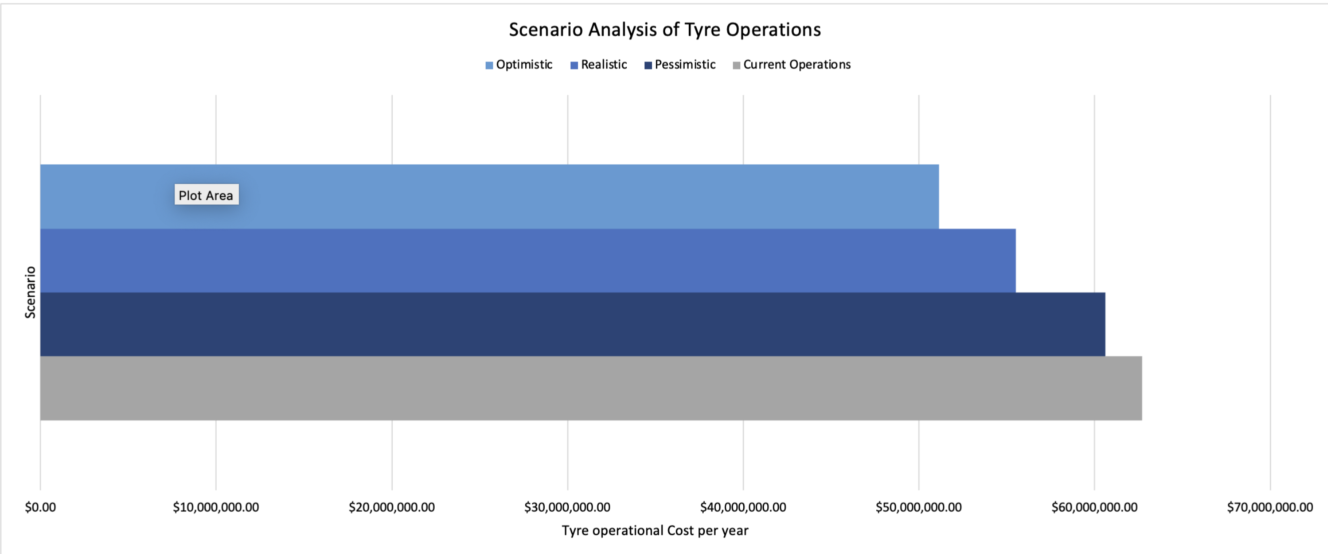


Figure 4.1 – Scenario Analysis of Tyre Operations Costs under Corehesion's ATMS

From the following analysis, it is clear that even small improvements in tyre lifespan and maintenance can lead to substantial cost reductions for MAC. While the optimistic scenario demonstrates the potential for a significant reduction in both replacement and repair operation costs, even the realistic and conservative scenarios show the potential benefits of the ATMS.

The table below outlines the present value of operation expenses saved across the next 6 years. The present value was determined using an inflation rate of 3%, which is realistic given the current condition of supply chains and geopolitical risk factors.

Scenario	Present Value
Scenario 1: Realistic	$40.00m
Scenario 2: Optimistic	$64.28m
Scenario 3: Convervative	$11.65m

Table 4.5 – Present Value of Operation Cost Reductions across the next 6 years

This analysis demonstrates that, regardless of the scenario, the introduction of Corehesion's tyre monitoring system can provide financial benefits through improved efficiency and maintenance practices for MAC. This, combined with further reductions in downtime and enhancements in safety not fully captured in this analysis, is likely to increase the overall long-term impact of the system.

4.1.5 Analysis Limitations

Given the lack of information provided by MAC, a full RCM Cost-Benefit Analysis could not be performed, as outlined in Section 2.2.7. While the scenario analysis above provides valuable insights into the potential impact of the tyre monitoring system on the lifespan of haul truck tyres, several limitations must be acknowledged. One key limitation of this analysis is the absence of data on the impact of haul truck DT. The scenarios primarily focus on tyre lifespan and repair frequency, without considering the potential reduction in DT resulting from early issue detection.

Decreases in DT can have a compounding effect on productivity, as the unavailability of haul trucks may delay operations and cause disruptions to other interconnected activities. However, without specific figures on DT, the full operational benefits of the system cannot be fully quantified.

Another limitation of the analysis is that it does not fully account for the increase in operational efficiency of the haul trucks, as only data on tyre lifespan has been provided. Tyre performance is not an isolated factor; it directly influences the overall efficiency of operations, impacting the wear and tear on associated components such as shock absorbers, axles, and other key stress points. By extending the lifespan of tyres and reducing the frequency of repairs, the system could potentially lead to smoother operations with fewer interruptions. However, without specific information gathered in this area, the Cost-Benefit Analysis remains incomplete. Increased efficiency could translate into notable impacts on operational costs, fuel consumption, and the ability of the mine to meet production targets, all of which are key considerations for any operation.

Additionally, the analysis does not account for potential safety improvements, which are a critical factor in any mining operation, particularly in Australian mines. Enhanced monitoring can significantly contribute to creating safer working environments by detecting issues before they escalate into more serious failures that could lead to hazardous situations for operators. Safety is considered the top priority for operations at MAC, and any reduction in the likelihood of accidents or near-misses would be a significant benefit. The absence of safety-related data in this analysis therefore leaves an incomplete picture of the system's overall impact.

The final limitation of this model is that it does not account for the operating costs associated with the Corehesion system. While this will represent an ongoing expense, including system maintenance, monitoring, and potential software licensing fees, it was not a major consideration in this analysis. This decision was made because the significant cost savings projected from reduced tyre replacements, fewer repairs, and increased operational efficiency are expected to far outweigh the operational costs of the system. However, it is important to acknowledge that these expenses will impact the overall cost-benefit equation and should be carefully considered in future analyses. Factoring in the costs of running the Corehesion platform would provide a more complete picture of its financial impact on MAC over the long term.

Despite these limitations, it is important to highlight that the missing information primarily relates to factors that could indicate further cost savings and operational efficiencies. In particular, reductions in downtime, improved safety conditions, and enhanced operational efficiency are likely to deliver additional benefits beyond those captured in the current projections. Given this, we remain confident in the positive impact of the system. While the figures provided in the scenario analysis are conservative, the full benefits are likely to surpass these estimates, further justifying the system's implementation. The projected outcomes, even in their current form, suggest that the new system will deliver significant value to MAC.

4.2 Key Stakeholder Interaction

This project has focused on developing a practical solution for the challenges faced by the research mine through Corehesion's current platform. A key part of this development has been interacting with key stakeholders at MAC to ensure that the proposed system aligns with their operational requirements and expectations. This collaboration provided valuable insights into how the tyre monitoring system could be enhanced to better serve the customer.

4.2.1 Presentation of System Solution

On the 14th of August, Corehesion presented their initial system proposal to key Otraco stakeholders from MAC. This presentation outlined the capabilities of Corehesion's current system and explored potential system expansions tailored to meet specific challenges faced by the customer. The proposed system design and its implementation strategy were introduced, and feedback from all those present was noted to inform further design iterations.

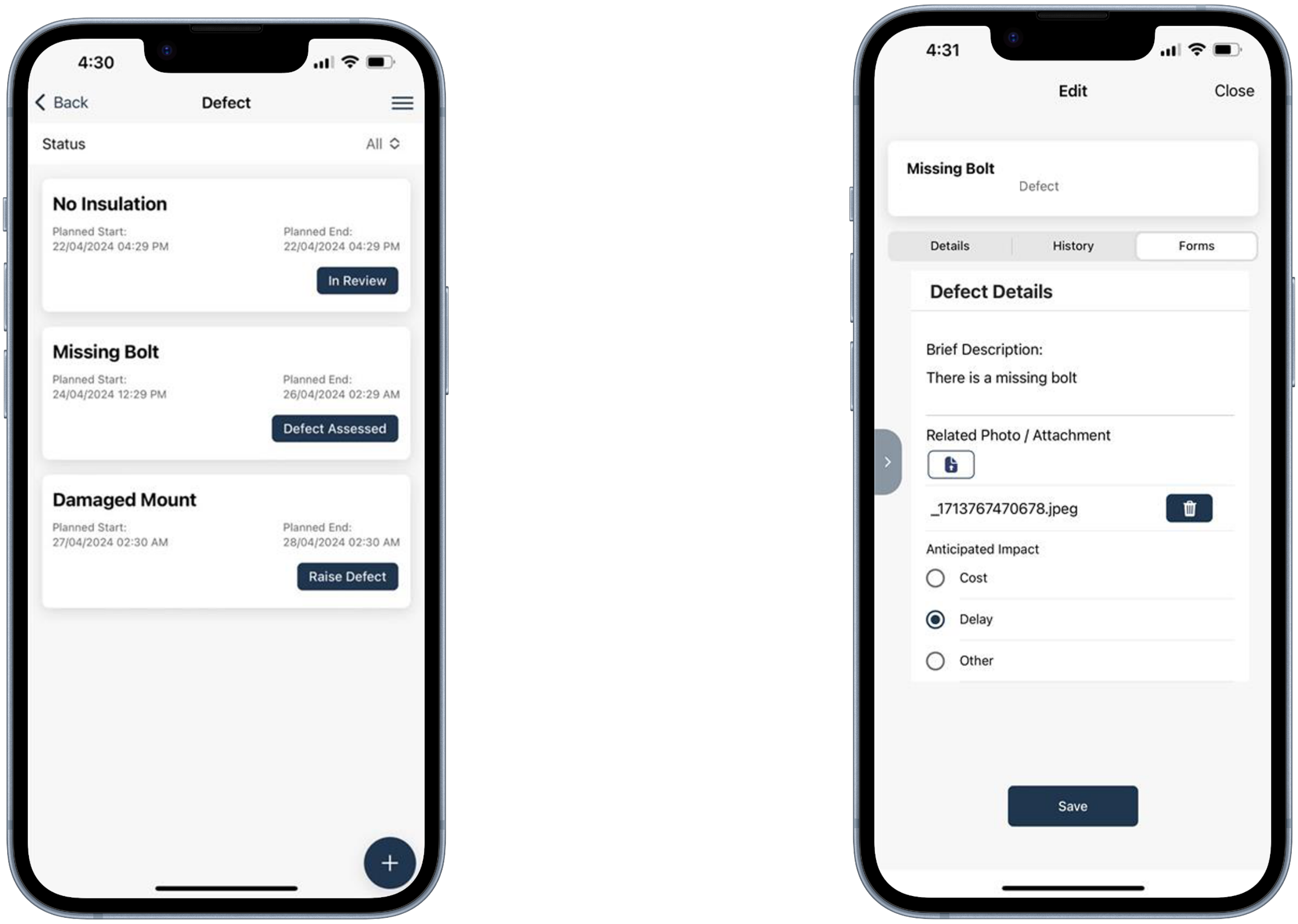


Figure 4.2 – Example of Form Function in Corehesion System

Figure 4.2. shows an example of a form functionality in Corehesion's current system. This was one of the main focus points for the presentation as a form such as this would be used to report a defect with tyre's out on the field. Images can be attached to this form and it is completely customisable based on the needs of the user.

Figure 4.3 and 4.4 shows the graphics used to explain the basic workings of how Phase 1 and Phase 2 deliver key insights to users across the mine. Phase 1 focuses primarily on providing capabilities to front-line workers, including haul truck operators and Otraco contractors. Phase 2 focuses more on delivering insights to decision-makers regarding the condition of tyres, enabling data-driven decisions to be made quickly.

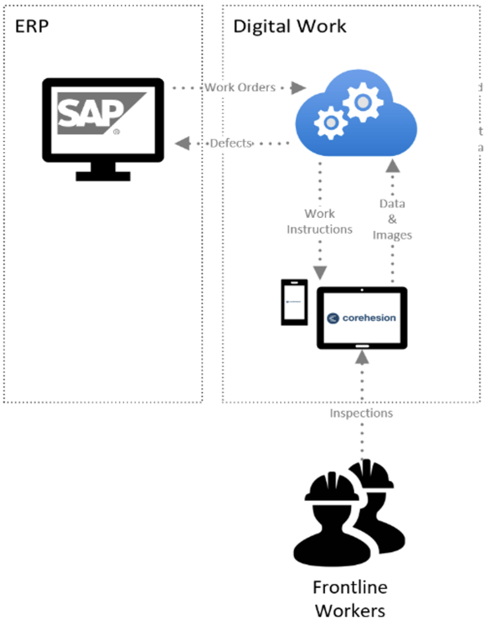


Figure 4.3 – Phase 1

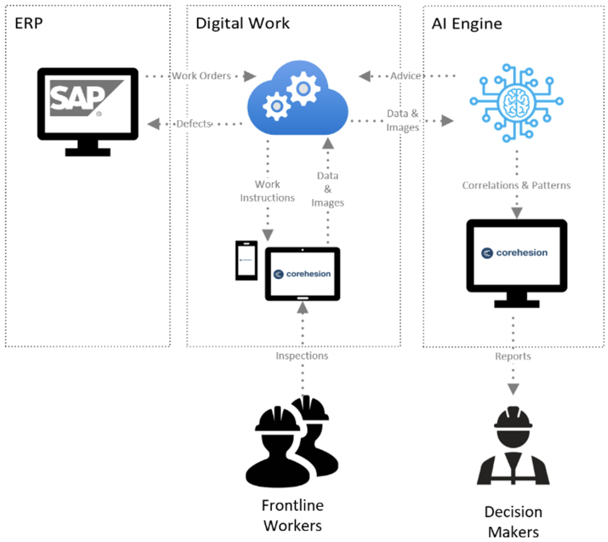


Figure 4.4 – Phase 2

4.2.2 Stakeholder Feedback

The Otraco tyre management team expressed their enthusiasm for Corehesion's current system capabilities and was impressed with the company's flexibility in developing customer-specific software solutions. The prospect of increasing visibility into tyre conditions was particularly well-received, as it would enhance their ability to monitor tyres throughout their lifespan.

Their key feedback was centred around the following areas:

- The Otraco team was confident in the system's ability to significantly increase tyre lifespan. With the increased understanding of the daily condition of all tyres in the fleet, they hypothesised that timely interventions could extend the lifespan of tyres beyond the current average of 4,700 hours.
- They also suggested a more streamlined method of integrating their current platform, used for maintenance work, with Corehesion's system so that it could access the information stored on their servers. They believed that this data could help make better predictions about the likelihood of tyre failure, in line with RCM practices.

- They were wary of the proposition to integrate an AI vision tool, believing that the training and integration of the system would not provide a sufficiently high return in terms of increased detection.
- It was suggested that the focus should begin clearly with the implementation of the alert system and image/video collection from the worksite, as this would have the most immediate impact. Following a successful rollout of this (Phase 1), an assessment should be made on the viability of proceeding with Phase 2.

Overall, the presentation with Otraco management was a successful one. The key takeaway was that the system was able to meet the current needs of the mine and represents a great first step in identifying issues affecting tyre lifespan. The management team expressed enthusiasm about the system and were eager to see it implemented as soon as possible through a pilot program. They are keen to assess the system's performance in a real-world environment and gather data to drive future optimisations and potential full-scale rollout.

4.3 Future Implementation Plan

To implement this system, a deliberate decision was made to split the development into two distinct phases. This business decision allows for an evaluation after the completion of Phase 1 to determine if it is financially viable to proceed with the project, make minor changes or to focus on expanding the developed system significantly.

Providing Corehesion with this option enables them to generate positive cash flow from the project more quickly, which can then be reinvested into the development of Phase 2 and into marketing efforts to support further system expansion into other mines or industries. This option also allows for further research into the viability to the technology integration suggested to be conducted to ensure it is the best tool for this system given operating conditions and users.

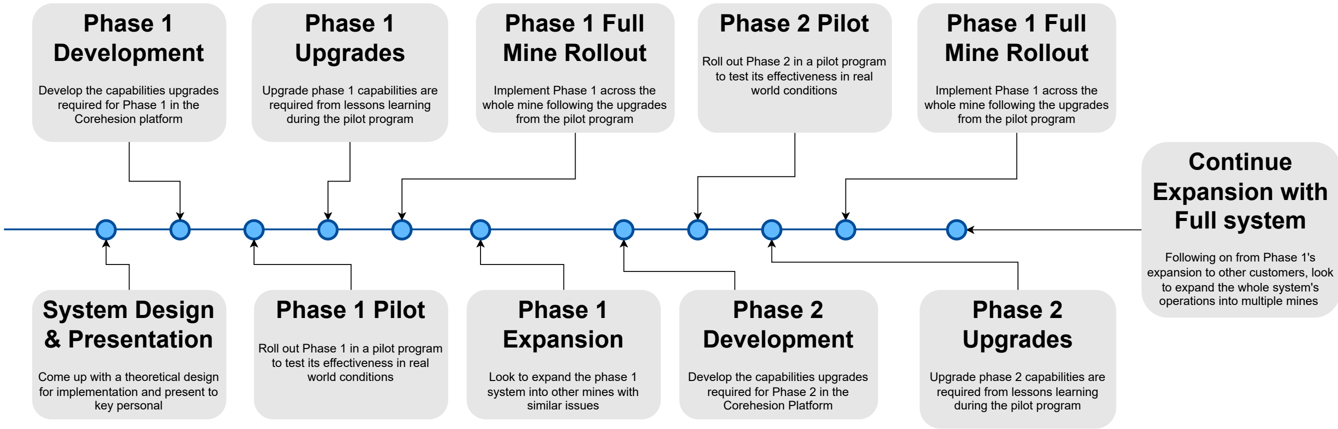


Figure 4.5 – Timeline of System Implementation

4.3.1 Pilot Program

The pilot program will focus on implementing the system in a controlled environment at the current research mine, MAC. This phase of development will involve deploying the daily notification and urgent alert system, as well as image and video collection tools for daily inspections. The goal is to ensure the tool integrates smoothly with existing workflows. By conducting a small-scale pilot rollout first, Corehesion can gather critical data on system performance and obtain valuable feedback from operators and managers on areas for improvement.

The success of the pilot program will be assessed based on how effectively the system integrates into existing workflows and the extent to which it provides additional information to key decision-makers in tyre monitoring and maintenance. Upon successful completion, the insights and developments gained from the pilot will guide the Phase 1 rollout and potentially inform a future Phase 2 implementation.

4.3.2 Full Mine Rollout

Following the pilot program, the full mine rollout will be the next step in Phase 1 implementation, expanding the system across the entire mine. This stage will involve scaling the alert and monitoring system to cover all relevant areas of the mine site, including the fuel depots, maintenance workshops, and key points along the haul truck roads. This will ensure that there is always a nearby point of contact when issues arise on the worksite and that daily data collection at the fuel depots can be conducted at all three depots onsite. A training program for haul truck operators and fuel depot attendants will also be implemented to bring all personnel up to speed with the new system and to establish updated operational procedures. This will also provide an opportunity for personnel to offer their feedback on the system and how it will operate moving forward.

The full mine rollout will include rigorous testing from Corehesion's software platform to ensure that the system can handle increased data loads and usage across the mine. Currently, the mine has 4G coverage across 90% of its area, and Corehesion's platform is already extensively used by MAC for scheduling and personnel management.

4.3.3 Future Expansion to Other Mines

After a successful mine-wide rollout of Phase 1, the focus will shift to expanding the system to other mining operations or potential industrial sectors that could benefit from this technology. This expansion will enable Corehesion to leverage the insights and lessons learned from the initial deployment at MAC and apply them to new clients with minimal disruption to their operations. The system will be adaptable to the specific needs of different mines, including challenges such as limited mobile coverage and varying regulatory requirements.

The future expansion plan will also include marketing efforts to promote the system to other mining companies and industries. This will involve presentations at industry events and identifying key personnel at mine sites to target for marketing the technology. As more sites adopt the system, Corehesion will be able to further refine and enhance the technology while maintaining a positive cash flow.

Chapter 5

Analysis and Discussion

This chapter will present a detailed discussion of the methodology outlined in Chapter 3 and the results from Chapter 4. It will include a critical reflection on the entire process, starting with the identification of the core problem, the research conducted to inform the proposal's development, and the collaborative work with stakeholders to craft a solution that would be viable for the research mine.

Following this evaluation of the overall progress, this discussion will also address the key challenges that emerged during the project. These included the constraints posed by a condensed project timeline, the difficulties encountered in stakeholder engagement and communication, and the competing business priorities for Corehesion. A reflection on the impact of these challenges on the project's momentum, and how they were overcome or at least mitigated, will also be conducted.

Finally, the discussion will highlight lessons learned from this industry placement research project, offering insights into potential improvements for future project implementations. This will focus on time management, increasing stakeholder engagement, and efficient resource allocation in a dynamic business environment such as Corehesion. By doing so, this chapter aims to provide a comprehensive and reflective analysis of the project's methodology and outcomes, while acknowledging areas of success for the project and potential opportunities for further refinement.

5.1 Problem Identification and Research Development

The first phase of the project involved working closely with senior managers at Corehesion and key stakeholders at the research mine to identify core problems that could potentially be addressed by upgrades to Corehesion's current platform. These efforts focused on identifying issues related to major operational cost pain points, where the introduction of more efficient management tools could make a significant difference. The research document produced from this investigation is provided in Appendix D and was used to inform Corehesion's management on which problem to further pursue.

In parallel with this work, research was conducted into maintenance management methodologies and emerging technologies that could potentially disrupt the industry. The findings from this research informed the structural development and writing of Chapter 2, which summarises the research conducted during the first four months of the placement at Corehesion, from January until the end of May. The extended timeline was due to competing priorities within Corehesion's management, which delayed the decision on the specific investigation area for the project.

5.1.1 Stakeholder Collaboration

After the first contact with key stakeholders at MAC in late May regarding the issue they were facing with unexplained decreases in tyre lifespan, further development of the project could commence. The initial phase of specifically identifying the problem the mine was facing proved difficult, given their limited data on tyre conditions beyond the monthly check-ins. This, in turn, led to the realisation by Corehesion that addressing this overarching problem would require increased monitoring of tyre conditions to better diagnose the issue.

This stage of working to recognise the key problem was further supported by additional meetings with MAC's tyre maintenance contractor, Otraco, in June. These meetings informed our decision on how to proceed with the solution development. They highlighted the challenges of inspecting haul truck tyres during operation, as haul trucks come into refuelling stops when they require it and not on a set schedule. The only time haul trucks stopped during operation was at fuel depots, which was determined to be the optimal point to implement a solution for gathering more data on tyre condition.

5.2 Solution Development

Chapter 3 outlines the current tyre monitoring system used at the research mine and identifies key areas of weakness that the newly proposed system from Corehesion aims to address. During this stage of the project, from mid-June until early August, the viability of different solution proposals, given the operating conditions and the realistic constraints of developing and implementing the new system, were all considered. It was ultimately decided to map out the implementation in two distinct phases. This approach not only allowed Corehesion to better plan the development of new capabilities but also gave the business the option to reassess and decide whether to continue the project based on its success at the halfway point. For the research mine, this was an advantageous timeline, as a slower implementation with a detailed pilot program ensured there would be minimal disruption to current operating practices.

The solution developed took into account all the key weaknesses of the current system, including the reliance on in-person inspections, which were often just visual, the lack of clear communication channels for reporting issues, and the insufficient recording of crucial information about tyre condition, health, and history. The key elements of Corehesion's proposed system included increased visual monitoring through image capture at each fuel depot and a dedicated notification/alert system for flagging issues.

5.2.1 Corehesion Platform Integration

An important consideration during the development of the solution was the viability of its implementation through Corehesion's existing software platform (website and mobile application), and the potential synergies that could be exploited between current capabilities and the proposed system. The solution was able to integrate much of the platform's existing tools with minimal requirements for upgrades, particularly in phase one of the project. This was an ideal outcome for the business as it reduced development requirements and, consequently, the costs associated with system implementation.

5.3 Project Challenges

This project faced some significant challenges from an extended project timeline, to development constraints from Corehesion and issues with consistent stakeholder engagement. These challenges, while overcome, were a significant limiting factor in both the overall success of the project and the point at which it could progress.

5.3.1 Time Constraints

One of the most significant challenges for this project was the considerable delay in deciding on the project topic, which was not finalised until mid to late May, four and a half months after the placement commenced. Given that the placement was originally scheduled to be completed within six months, this delay placed immense pressure on the development process. As a result, the project timeline had to be extended until mid-September for continued work with the company, with the presentation and submission of the final project not completed until late October.

Compounding this issue was the fact that university classes resumed at the beginning of August, creating conflicting priorities between academic commitments and the demands of the project. Balancing these responsibilities proved to be a significant challenge, impacting the overall momentum and the ability to dedicate the necessary time to the project. This overlap led to the need for careful time management and prioritisation, as both the project and university work required substantial attention. Despite these challenges, the project was completed, but the extended timeline and competing demands emphasised the need for better initial planning and more timely decision-making to avoid similar delays in future projects.

5.3.2 Stakeholder Engagement and Communication

Stakeholder engagement was a consistent challenge during the latter stages of the project, largely due to the numerous competing priorities of key personnel at both MAC and Otraco. Additionally, one of the key individuals at Otraco went on leave in June, further exacerbating communication difficulties. This lack of consistent engagement led to significant delays in decision-making and information gathering during June and July, both of which were critical to developing the correct solution for the customer.

The absence of timely communication created bottlenecks in the project's progress, as vital input from stakeholders was needed to refine and validate the proposed system. Without this feedback, the development team had to proceed with limited information, increasing the risk of misalignment between the solution and the customer's operational needs. These delays highlighted the importance of establishing more robust channels of communication and ensuring that backup plans are in place when key personnel are unavailable, especially in projects with tight timelines and critical decision points.

5.3.3 Competing Business Priorities

Corehesion's business priorities also contributed significantly to the delays in the project, as the company was focused on current project developments already in progress. This is completely understandable when viewed in the context that Corehesion is a startup SaaS provider with limited capacity to undertake extensive research and development projects. The competing demands of maintaining ongoing business operations while attempting to innovate placed considerable strain on the company's resources, further slowing the project's momentum.

5.3.4 Impact of Challenges on Project Outcomes

The impact of these challenges on the project was substantial, with the project completion being delayed from the end of July to the end of October—a three-month extension. Additionally, the lack of concrete results was evident due to the inability to roll out the pilot or full system by the time I finished with Corehesion in September. These delays hindered the full implementation and testing of the proposed solution, leaving some critical aspects of the project unverified at the time of completion.

5.4 Lessons Learned

Reflecting on the project's challenges and outcomes, several key lessons were learned that can both inform future projects within Corehesion as well as guide future students in the ESIPS program.

5.4.1 Time Management

One of the primary lessons learned from this project is the importance of effective time management and clear communication regarding timeline constraints. A more structured communication process for finalising the project topic and allocating time for each stage could have allowed for a more thorough exploration of potential solutions and further refinement of the solution presented. Future ESIPS projects would greatly benefit from clearer milestone setting and ensuring sufficient time and resources to at least begin a pilot program before the conclusion of the placement. By doing so, both the company and the student would have the opportunity to test the viability of the solution and make adjustments if necessary.

5.4.2 Increasing Stakeholder Engagement

Stakeholder engagement was a critical factor in the success of this project, much more important than I had originally considered. If this had been identified earlier in the project cycle, a more proactive approach could have been taken to ensure fluid communication was maintained between all parties—Corehesion management, Otraco, managers at MAC, and myself—which would have sped up the project. Regular check-ins and clearer lines of responsibility could have prevented delays and ensured that key decisions were made in a more timely manner.

Another key takeaway from this project has been that development projects are difficult for leadership to prioritise, as they are usually secondary to ensuring operational efficiency and consistency of existing operations. It showed that development projects need leaders to allocate consistent resources and prioritise them to be completed promptly. Therefore, effective and frequent communication about the project's progress, potential impact including savings, and other positive aspects should be regularly conducted with management to maintain their interest and investment in the project. This will help ensure that the project remains a priority despite competing business demands.

5.4.3 Efficient Resource Allocation

Efficient resource allocation is essential in a dynamic startup business environment like Corehesion. Future projects should keep this in mind early in the project lifecycle to ensure that resource requirements and potential implementation timelines accurately reflect the company's limitations. This type of planning also ensures that potential bottlenecks are identified and accounted for, allowing for a more realistic and achievable project timeline. Proactively addressing these constraints can help prevent delays and ensure smoother project execution.

Chapter 6

Conclusion

This chapter summarises the work completed throughout this thesis, highlighting how the results addressed the aims and objectives of the project. It also comments on the significance of the contribution this work has made to research in this field and suggests potential future work and improvements that could further expand upon the ATMS. In addition, this chapter reviews the outcomes of the research in terms of practical implementation and discusses the feedback from key stakeholders involved. It also provides an outline of possible next steps for refining and scaling the system for broader application.

6.1 Summary of Findings

This section highlights the value proposition of the proposed ATMS system, along with how the thesis successfully met its aims and objectives by addressing the core operational issues identified at the research mine. It also discusses the potential long-term benefits of the system, including its scalability and adaptability to other asset management contexts beyond the initial mining application.

6.1.1 Value Proposition

This thesis was commissioned by Corehesion Group Pty Ltd with the intention of providing a new source of value creation and business opportunity for the company. The SaaS business model that

Corehesion operates focuses on attracting new customers through the development and presentation of new digital products that can be customised to solve particular business systems. This project addresses the issues raised by MAC, as outlined in Section 1.3. Producing a product that can address this core issue without requiring large amounts of additional software development on Corehesion's part generates significant value for the company. This product will benefit Corehesion by:

1. Producing recurring revenue through a periodic subscription fee paid by the research mine for the use of this system. Particularly with the implementation of Phase 1 of the ATMS, given the limited work item requirements, the value created through this predictive cash-flow stream with minimal capital investment will provide long-term financial stability and increase the customer's lifetime value. In addition, it provides a scalable product able to be replicated for other similar mines, with further tailoring to other mining industries and then into other heavy industries such as transportation and logistics. Annuity and 'sticky' revenue streams are highly valued by investors which deliver growth for Corehesion. Given that the project was based on a major global mining company like BHP is extremely valuable given they have diverse mining operations around the world and could become a lucrative client for Corehesion. In addition, learnings are easily transportable to other customers such as Rio, Anglo, Peabody etc. This is a key driver of future growth for the business.

2. The solution presented, while focused on tyre degradation, has been deliberately generalised to ensure it can be adapted quickly to other asset management use cases, as per the aims and objectives outlined in Section 1.4. This nuance is important to consider because the research was not conducted for a single organisation but rather as a demonstration of how a low-cost digital technology approach to asset monitoring could effectively implement RCM theory in a practical work environment. Therefore, this research has value beyond its current proposed application, potentially across the mining industry, heavy industry, and even sectors such as transportation or logistics. A product that significantly improves the monitoring process at a low cost, with a broad potential customer base, and is easy to implement, develop, and maintain, offers high value for a SaaS provider. These characteristics ensure that the industry partner can leverage economies of scale effectively across the industry both domestically and globally, thereby enhancing value creation.

While the value creation avenues outlined above are inherent to the SaaS business model, their realisation in the context of this research depends on the quality of the proposed product and the efficiency gains achieved by customers and therefore their willingness to pay the SaaS subscription. Therefore, the success of this product's development can be evaluated by comparing the research outcomes to the aims and objectives outlined in Section 1.4.

6.2 Thesis Aims and Objectives

This thesis successfully carried out the detailed design, implementation plan, and groundwork required for the development of a real-world, practical asset monitoring system that utilises accessible digital technology to provide a low-cost approach to asset management and maintenance. The final ATMS design takes into account real-world considerations from the research mining operation and effectively balances the need for a cost-effective solution to a core issue: the lack of visibility of asset conditions during operations.

A review of existing literature on theoretical systems revealed a clear gap in research concerning low-cost, practical systems with real-world applications. This, combined with a comprehensive evaluation of current operational procedures and personal responsibilities, enabled the ATMS to be designed to effectively address this gap.

Finally, through an extensive design process conducted in conjunction with key stakeholders at the research mine, the system was iteratively developed using feedback from individuals at the site. Existing procedures and normal practices were carefully considered in the design, with a focus on seamless integration with current operations. The thesis details how the ATMS and this research effectively addressed the mine's core issue. Following this, an in-depth cost-benefit analysis of the potential savings was conducted. A key finding was that, even with a conservative outlook, the potential cost reductions amounted to approximately $2m per anum, which is a substantial reduction and validates the value of the system. This is extremely valuable as these cost savings translate directly to anincrease in profits, as there are minimal expenses apart from the SaaS period subscription cost.

All stages of this thesis were conducted in alignment with the objectives outlined in the introduction, thereby satisfying the aim of increasing the visibility of asset conditions to enable efficient gains at a low cost to the mine.

6.3 Significance and Contribution

This thesis and the development of the ATMS have contributed valuable advancements to the field of asset management in open-cut mining operations. The project has addressed critical operational gaps related to tyre maintenance and monitoring, particularly regarding the lack of real-time data collection and predictive maintenance capabilities. Through the iterative design and successful implementation of the ATMS, the system has improved visibility into tyre conditions, allowing mine operators to make more informed, data-driven decisions that enhance safety and reduce operational expenses.

The thesis also highlights the practical applications of modern digital technologies, including AI-based data analytics and image recognition, in enhancing the implementation RCM framework within the mining industry. These advancements are poised to have broader applications across heavy industries, demonstrating the scalability and cost-effectiveness of leveraging everyday technology to enhance asset management.

The ATMS has received positive feedback from key stakeholders at the research mine, demonstrating its potential for real-world impact. Furthermore, the system has laid the groundwork for future expansions, both within the mine and potentially across other sites, industries, and asset management applications. The significant cost savings and operational improvements evidenced by the ATMS validate its contribution to both the industry and the field of RCM, offering a replicable model for improving maintenance strategies in heavy industry operations.

6.4 Future Work

While the development and implementation of the ATMS has yielded significant improvements in the monitoring and maintenance of tyre conditions within open-cut mining operations, there are several areas that could be further explored to enhance the system and its applications.

6.4.1 Enhancing Predictive Capabilities and System Scalability

One potential avenue for future work is the integration of additional predictive analytics tools that incorporate machine learning algorithms to further refine the system's forecasting abilities. While the current ATMS leverages real-time data to identify issues before they become critical, more sophisticated models—such as those incorporating deep learning—could improve the accuracy of tyre failure predictions by considering a broader array of variables, including weather conditions, terrain types, and vehicle load patterns.

Another area worth exploring is the scalability of the ATMS to different types of mining environments, including underground mining. The challenges faced in underground operations, such as limited visibility and more extreme working conditions, provide an opportunity to adapt the system for harsher environments. This would involve re-evaluating sensor placements, data collection methodologies, and the robustness of the system to withstand extreme conditions. By adapting the ATMS to work across various mining settings, the system's impact could be broadened significantly generating more significantly more value for Corehesion. In addition, the models developed for the Australian markets are easily transportable into other markets such as the Americas, Canada, Europe, the Middle East and Africa (EMEA) and Asian heavy industry markets.

Expanding the scope of the ATMS to other asset management areas within the mining operation is another logical progression. For instance, applying the system's underlying principles to the monitoring of other critical and expensive mining equipment, such as conveyor belts, crushers, and drilling rigs, could create a unified, comprehensive asset management platform. This would allow for consistent monitoring across different equipment types and further optimise maintenance strategies, reducing downtime and extending asset life across the board.

6.4.2 Cross-Industry Applications

Future work could explore the adaptation of the ATMS for industries outside of mining. Given the universal principles of asset monitoring and maintenance, sectors such as logistics, construction, and transportation (road, rail, shipping and airtravel) could benefit from similar systems. By tailoring the system to meet the specific challenges of these industries, the ATMS could become a versatile tool for asset management in a variety of industrial settings.

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Appendix A

Case Study - AMME4710: Computer Vision and Image Processing

This unit of study introduces students to vision sensors, computer vision analysis and digital image processing. This course will cover the following areas: fundamental principles of vision sensors such as physics laws, radiometry, CMOS/CDD imager architectures, colour reconstruction; the design of physics-based models for vision such as reflectance models, photometric invariants, radiometric calibration. This course will also present algorithms for video/image analysis, transmission and scene interpretation. Topics such as image enhancement, restoration, stereo correspondence, pattern recognition, object segmentation and motion analysis will be covered. [117]

- **LO1:** Demonstrate skills in presenting a final design solution to a computer vision/image processing problem.
- **LO2:** Demonstrate skills in working on a design project within a team including communicating with team members, planning, and managing tasks,
- **LO3:** Design an engineering solution to a given image processing task by selecting, developing and evaluating appropriate algorithms and techniques.
- **LO4:** Understand the fundamental principles of how images are formed including the basics of image sensors, radiometry, colour, and projectile geometry.

- **LO5:** Apply basic techniques in image processing including the use of image filtering, features, edge detection, colour spaces/transforms, and matching.
- **LO6:** Apply advanced techniques in computer vision including stereo vision, 3D mapping, object detection, image classification, and use of machine learning algorithms in vision.
- **LO7:** Apply a wide range of image processing techniques to real world applications.
- **LO8:** Understand the type of algorithm required for a particular image processing task.

A.0.1 ESIPS Requirements

"Ensure that you meet at least 75% of the learning outcomes from the published Unit of Study outlines."

In line with this requirement, 6 of the 8 learning objectives for this course will be addressed within the scope of this project: LO1–LO5 and LO8. However, in meeting the case study aim and throughout the extensive research and experience undertaken in this thesis, the remaining two objectives – LO6 and LO7 – were also achieved.

A.1 Case Study Aim

This case study aims to demonstrate a thorough understanding of the fundamentals of image processing and computer vision models, with a focus on implementing these tools in real-world scenarios. It will contribute to the research conducted above for Phase 2 of the proposed ATMS. To achieve this goal, the case study will directly address the following objectives:

1. Investigate and communicate the key principles of image processing, from image formation to various processing techniques.
2. Apply advanced object detection techniques to the real-world problem of tyre fault detection.
3. Assess the feasibility of using this technology for the ATMS proposed in this research, including evaluating whether the proposed solution of using iPad images to identify tyre issues is viable.

4. Collaborate with project stakeholders to explore potential implementations and use cases for this technology.

5. Integrate the findings of this research into a real-world project, where they can provide a business case benefit by addressing a customer issue.

A.2 Overview of Project – Detection of Faults in Haul Truck Tyres

This case study closely follows the proposed system in this thesis project, specifically addressing the feasibility of Phase 2 as outlined in section 3.2.2. The context, business case, and requirements for this system are detailed in sections 1.2 and 3.2.

The study investigates how Image Processing Image Processing (IP) and Computer Vision CV can be used to reduce or eliminate the need for human inspection of images gathered daily by the ATMS. The system is designed to automatically identify, monitor, and alert users based on the severity of tyre issues, including:

- Damaged valve stem
- Shoulder separation
- Sidewall bubbles
- Sidewall cuts

Due to limitations in the available data and system constraints, this case study will focus specifically on detecting sidewall cuts in tyres. Following this initial investigation, further work may address other major issues based on the success of this study. The tyres used in this study are from Liebherr haul trucks, as shown in Figure A.1.

Figure A.1 – Liebherr Haul Truck

The importance of this system is discussed extensively in Chapter 3, where this monitoring tool aims to significantly increase the efficiency of data collection and analysis in tyre management. The system is designed to analyse images, such as the one shown in Figure A.2.

Figure A.2 – Sidewall Cut on a Liebherr Haul Truck

Several potential methods for gathering image data were considered for this project, including but not limited to:

- Drones
- Surveillance cameras
- Cameras on other vehicles
- iPads / handheld devices
- Digital cameras

Given the project's requirements – specifically for low implementation costs – it was decided that iPads or mobile phones would be the optimal choice, particularly as Corehesion already has a mobile application compatible with this system. Drones were seriously considered; however, the high capital investment required for their implementation was a primary barrier.

A.3 Image Formation and Properties

Digital images represent a static, discrete view of an observable object, capturing only the visible portion of the Electromagnetic spectrum (EMS) at a specific point in time. According to Cromey, digital images are "numerically sampled data that represent the state of a specific sample when examined with a specific instrument" [27, p. 1]. At their most basic, digital images are a two-dimensional, pixel-based representation, capturing intensity values of light that is either reflected from or emitted by an object [115]. This representation is fundamental for both IP and CV, as it serves as the primary medium through which computer systems interpret and analyse visual information.

A digital image is composed of individual pixels, with each pixel representing the intensity of light (I) at a specific coordinate (x, y). Digital images are typically classified into three main types: **Binary images**, where pixels are purely black or white; **Grayscale images**, where pixels display varying shades from black to white; and **Colour images**, where each pixel represents multiple colours through a combination of intensities.

(a) (b) (c)

Figure A.3 – Colour, Grayscale and Binary Image

The intensity of each pixel is represented by an 8-bit number, which allows 256 possible values (0–255), with the maximum intensity being 255. When colour is required, each pixel at a specific coordinate is expanded into a 1×3 matrix containing intensity values for the three primary colours: red, green, and blue [115]. Figure A.4 illustrates this concept with a zoomed image of a cat, where individual pixels are visible.

Figure A.4 – A digital photo with magnified section showing pixels [11]

In this example image, the top-left corner of the digital photo captures a section of carpet with varying colour patterns. The following (1x3) matrices represent each pixel's colour values in this area. Table A.1 displays the colour values for the first 4x4 pixels in the top-left corner.

70, 48, 36	70, 49, 38	71, 52, 42	71, 52, 44
64, 38, 30	71, 45, 39	80, 58, 52	81, 61, 53
58, 29, 23	67, 37, 34	85, 58, 53	90, 67, 57
53, 34, 22	60, 38, 29	78, 55, 45	84, 67, 52

Table A.1 – 4x4 Pixel Values from the Top-Left Corner of Figure A.4 [11]

A.3.1 Radiometry

Radiometry refers to a sensor's ability to detect fine variations in the intensity of visible Electromagnetic Radiation (EMR). It provides the foundational principles for capturing light intensity in digital images. The following three radiometric properties are essential for interpreting information collected in digital images:

- **Radiance**: Measures the amount of energy emitted, reflected, or transmitted by a surface, indicating the object's perceived brightness.
- **Irradiance**: Refers to the energy received by a surface from a light photon, providing information related to the object's distance.
- **Intensity**: Represents the power emitted by a source in a particular direction, revealing the source's energy output.

In digital imaging, radiometric principles are inputs for algorithms designed to enhance image quality. They are also applied in fields where precise light measurement is critical, such as in medical imaging and remote sensing.

A.3.2 Image Sensors

Image sensors are devices that convert visible EMR into discrete electronic signals, allowing the information to be stored and processed. These sensors, found in most handheld devices (e.g., phones, iPads, cameras), typically use either Charge-Coupled Device (CCD) or Complementary Metal-Oxide-Semiconductor (CMOS) technology. Both types of sensors operate through a grid of photodetectors, where each photodetector captures light intensity as an analogue signal. This grid of photodetectors translates directly into the pixels that form a digital image. The analogue signal collected from the detectors initially represents a continuous distribution of information, which is then divided into individual pixels to approximate the infinite gradations of intensity found in the real world [11]. Figure A.5 demonstrates the analogue signal for the intensity of the colour green in the provided image.

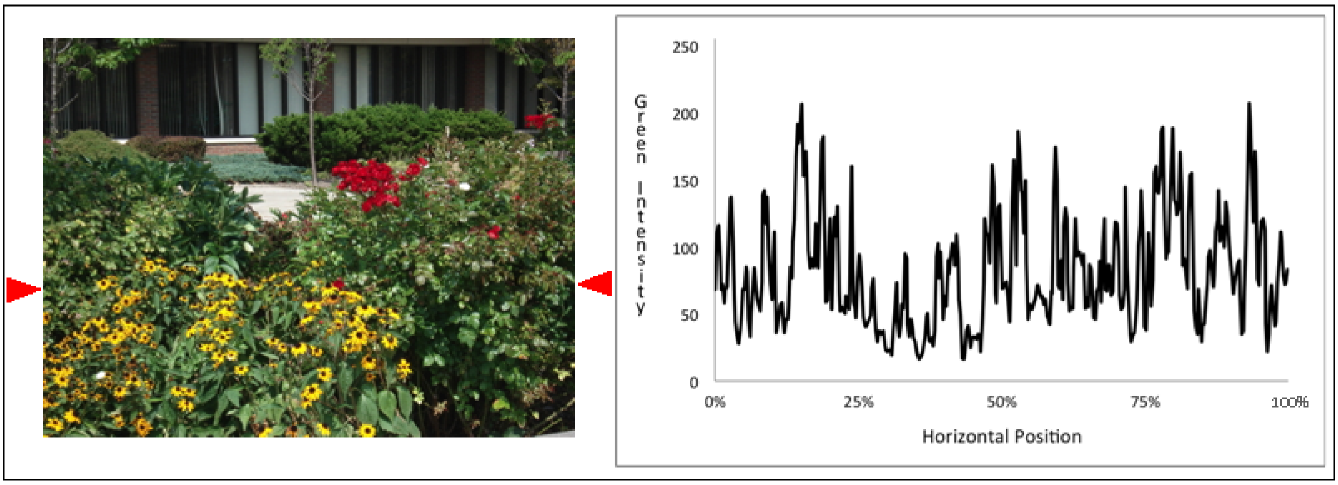

Figure A.5 – Variations of light intensity over space [11]

CCD sensors are often preferred for high-quality imaging due to their low noise levels, while CMOS sensors are typically chosen for their faster processing speeds and lower power requirements. The digitisation of this analogue signal assumes that light intensities remain constant over small spatial intervals, as shown in Figure A.6, which simplifies the signal. The smaller these intervals are during digital conversion, the more accurately the image represents the actual object or scene [49].

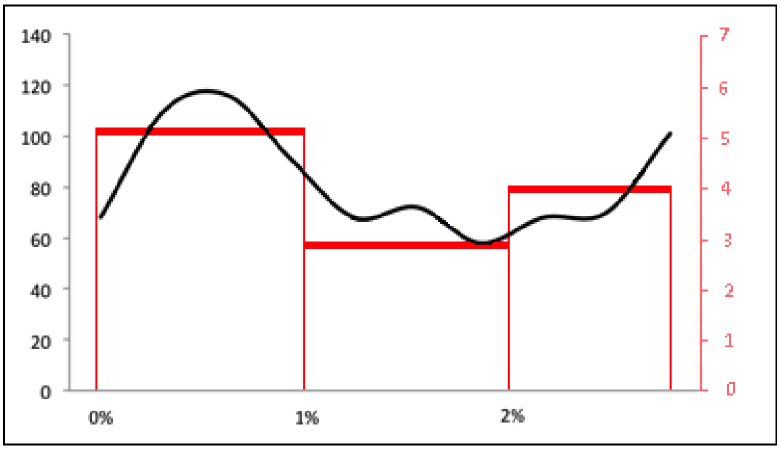

Figure A.6 – Analogue to Digital Conversion [11]

A.3.3 Projective Geometry

Projective geometry provides the mathematical foundation for representing three-dimensional objects on a two-dimensional image plane. This geometry helps explain concepts such as perspective, scaling, and foreshortening, which are essential for translating real-world spatial relationships into a digital two-dimensional image. By applying transformations like rotation, translation, and scaling, projective geometry enables an accurate representation of these spatial relationships.

In IP and CV, understanding projective geometry is crucial, as it provides the foundation for recognising and interpreting the shapes and positions of objects within images. This allows for accurate analysis of spatial relationships, enabling the system to detect and understand the layout and form of objects in a scene.

A.4 Image Recognition and Current Market Tools

The literature review of this thesis conducted extensive research into the methodology, technology , current research and systems within the IP and CV field. This research can be found in section 2.3.5 and encompasses the learning objectives required by this case study.

A.5 Tyre Fault Detection System Methodology

The proposed TFDS utilises CV methods to identify and assess damage to tyres from photos taken with a handheld device. For this project, 25 images of tyres that I took while working onsite will be used to train the system. The proposal outlined in Section 3.2.2 identified Microsoft Azure AI Image Recognition technology as the software to be used for the ATMS. However, due to accessibility limitations, Microsoft Azure's Custom Vision service—a platform that enables regular users to train an object detection system based on a user-provided dataset—has been employed. Similar to the paid version, Custom Vision employs a fast region-based convolutional neural network (Region-based Convolution Neutral Network (R-CNN)) to detect objects. Section 2.3.5 provides an overview of CNNs, widely used in image recognition. An R-CNN applies a CNN to specific regions of an image, using the features from each region to predict the 'class' of that region. In fast R-CNNs, like the model used by Custom Vision, the Edge Boxes algorithm generates region proposals and combines the features of each proposal to improve processing efficiency.

The TFDS employs the Customer Vision platform and uses images taken onsite of different haul truck tyres to attempt to identify issues, ensuring the testing of the proposed software using realistic imagery, as the photos were taken using an iPhone in the workshop at MAC.

A.5.1 Classifying Images

The dataset utilised for training the model comprises 25 images of haul truck tyres, collected during on-site observations at Mt Arthur Coal (MAC). This sample size is considerably smaller than the recommended range of 60-100 images for optimal model training. Consequently, the limited dataset may yield results that are less accurate than if a larger set were available. A sample image from this collection is illustrated in Figure A.7.

Figure A.7 – Image of a Haul Truck Tyre taken at MAC

For each image in the dataset, the sidewall cut areas were classified using the built-in tool in the platform. An example of this classification can be seen in Figure A.8 where the sidewall cuts on the image above were noted.

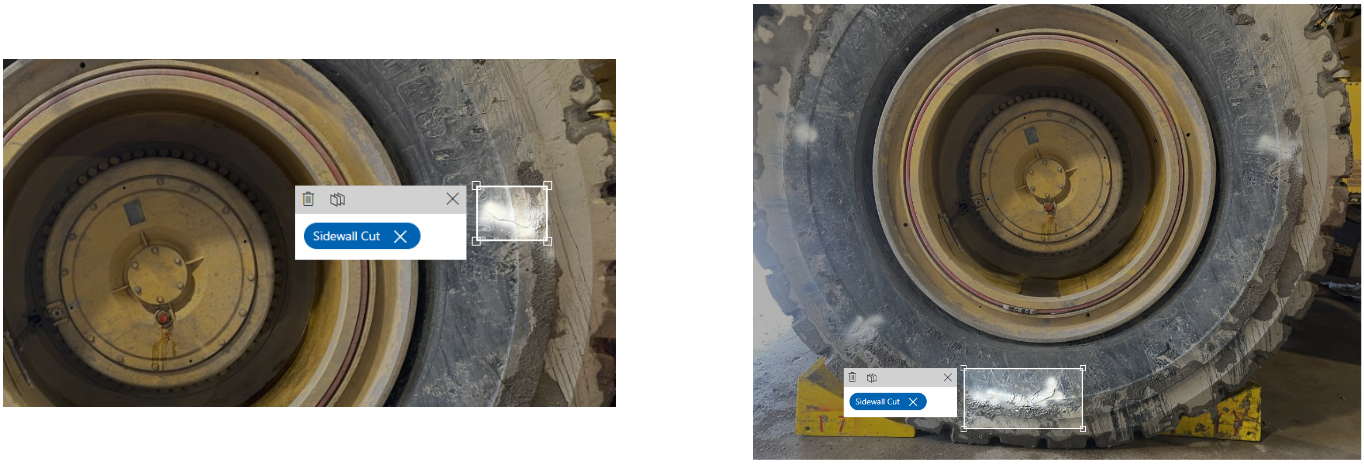

Figure A.8 – Tagging of Sidewall Cuts in Custom Vision's Training Area

Once the regions were identified for the entire 25-image dataset, the model was trained using the training programme built into Custom Vision. After this, 15 images sourced from online will be used validate and then test the model. As there were very few haul truck tyre images online, a number of normal car tyres were used in this testing.

A summary of the Data parameters used for the testing of the model can be seen in Table A.2

Parameter	Value
Probability Threshold	40%
Overlap Threshold	30%
Training Images	25
Validation Images	5
Test Images	10

Table A.2 – TFDS Data Parameters

A.6 Results and Feasibility Evaluation

The outcome of the preliminary testing phase was remarkably positive, considering the constraints imposed by the limited dataset available for training the model. As depicted in Figure A.9, the model demonstrated a notable capacity to identify structural cracks in both specialized haul truck tyres and standard automotive tyres. Notwithstanding, the system successfully identified cracks in only 8 out of the 10 images during the testing phase, indicating room for improvement in model robustness.

Figure A.9 – Results from Preliminary Testing in Custom Vision

The quantitative outcomes of the model's training phase are summarized in Table A.3, which details the precision, recall, and Mean Average Precision (mAP) as calculated by Custom Vision using both validation and test inputs. These metrics reflect a solid initial performance but also highlight potential areas for enhancement in terms of model accuracy and generalization capability.

Parameter	Value
Precision	85%
Recall	60%
Mean Average Precision	75%

Table A.3 – Training Outcomes of TFDS

This outcome, albeit tested with relatively low confidence due to a probability threshold set at 40%, suggests that the system possesses a moderate degree of confidence (40%) in detecting sidewall cuts with a high level of accuracy (80%). While initially, these figures might not appear overly promising, it is important to consider the challenging conditions under which the testing was conducted. Despite these challenges from the limited dataset, the results were very promising. They indicate that, with further refinement and expansion of the training dataset, the TFDS possesses significant potential to be a robust solution in the next phase of implementation. Consequently, this case study supports moving forward with TFDS in Phase 2, aiming to enhance data collection protocols, expand the dataset size, and optimize the model's training algorithms to improve both precision and recall metrics.

A.7 Limitations and Future Work

The tests were conducted on a highly limited number of images, many of which were not captured under ideal conditions. This complexity added challenges to the task of accurate crack detection. Despite these conditions, the results clearly demonstrated that the system was incredibly successful at identifying issues, given its limited training. Future work should focus on increasing the number of images collected to train the model more effectively.

This future work will be supported by the design proposal of the ATMS with its two-phase implementation strategy. This approach will allow for the collection and storage of vast amounts of images on the Corehesion platform, which can then be used to refine the model to a very high accuracy rate.

Another limitation of this system and its implementation is its dependence on Microsoft and the Azure AI platform. As the process behind it requires training a specific model for the business, Corehesion is tied to paying for this service as part of the ATMS. However, considering the potential savings the ATMS can offer a mine, this cost will be relatively insignificant.

A.8 Communication and Presentation

As part of this thesis, I was required to present the development of the ATMS, which unfolded over the course of the project. This included the integration of Microsoft's Azure AI image recognition software into Corehesion's existing platform. The presentation was delivered to key personnel at the research mine where the project was undertaken, aiming to communicate the capabilities and benefits of utilising computer vision/image processing in the new system. Figure A.10 shows how simple methodology and results images were used to clearly explain to technologically illiterate stakeholders how an image processing system would benefit their operations.

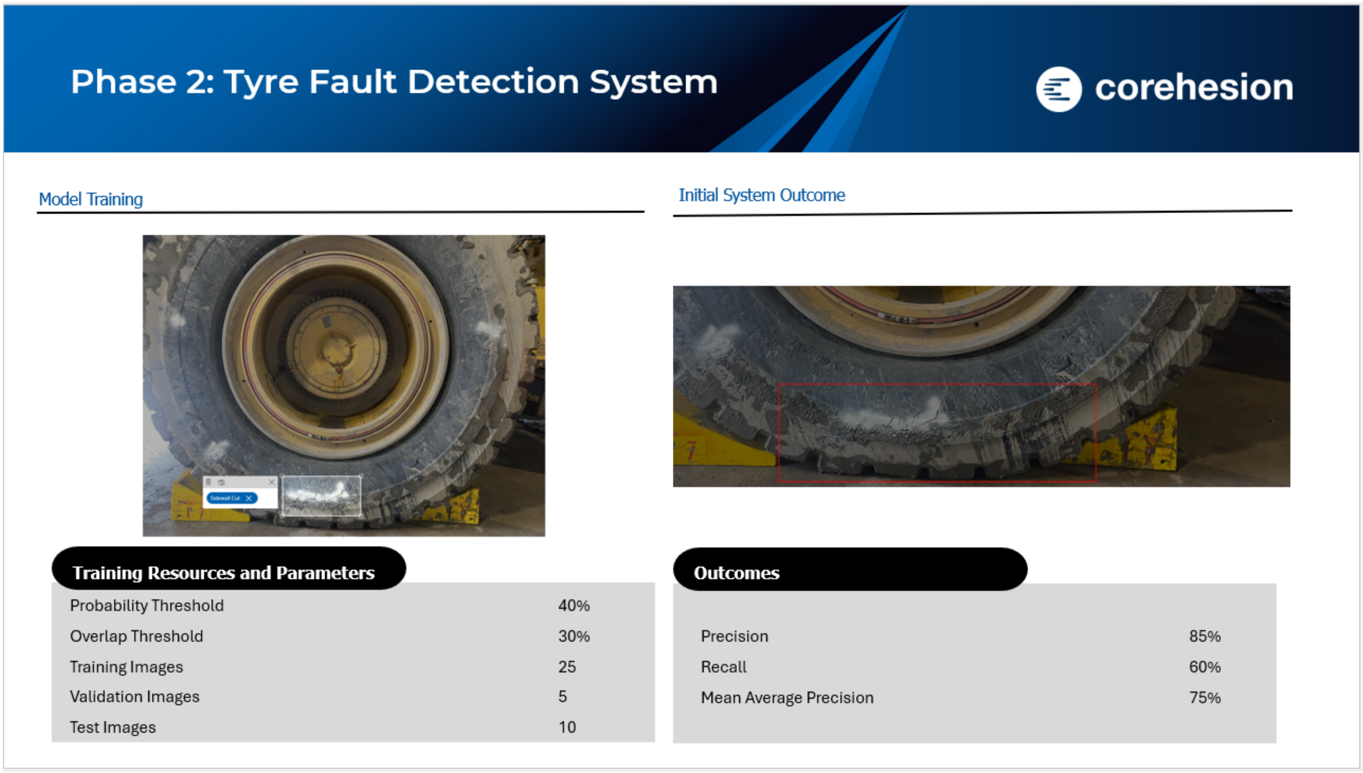

Figure A.10 – Presentation Slide on the TFDS

A key aspect of this communication was to enhance understanding of IP and CV capabilities and how they could be applied onsite.

A.9 Conclusion

This case study definitively showed that the use of CV with the proposed system in this thesis and in particular Microsoft's Azure Custom Vision is a viable tool for the proposed implementation. Based on limited imagery, a model was able to be trained with a relatively good success rate which when given adequate amounts of data - as planned in the 2 Phase launch of the ATMS - will be able to very accurately detect tyre issues at the mine. Through the development of the TFDS, this case study also ensured to address the learning outcomes of the subject AMME4710 in conjunction with the work conducted in the thesis as per the requirements for ESIPS.

Appendix B

Case Study - ENGG5205: Professional Practice in Project Management

B.1 ENGG5205: Unit Outline

This unit of study teaches the fundamental knowledge on the importance, organisational context and professional practice in project management. It serves as an introduction to project management practices for non-PM students. For PM students, this unit lays the foundation to progress to advanced PM subjects. Although serving as a general introduction unit, the focus has been placed on scope, time, cost, and integration related issues. Specifically, the unit aims to: Introduce students to the institutional, organisational and professional environment for today's project management practitioners as well as typical challenges and issues facing them; Demonstrate the importance of project management to engineering and organisations; Demonstrate the progression from strategy formulation to execution of the project; Provide a set of tools and techniques at different stages of a project's lifecycle with emphasis on scope, time, cost and integration related issues; Highlight examples of project success/failures in project management and to take lessons from these; Consider the roles of project manager in the organization and management of people; Provide a path for students seeking improvements in their project management expertise. [116]

The learning objectives listed as part of the subject ENGG5205 are as follows

- **LO1:** Understand the major roles and responsibilities of project managers and recognize the core competencies required of each role
- **LO2:** Define a project and apply the differences between projects or programs and “business as usual” activities in organisations and their major risks and critical success factors
- **LO3:** Understand and identify ethical issues facing project management professionals in projects
- **LO4:** Understand the project context within organisations, including project selection methods and life cycles, and the organisational constraints which affect the choice of project management methods/approaches, and how these approaches are implemented in practice
- **LO5:** Understand the tasks involved in scope, time and cost planning and control, and demonstrate the capacity to carry out the plan, and control project performance
- **LO6:** Demonstrate a broad understanding of the other requirements/components of project plans and performance monitoring, such as quality and risk management, procurement, communications and team leadership.
- **LO7:** Understand the usefulness and limitations existing within bodies of knowledge on project management (PMBOKs) from various project management institutions, and integrate (PMBOKs) into studies and projects.

B.1.1 ESIPS Requirements

"Ensure that you meet at least 75% of the learning outcomes from the published unit of Study outlines"

Following this requirement, 6 of the 7 learning objectives for this course will be addressed within the context of this project. They are, LO1 through to LO6 as listed in the section above. However, in addressing these objectives and through the research and experience conducted throughout this project, LO7 was also met.

B.2 ENGG5202: LO1

LO1: Understand the major roles and responsibilities of project managers and recognize the core competencies required of each role

A project manager, according to Atlassian, "is a leader who guides projects from the drawing board to the finish line, [making] sure everything runs smoothly and stays on schedule. They gather necessary resources, unite team members, and work on continuous improvement" [7]. In the engineering discipline, project management is a crucial tool, as projects often span multiple engineering domains and require input from a diverse range of individuals with unique skill sets. The role of a project manager is to ensure that project objectives are met within predetermined constraints, including budget, time, and quality standards. This section will discuss the key roles and responsibilities of project managers in technical projects, such as the thesis project, and outline the core competencies required to excel in each role.

B.2.1 Roles and Responsibilities of Project Managers

Project managers are responsible for several core activities that guide a project through its stages. They oversee every phase of the project to ensure alignment with strategic goals. The key roles and responsibilities are [7, 77];

- **Project Planning and Scheduling:** Project managers are responsible for defining the project scope, establishing milestones, and scheduling tasks. They initiate the planning processes for these activities and oversee the development of detailed plans to outline tasks, resources, timelines, and deliverables, creating a solid foundation for the project. Planning ensures that all members of the team understand their roles and deadlines, which is critical in maintaining project flow.
- **Risk Management:** Project managers identify potential risks early in the project lifecycle and are responsible for proactive risk management. This involves assessing the impact of uncertainties and developing mitigation strategies for risks.

- **Team Coordination:** Project managers assemble and instruct project teams on what to work on and when. They are responsible for assigning tasks based on individual team members' skills and experience. A project manager also focuses on maintaining team unity through promoting collaboration, resolving conflicts, and leading.
- **Stakeholder Management and Communication:** Ensuring that clear communication lines are maintained among all project stakeholders (clients, team members, vendors, etc.) is another key responsibility. This could involve regular project reports, addressing stakeholder concerns, or ensuring that communication strategies are tailored to suit the audience (e.g., technical or non-technical stakeholders).
- **Budget Oversight:** Establishing budgets, tracking spending, estimating costs, and making adjustments as necessary are all part of a project manager's role. This ensures the project is completed within its financial boundaries.
- **Quality Control and Assurance:** Ensuring the project outputs meet the required quality standards is another critical responsibility. Project managers must implement control measures and conduct quality assessments throughout each phase of the project.

B.2.2 Core Competencies Required for Project Management

To fulfil these responsibilities, project managers need a diverse skill set that spans technical knowledge, leadership abilities, and soft skills to ensure they can meet their requirements. These skills are particularly important in engineering project management, as the work can be highly specialised with many different disciplines required to work together towards the completion of the project [7, 77, 108].

Figure B.1 – Necessary Competencies for a Project Manager [108]

- **Communication:** Effective communication is central to a project manager's role. They must be able to convey complex information clearly to both technical and non-technical stakeholders.

- **Leadership:** Project managers must be able to inspire and lead their teams to achieve the project goals. Leadership includes motivation, conflict resolution, and fostering collaboration across disciplines.
- **Decision-Making:** The ability to make timely and informed decisions is another critical competency. Project managers are often required to make high-stakes decisions under pressure, such as resource allocation, adjustment of schedules, or managing unforeseen risks. A strong decision-making process, based on accurate data analysis and an understanding of the project impacts, is a key skill.
- **Strategy Development:** Strategic thinking, including identifying, assessing, and mitigating potential risks that can affect the project's success, is another core competency. Being able to develop clear roadmaps, align resources, and forecast potential challenges are all part of this competency.
- **Risk Management Expertise:** A deep understanding of risk management techniques, including methods of identifying, assessing, and mitigating potential risks that could affect a project's success, is a vital skill for all project managers. Proactive risk management can ensure that risks are neutralised before they become major issues.
- **Business Acumen:** Understanding the project within a business context is essential to ensure that decisions are made in alignment with the organisation's strategic goals. A project manager must be able to budget, allocate resources effectively, manage costs, and ensure an acceptable return on investment (ROI). A strong grasp of business fundamentals enables project managers to balance technical needs with financial realities.
- **Stress Management:** The pressures of tight deadlines, competing priorities, and unforeseen challenges make stress management vital for a project manager. Being able to not only manage individual stress but also effectively handle team stress and maintain team morale during high-pressure situations is an essential skill. A project manager must be competent in skills such as prioritisation, delegation, and time management.
- **Negotiation Skills:** Project managers are often required to negotiate with suppliers, stakeholders, and team members to resolve conflicts, secure resources, or achieve project deliverables. Strong negotiation skills ensure that project managers are able to find acceptable solutions to problems while maintaining positive relationships with all parties involved.

- **Organisation Skills:** A project manager must be able to quickly organise tasks, schedules, and resources to ensure project delivery is on time and within scope. Being competent in managing multiple tasks simultaneously, tracking progress, and ensuring that all project components are aligned is key. A project manager must be competent in tools such as Gantt charts, project management software, and task lists as ways of organising workflow.
- **Adaptability:** Being able to quickly adapt to changing circumstances is critical for project managers. Whether this is facing new client demands, shifting project scopes, or unexpected technical challenges, adaptability ensures that a project manager can quickly pivot and adjust plans to maintain the project timeline and budget. This competency is a key requirement, especially in fast-paced, high-tech industries such as engineering development.

B.3 ENGG5202: LO2

LO2: Define a project and apply the differences between projects or programs and "business as usual" activities in organisations and their major risks and critical success factors

In general organisational management, understanding the distinction between projects, programs, and "business as usual" activities is critical for the success of a business. This section will investigate what specifically defines a project in comparison to routine business activities, exploring their associated risks and critical success factors.

B.3.1 Project Definition

A project, according to Zero, is a "unique and temporary (definitive beginning and ending) [business activity]" [125]. A project is undertaken to achieve a specific goal or deliverable within a defined start and end point, constrained by scope, time, and resources, aiming to create something new, such as a product, service, or process improvement. The key characteristics of a project include:

- **Unique Deliverable:** A project creates a new product, service, or result that did not exist before within the business.

- **Defined Timeline:** Projects have a specific start and finish. Once the project goal is achieved, it concludes.
- **Specific Objectives:** A project has clear objectives that align with an organisation's goals.
- **Resource Constraints:** Projects are limited by time, budget, and resources such as labour, materials, and technology.

B.3.2 Program Definition

While a project focuses on achieving a specific outcome, a *program*, as described by [39], "is a unique and transient strategic endeavour undertaken to achieve a beneficial change and incorporating a group of related projects and business-as-usual activities" [39]. Programs are ongoing and may evolve with a business as it grows. A program has the following key characteristics [121]:

- **Broad Scope:** Programs tend to deal with large, overall company goals as opposed to smaller targets and deliverables.
- **General:** A project management program will be general in its approach, allowing the specific details to be outlined within each project in the program.
- **Strategic:** A program will focus on the longer-term strategic objectives of a business and incorporate multilayered plans to achieve them.

B.3.3 Projects vs Business as Usual (BAU) Activities

BAU is a colloquial term that refers to the regular, ongoing operations required for a business's day-to-day functionality. Unlike a project, BAU activities are continuous, repetitive, and focused on maintaining the business's stability. The key differences between a project and BAU activities can be summarised into the following key areas [125].

Aspects	Projects	Business as Usual (BAU)
Duration	Temporary with a defined end	Ongoing and repetitive
Objective	Focused on delivering a unique output	Maintaining existing operations
Change	Involves innovation or significant change	Focuses on stability and incremental improvements
Risks	Higher uncertainty and risk due to newness	Lower risk; focused on maintaining existing standards and practices
Success Measurement	Based on achieving specific project goals	Based on operational efficiency and continuity

Table B.1 – Key differences between Projects and BAU

B.3.4 Major Risks in Projects

Projects, while they can have large potential upsides for businesses, also carry significant risks due to their innovative and time-bound nature. The most common risks for projects are [4]:

- **Scope Creep:** Uncontrolled changes, expansions, or additions to the project scope that typically occur when the initial project objectives are not well defined. These can lead to significant delays and budget overruns.
- **Operational Mishaps:** Failures in processes, equipment, or personnel required for a project, which disrupt timelines and efficiency.
- **Resource Overruns:** Excessive consumption of time, money, or personnel due to unforeseen events or inaccurate estimates is another major risk. Businesses usually allocate a finite amount of resources for projects and may not have much appetite or capacity for the project to exceed those resources, no matter the circumstances. On average, 67% of projects run out of budget or time.
- **Technological Uncertainty:** There are always risks associated with the development and implementation of new or untested technologies not performing as expected.
- **Stakeholder Misalignment:** Conflicting expectations, goals, or visions between stakeholders can cause delays, project redirection, or other disruptions.

- **Market Risk:** External factors not controlled by the business, such as economic changes, competitive pressures, or inflated costs of resources, can all impact a project's success.

B.3.5 Critical Success Factors for Projects

For projects, the critical success factors revolve around mitigating the risks mentioned above while ensuring that the correct environment is built to allow for creativity throughout the process [40]. The key critical success factors for projects can be summarised into the following five areas:

- **Clear Objectives and Scope:** Well-defined goals and deliverables are essential for keeping the project focused and ensuring that all team members understand their role, what is expected from them, and what needs to be achieved. This also mitigates scope creep and misalignment between different project resources.
- **Effective Risk Management:** Identifying, assessing, and implementing controls for potential risks early in the project lifecycle helps to prevent delays and potential resource overruns, ensuring smoother project execution.
- **Stakeholder Engagement:** Actively maintaining involvement and alignment with all stakeholders ensures the expectations for the project are met, their input is heard, and it fosters support for the project, reducing the likelihood of conflicts and delays.
- **Strong Leadership and Team Collaboration:** Effective leadership from project managers fosters teamwork and ensures open communication across different project functions. This is critical for overcoming challenges and driving the project to a successful outcome.
- **Effective Monitoring and Control Measures:** Continuous tracking of project progress, performance, and quality through project management tools and other methods ensures that deviations from the project scope are identified early, and corrective actions are taken promptly, ensuring the most effective allocation of resources possible.

B.4 ENGG5202: LO3

LO3: Understand and identify ethical issues facing project management professionals in projects

While a project manager's main responsibility is to deliver a project successfully (on time, within budget and addressing the scope) they are also responsible for upholding ethical standards throughout the project lifecycle. Ethical challenges can arise from numerous situations and may require project managers to balance professional responsibilities with the interests of stakeholders and the project's eventual success. Shouche explores these considerations in her 2008 work "Ethical Project Management", published through the Project Management Institute, identifying how a project manager's role in ethical considerations extends beyond black-and-white issues like conflict of interest [103]. These considerations can be condensed into the following eight typical dilemmas.

- **Pulling Their Weight:** Project managers must drive projects forward, rather than rely on the initiative of other stakeholders. Ethical leadership requires responsibility for project progress, working with all team members to ensure everyone is working together and each is doing their part.
- **Reporting the Truth:** Reporting by project managers to key stakeholders must reflect the true status of the project, avoiding pessimism, over-optimism, or hiding issues. This includes providing early visibility of risks to stakeholders, ensuring they can make informed decisions while building trust.
- **Protecting All Stakeholders' Interests:** The needs of all stakeholders must be respected throughout projects, not just the most vocal or influential. Ethical decisions should consider the impact of key decisions on everyone involved, using negotiation and conflict resolution techniques to reach equitable outcomes as required.
- **Remaining Objective:** Maintaining objectivity, especially during technical discussions, is critical for project managers, particularly in engineering projects. They must avoid bias, ensuring decisions are based on project needs, not personal preferences or team loyalties.
- **Engaging Leadership:** Communication with leadership within the project (senior managers, superiors, or sponsors) must be used to ensure support, escalate issues when needed, and ensure individuals are acting in the project's best interests. This includes addressing unreasonable

demands or barriers that threaten the project's success.

- **Asking for the Right Authority:** To fulfil their responsibilities, project managers must ensure they have the required authority across the project team to make decisions, manage resources, and influence project plans.
- **Assigning Responsibility:** Project managers must evenly assign responsibility for the success or failure of a project, ensuring others are correctly held accountable for their roles. Open communication about performance and challenges can ensure that an environment of trust is fostered, which promotes accountability and improvement.
- **Using the Right Processes:** Implementing the best processes to manage risks, changes, and project progress is an important consideration, and ignoring gaps in these areas is an ethical failure. To mitigate this, managers must advocate for necessary improvements when applicable.

Ethical issues that can potentially face project managers can come from a broad range of areas. However, if project managers establish the correct practice methodology early, they will be able to effectively control, mitigate, and navigate these issues as they arise. Proactive, transparent, and fair leadership, reporting truthfully to all stakeholders, and ensuring that the correct processes are in place early will ensure that managers can fulfil their professional responsibilities and uphold their integrity.

B.5 ENGG5202: LO4

LO4: Understand the project context within organisations, including project selection methods and life cycles, and the organisational constraints which affect the choice of project management methods/approaches, and how these approaches are implemented in practice

Projects and therefore project management within organisations are influenced by numerous factors, including how a project is selected, the lifecycle of that project, and other organisational constraints that must be taken into account. As a result, the context in which a project operates will determine the choice of project management methodology and how it is subsequently implemented. This section will explore these elements of project management and their impact on a project [5, 36].

- **Project Selection Methods:** Organisations will use different criteria during project selection, which is based on a project's strategic alignment, potential financial return, the company's resource availability, and the project's risk assessment. Common selection methods used within industry include:
  - *Cost-Benefit Analysis:* Compares the potential benefits against the costs of a project to ascertain its feasibility and potential value add to the business.
  - *Net Present Value (NPV):* Calculates the value of future cash flows discounted back to the present time to assess the financial viability of a project.
  - *Payback Period:* Measures the time required to recover the initial investment of a project.
  - *Strategic Fit:* Projects are chosen based on how well they align with the organisation's long-term goals and current operating model.
- **Project Life Cycles:** Projects typically follow a clearly outlined life cycle that provides a structured approach from its initiation to completion/closure. The key phases of this cycle include [6]:
  - *Initiation:* The beginning of the project, where the project manager will define the project's scope and objectives.
  - *Planning:* Project managers will develop a detailed project plan and roadmap which includes scheduling details, resource allocation, and risks.
  - *Execution:* Team implements the project plan, with the project manager coordinating resources and ensuring communication lines are clear across the project.
  - *Monitoring and Control:* Regularly checking the project's progress and teams performance, ensuring that the project is proceeding on time, within resource limitations and within scope.
  - *Closure:* Completing and formally closing the project, including final approvals, lessons learned, and final reports.

- **Organisational Constraints:** Various organisational factors can influence the choice of project management methods. These include [6];
  - *Resource Availability:* Limited resources (e.g., time, budget, personnel) that will affect project scope, timeline, and available outcomes.
  - *Organisational Structure:* Whether the organisation is functional, projectised, or matrix, impacts the flow of authority and resource allocation.
  - *Corporate Culture:* The values, culture, and standard practices of an organisation dictate how flexible or rigid project management processes will be.
  - *Regulatory and Compliance Requirements:* External regulations may require specific project documentation and reporting as part of a company's compliance.
- **Implementation of Project Management Approaches in Practice:** In practice, project management approaches are tailored to fit the project's context. Some key considerations during this tailoring include [6]:
  - *Customisation:* It is common for organisations to adapt standard methodologies to better suit specific needs and constraints.
  - *Tool Usage:* Project management tools (e.g., Microsoft Azure, JIRA, Trello) assist in tracking progress, managing resources, and facilitating communication across a project.
  - *Team Dynamics:* Project success depends heavily on team collaboration, communication, and general culture all of which can be shaped by the management approach used.

B.5.1 Project Management Methods and Approaches:

The choice of project management method depends on the project's context and organisational constraints. It also is heavily dependent on the type of team that can be put together including their strengths, weaknesses and dedication to the work. Some common project management methods used include [113, 63, 29];

Waterfall

The Waterfall model is a more traditional project management style that follows a linear and sequential approach, where each phase of the project must be completed before moving on to the next, ensuring that no phase overlaps with another. The stages typically include requirement analysis, system design, implementation, integration and testing, deployment, and maintenance. Each phase is critical to the project's success, as it builds upon the work completed in the previous stage, making thorough documentation and planning essential for effective execution and minimizing costly errors later on.

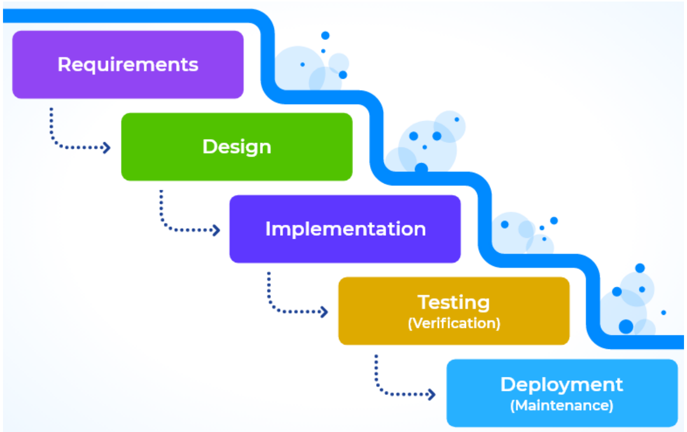

Figure B.2 – Waterfall Project Management Model [35]

Strengths:

1. *Structured and Sequential:* The linear approach allows for clear milestones and deadlines, making it easier to track progress and manage expectations.
2. *Documentation:* The extensive documentation used throughout each phase helps to maintain clarity in projects and ensures all requirements are met.
3. *Predictability:* The well-defined phases and timelines make project outcomes predictable, which is beneficial for stakeholders.

Weaknesses:

1. *Inflexibility:* The rigidity of the model makes it difficult to accommodate changes once one phase has been completed.
2. *Late Testing:* Testing in this model is performed late in the project cycle, which can lead to the discovery of critical issues very late.
3. *Client Involvement:* There is limited client interaction after the initial requirements development phase, which can result in a final product that does not fully meet client needs.

Agile Project Management

Agile project management is a flexible and iterative approach to project management that focuses on delivering small, incremental improvements to the project, allowing for frequent reviews and testing after each increment. This continuous feedback loop enables teams to make adjustments quickly, addressing changing requirements or unforeseen challenges. The Agile model is particularly popular in software development due to its adaptability, emphasis on stakeholder collaboration, and ability to respond effectively to evolving customer needs, resulting in a more responsive and customer-focused development process.

Figure B.3 – Agile Project Management Model [66]

Strengths:

1. *Flexibility:* Agile's iterative nature allows for small or major changes to be made throughout the project.
2. *Customer Collaboration:* Continuous stakeholder involvement in each stage of the project ensures that the product meets their needs.
3. *Faster Delivery:* By breaking the project down into small increments, an agile team can quickly develop usable components and deliver a minimum viable product quicker.

Weaknesses:

1. *Scope Creep:* The flexible nature of the process can lead to scope creep, where additional features beyond the original requirements are added.
2. *Lack of Documentation:* This model often prioritises working on the project over clear and comprehensive documentation, which can lead to issues for future maintenance.
3. *Resource Intensive:* Agile requires significant time and commitment from all stakeholders on the project, including clients who may not have the capacity to give.

B.5.2 Scrum Project Management

This model, derived from Agile project management, the Scrum methodology focuses on completing work in short bursts known as sprints. Teams have daily stand-ups, which are brief meetings to discuss task progress, raise any issues, and coordinate responses to work items. These meetings are led by a Scrum master, whose main responsibility is to oversee the day-to-day work and remove impediments to productivity.

Figure B.4 – Scrum Project Management Model [112]

Strengths:

1. *Clear Roles and Responsibilities:* The Scrum model defines specific roles such as Scrum Master, Product Owner, and Development Team which help in the management of the project.
2. *Regular Feedback:* Frequent reviews through daily stand-ups allow teams to adapt and improve constantly.
3. *Transparency:* Daily stand-ups promote transparency for each individual working on the project and can quickly identify issues when they arise.

Weaknesses:

1. *Team Dependency:* The success of the Scrum model depends heavily on the team's commitment to the project and its ability to collaborate. This environment can be very challenging to maintain.
2. *Scope Changes:* Similar to Agile, Scrum projects can suffer from scope creep if not carefully managed by the Scrum Master.
3. *Training Required:* Implementing Scrum effectively requires training and experience, which must be sourced. This can be a serious barrier for some organisations.

B.5.3 Kanban Project Management

Another model derived from Agile project management, the Kanban methodology helps managers visualize and organize their team's workflow through the use of a visual board or cards to represent tasks. It emphasizes limiting work in progress, reducing bottlenecks, and eliminating wasteful work and inconsistencies to increase productivity and efficiency. By focusing on continuous delivery and real-time communication, Kanban allows teams to adapt to changing priorities and manage workloads more effectively, ensuring smoother and more efficient project completion.

Figure B.5 – Kanban Project Management Model [105]

Strengths

1. *Visual Management:* The Kanban board provides a very clear visual representation of the current project status, making it easy to identify bottlenecks and inefficiencies across the project.
2. *Flexibility:* Kanban does not prescribe to specific roles or time frames, allowing teams to adapt methodology as their specific needs change across the project
3. *Continuous Improvement:* By constantly focusing on continuous delivery, the Kanban model encourages regular process improvements.

Weaknesses

1. *Less Predictability :* Without clear time frames, it can be challenging to predict project completion dates and projects can be delayed by competing priorities.
2. *Risk of Overload:* Teams can take on too many tasks simultaneously, leading to much content switching resulting in inefficiencies and burnout of team individuals
3. *Limited Structure:* The lack of prescribed roles and processes across the model can cause confusion and inconsistency in output and implementation.

Understanding the project context within organisations is essential for selecting the appropriate methodology. Project selection, life cycles, organisational constraints, and practical implementation are all reliant on each other and influence how projects are managed to achieve a successful outcome.

B.6 ENGG5202: LO5

LO5: Understand the tasks involved in scope, time and cost planning and control, and demonstrate the capacity to carry out the plan, and control project performance

A key benefit of project management is around the planning and control it can exert over scope, time and resource usage during a project. These elements are critical to ensuring that a project stays on time, correctly addresses its scope of work and is delivered within its resource allocation. This section will explore the tasks involved in planning and controlling the scope, time, and cost of a project while demonstrating the ability to carry out and monitor project performance.

- **Scope Planning and Control:** A project scope defines the boundaries of a project, specifying what will be included and excluded from the area of investigation. Managing scope ensures that all work necessary to achieve the project objectives is completed and that no unnecessary tasks which will bleed resources and time are introduced. The key tasks in scope planning and control include [6]:
  - *Define Scope:* Create a scope statement that clearly outlines the project deliverables, boundaries, and criteria for success.
  - *Work Breakdown Structure (WBS):* A method of breaking the project scope into smaller, manageable components to better organize and track the work.
  - *Scope Verification:* Communicate the scope with project stakeholders and seek their agreement to them, ensuring the project deliverables meet their expectations.
  - *Scope Control:* Implemented a formal change control process for the scope of work to mitigate the risk of scope creep.

- **Timeline Planning and Control:** Timeline planning lays a clear road map for the project, ensuring it is completed within an acceptable timeframe. This involves dedicated monitoring of progress and the ability to make adjustments through the project as roadblocks arise to maintain the timeline length. Key aspects of timeline planning include [6]:
  - *Activity Definition:* Identify and define all the tasks required to complete the project.
  - *Activity Sequencing:* Determine the order of tasks and map the dependencies between them.
  - *Estimate Activity Duration:* Estimate the time required to complete each task based on available resources and the timeline of dependent tasks.
  - *Schedule Development:* Use tools such as Gantt charts, Kanban boards or network diagrams to create a project schedule that clearly communicates the timeline plan to the whole team.
  - *Time Control:* Regularly monitor progress against the schedule, making sure to actively make adjustments to the timelines as needed. Manage any deviations through corrective actions.
- **Resource Allocation Planning and Control:** Cost planning involves estimating the resources required for the project, including labour, material, cash and any other resources essential to the project. This control function focuses on monitoring the use of resources and making any deviations that can have a negative effect on the budget. The key areas are [6];
  - *Cost Estimation:* Determining a realistic estimate of the costs for all project activities, including labor, materials, equipment, and contingency reserves.
  - *Budgeting:* Develop a project budget by collating all the estimated costs over the project timeline.
  - *Cost Control:* Track actual spending against the budget, identifying any variances, and implement corrective measures if needed in or to stay within budget.
  - *Earned Value Management (EVM):* A way of assessing project performance by comparing the planned work to actual work completed and the costs that were incurred compared to costs planned for those works.

- **Carrying Out and Controlling Project Performance:** To ensure that the project stays on track with regard to scope, time, and cost, the following actions by project management are essential [5, 6]:
  - *Monitor Performance:* Regularly track progress against the project scope, schedule, and budget using tools such as performance reports and dashboards.
  - *Identify Variances:* Compare actual project resource allocation usage to the expected usage and identify any variances in scope, time, or cost.
  - *Take Corrective Actions:* Implement any necessary changes to bring the project back on track when variances occur, including reallocating resources, adjusting timelines, or managing scope changes.
  - *Reporting:* Communicate project performance to stakeholders and project team through regular reporting and open communication channels with ensure transparency with deviations or issues encountered.

B.7 ENGG5202: LO6

LO6: Demonstrate a broad understanding of the other requirements/-components of project plans and performance monitoring, such as quality and risk management, procurement, communications, and team leadership

In addition to the main areas of focus (scope, time, and resource management), successful project management requires a broad understanding of other critical components such as quality management, risk management, procurement, communications, and team leadership. These elements are vital in ensuring that projects are delivered effectively and meet all required objectives.

- **Quality Management:** Quality management is the process of ensuring that project deliverables meet the required standards and satisfy stakeholder expectations. It involves planning, controlling, and improving quality throughout the project lifecycle. Key tasks include:
  - *Quality Planning:* Define the quality standards and requirements for the project deliverables, and establish how these will be measured.

  - *Quality Assurance:* Ensure that quality processes are followed throughout the project to maintain standards.
  - *Quality Control:* Monitor project deliverables to ensure they meet the defined quality standards, using techniques such as inspections and testing.
- **Risk Management:** Risk management involves identifying, assessing, and responding to risks that may impact the project's success. It is essential for minimising potential negative impacts on project performance. The main tasks include:
  - *Risk Identification:* Identify potential risks that could affect the project's scope, time, or cost.
  - *Risk Assessment:* Evaluate the likelihood and impact of each risk to prioritise responses.
  - *Risk Mitigation:* Develop strategies to reduce the likelihood or impact of risks, including contingency plans.
  - *Risk Monitoring:* Continuously monitor risks throughout the project lifecycle and adjust plans as necessary.
- **Procurement Management:** Procurement management is the process of acquiring goods and services needed for the project from external suppliers. Effective procurement ensures that the project has the necessary resources at the right time and cost. Key tasks include:
  - *Procurement Planning:* Define what goods and services are needed and establish procurement methods.
  - *Vendor Selection:* Evaluate and select suppliers based on criteria such as cost, quality, and reliability.
  - *Contract Management:* Manage relationships with vendors to ensure they meet contractual obligations and deliver goods or services as required.
  - *Procurement Control:* Monitor procurement performance, ensuring timely delivery and managing any changes to contracts.
- **Communications Management:** Effective communication is essential for ensuring that all stakeholders are informed about project progress and decisions. Communications management involves planning, distributing, and managing project information. The main tasks include:
  - *Communications Planning:* Identify stakeholder communication needs and establish the frequency and method of communication.

  - *Information Distribution:* Ensure timely and accurate information is shared with stakeholders through reports, meetings, and other channels.
  - *Performance Reporting:* Provide regular updates on project performance, including status reports and forecasts, to ensure transparency.
  - *Stakeholder Management:* Manage expectations and ensure that all stakeholders are aligned with project goals and objectives.
- **Team Leadership:** Team leadership is critical for guiding the project team towards achieving its objectives. Effective leadership fosters collaboration, resolves conflicts, and keeps the team motivated. Key responsibilities include:
  - *Team Building:* Assemble and develop a cohesive team with the necessary skills to execute the project.
  - *Conflict Resolution:* Address conflicts promptly to maintain team harmony and focus on project goals.
  - *Motivation:* Keep the team engaged and motivated by recognising achievements and providing support when needed.
  - *Delegation:* Assign tasks and responsibilities based on team members' skills and strengths, ensuring the workload is balanced.

B.8 Conclusion

This case study performed an in-depth evaluation of the core areas of research for ENGG5202. Many of these skills were utilised throughout my thesis to plan, manage, and complete the project while coordinating with a wide variety of stakeholders in a pressured environment. Given this experience and the research conducted in this section, I am confident that all the learning objectives for this course have been met.

Appendix C

Work Health and Safety Report

My ESIPS placement spanned 8 months with Corehesion, a SaaS provider. The company operates without a physical office space, as its employees are spread across both Australian and international locations. Consequently, all staff, including myself, worked remotely for the majority of the placement. Australian employees also travel to worksites across the country, primarily in NSW and QLD, to meet clients and visit worksites when necessary. Throughout my placement, I travelled to a mine located just outside Muswellbrook, NSW, on at least four occasions to engage with key stakeholders and conduct research for this thesis project.

C.1 Regulations and Procedures

C.1.1 Australian and NSW Regulations

Australia's national WHS laws focus on ensuring the health, safety, and overall well-being of workers and workplaces across the country. The aim is to ensure that, as far as reasonably practicable, risks and hazards are eliminated or minimised in the workplace. The enforcement of WHS laws is the responsibility of both the Commonwealth and State/Territory governments, with most States and Territories having WHS laws that closely align with national standards. In NSW, the State where the entirety of this placement took place, the primary objective of the Work Health and Safety Act

2011 is "to provide for a balanced and nationally consistent framework to secure the health and safety of workers and workplaces” [46].

C.1.2 University of Sydney Procedures

The University of Sydney also has its own WHS procedures – the ’Work Health and Safety Policy 2026’ – which outlines the expected working conditions for anyone "involved in or affected by" the university [87]. The university provides a WHS module that outlines standard processes and available support resources for the implementation of safety management across the organisation. The university uses the risk matrix shown in Figure C.1. to assess hazards and their associated levels of risk.

			Potential Consequences				
			Class 3	Class 2	Class 2	Class 1b/1c	Class 1a
			Minor injuries or physical discomfort. Short-term psychological impact (isolated or one-off event).	Injury or illness requiring medical treatment and/or short-term impairment (less than 2 weeks). Psychological impact requiring support.	Injury or illness requiring hospital admission and/or temporary impairment (less than 6 months). Psychological impact requiring medical treatment.	Injury or illness (physical or psychological) resulting in long-term or permanent impairment (more than 6 months). Injury or illness resulting in temporary impairment to multiple people.	One or more fatalities. Injury or illness resulting in long-term or permanent impairment to multiple people.
			Insignificant	**Minor**	**Moderate**	**Major**	**Severe**
Likelihood	Expected to occur regularly under normal circumstances	**Almost Certain**	Medium	High	Very High	Very High	Very High
	Expected to occur at some time	**Likely**	Low	Medium	High	Very High	Very High
	May occur at some time	**Possible**	Low	Medium	Medium	High	High
	Not likely to occur in normal circumstances	**Unlikely**	Low	Low	Medium	Medium	High
	Could happen, but probably never will	**Rare**	Low	Low	Low	Medium	Medium

Figure C.1 – The University of Sydney Risk Matrix

C.1.3 Corehesion Procedures

Corehesion also has its own Risk Policy (POL-04) and Risk management Standard (STD-11) to ensure that an acceptable level of risk is maintained across business operations. This process used for assessing, treating, monitoring and reviewing risks that occur during operation is outlined in Figure C.2.

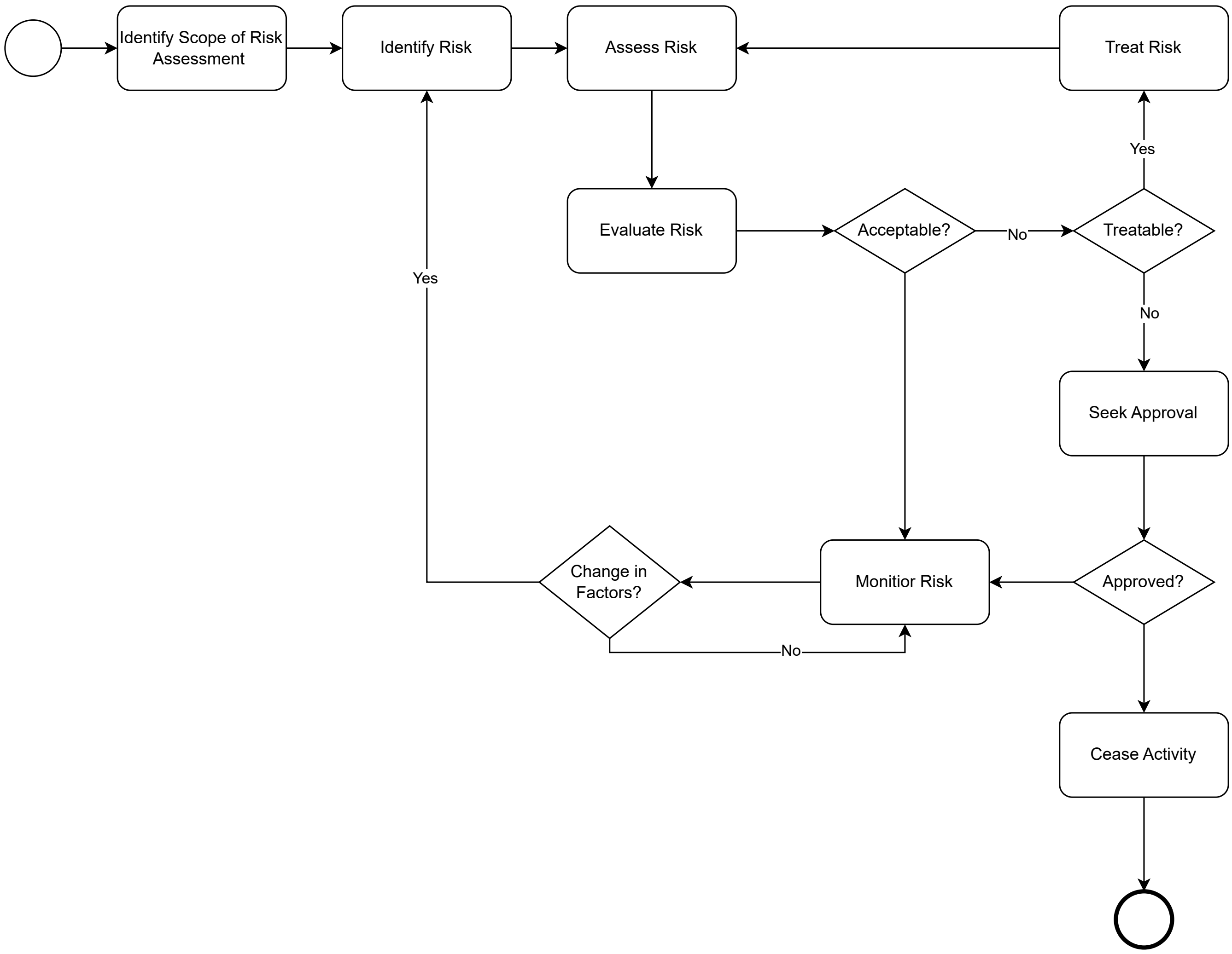

Figure C.2 – Corehesion's Risk Assessing, Treating and Monitoring Procedural Diagram [25]

C.2 Working Arrangements

Throughout my industry placement, I primarily worked in two locations: remotely from my personal residence in Sydney and onsite at MAC. The associated risks for this work are therefore divided into two categories, with site visits encompassing all risks related to onsite activities.

C.2.1 Remote Work Environment

While most work at Corehesion is computer-based and conducted from employees' homes, there are still several health and safety risks inherent in this environment. Since the shift to remote work due to COVID-19, many of these risks have become well-documented, including:

- Distractions and challenges in managing workloads
- Sedentary work, such as prolonged sitting and limited physical activity
- Periods of high workload without the support network of an office environment
- Limited face-to-face support and a reduced sense of workplace community
- Few opportunities to debrief after difficult conversations or discuss ideas outside the typical confines of a meeting
- Feelings of disconnection from managers, colleagues, and support networks

Corehesion has systems and procedures in place to mitigate these risks as much as possible. Upon starting, employees are given the option to acquire suitable home office equipment, including monitors, ergonomic chairs, and other office improvement tools. This mitigates ergonomic risks, which can otherwise lead to issues such as back, neck, wrist, or hand pain. Despite the availability of appropriate equipment, employees are encouraged to incorporate regular physical movement and stretching throughout the workday to prevent injury and maintain flexibility.

To further promote team cohesion and support employee well-being, Corehesion has implemented several processes suited to a remote work environment. A key initiative is the daily "stand-up" meeting, where team members check in with each other and management. These meetings provide an opportunity to discuss progress, share updates, and ensure tasks are on track. Additionally, meetings begin with a "wellness share," encouraging participants to express gratitude, share personal experiences, or discuss challenges they may be facing. This practice fosters a sense of community and support among team members, promoting mental well-being by allowing individuals to openly share both positive and negative experiences.

Corehesion also introduced a weekly Virtual Afternoon Tea, held every Thursday after lunch. This informal, hour-long gathering provides team members with a chance to step away from work and engage in lighthearted conversation. It serves as a relaxed space for colleagues to connect on a more personal level, strengthening relationships and boosting morale. This initiative plays an important role in maintaining a positive team culture and supporting mental health within a distributed work environment.

C.2.2 Mt Arthur Coal Site Visits

When working with Corehesion, the greatest risks to employee safety arise during visits to client mine sites, where multiple hazards significantly increase the potential for harm. As a result, various stringent safety protocols are in place to manage and mitigate these risks. One of the most critical measures is the mandatory use of Personal Protective Equipment (PPE) when moving around the mine site. The required PPE items to enter MAC facilities at any time include the following four items, shown in Figures C.3 and C.4.

- High-visibility, long-sleeved shirts, which reduce sun exposure, prevent minor scratches and other surface injuries, and ensure all personnel are highly visible while on site. Long work pants are also required at all times.
- Steel-capped boots, essential for protecting feet from falling heavy or sharp objects.
- Hard hats to safeguard workers from falling debris and other risks.
- Protective eyewear to shield eyes from dust and foreign particles.

In addition to PPE, strict safety procedures and limitations are enforced to ensure that only qualified personnel carry out specific on-site tasks. Before performing any task, workers must complete training and competency checks to confirm they have the necessary knowledge and experience. Furthermore, random drug and alcohol testing is frequently conducted to minimise the risk of impaired individuals performing high-risk jobs, such as operating heavy machinery, thereby safeguarding both themselves and others.

Figure C.3 – High-Visibility Long-Sleeve Shirt and Steel-Capped Boots

Figure C.4 – Hard Hat and Safety Glasses

During my visit to the research mine MAC just outside of Muswellbrook, NSW, I was required to adhere to all mine-specific work health and safety regulations. Before being allowed on-site, I was escorted around the mine at all times, as I was a guest who had not completed the mandatory induction training.

Travel to Site

During all site visits, I drove from Sydney to a property that Corehesion rents near the Muswellbrook area. This drive, approximately three hours along major roads and the Pacific Highway, is considered in this WHS investigation due to the travel risks involved. To minimise these risks, I took the following precautions:

- Travelled only during daylight hours (between 6 am and 6 pm)
- Took breaks every two hours, following NRMA recommendations
- Planned travel times to avoid peak traffic periods, reducing the risk of accidents
- Ensured my car was well-maintained and in proper working condition

These mitigation strategies helped to control and manage the risks associated with driving, ensuring a safer journey to the site.

C.3 Risk Assessment

Throughout the placement, I felt adequately supported in identifying the hazards present in my work environment, assessing their associated risk levels, and developing strategies to mitigate these risks. Common WHS issues were highlighted during both the University of Sydney's and Corehesion's WHS induction modules. I received extensive training for various work conditions encountered, both at home and during client visits to the mine site. I learned how to effectively identify different hazards, assess their risks, and implement appropriate actions to mitigate or eliminate these risks.

Figure C.5 outlines the key risks encountered over the course of this project and the proposed mitigation strategies aimed at controlling these risks as much as possible.

Item	Pre-Mitigation					Mitigation Measures	Post-Mitigation		
	Hazard	Risk	Likelihood	Consequence	Rating		Likelihood	Consequence	Rating
1	Ergonomic hazards	Musculoskeletal disorders Neck and shoulder pain	Almost certain	Minor	Medium	Offer ergonomic workstations with adjustable chairs, desks, and monitors Promote regular breaks for stretching and movement Ensure workspace dimensions align with SafeWork NSW guidelines	Possible	Not significant	Low
2	Insufficient lighting conditions	Eye strain and headaches Injuries from slips, trips, and falls due to insufficient lighting	Possible	Minor	Medium	Make use of adjustable and adequate lighting fixtures Modify screen settings to reduce blue light and enhance warmth Incorporate a monitor light bar for extra illumination Organise the workspace to adapt to natural light variations throughout the day	Unlikely	Not significant	Low
3	Eye strain from using bright blue light screens for long periods of time	Headaches, insomnia and gradual decline of eyesight	Possible	Moderate	Medium	Ensure to take a 5 minute break every hour from bright screens, drink plenty of water and schedule time away from electronic devices everyday	Possible	Moderate	Medium
3	Electrical/cooking equipment	Electric shocks or burns Fires resulting from faulty wiring, overloaded circuits, or malfunctioning electrical equipment	Unlikely	Severe	High	Use surge protected powerboards for all electrical appliances Conduct regular inspections and maintenance of electrical equipment and wiring Receive induction for cooking appliances (coffee machine)	Rare	Severe	Medium
5	Driving	Fatigue and drowsiness Distractions from mobile devices or passengers Increased accident risk due to adverse weather conditions Reduced reaction time from speeding or aggressive driving Limited visibility during night driving	Unlikely	Severe	Very high	Take regular breaks to prevent fatigue Minimise distractions by setting devices to "Do Not Disturb" mode while driving Adjust driving speed according to weather and road conditions Avoid aggressive driving; maintain safe following distances Use headlights and ensure windows and mirrors are clean for optimal visibility Only drive during daylight hours	Rare	Severe	High
6	Working on a Mining Site	Exposure to dangerous materials or chemicals. Risk of injury from falling objects within a workshop. Risk of injury from heavy machinery. Risk of slips, trips, and falls on wet or uneven surfaces. Exposure to loud noise levels leading to hearing damage. Risk of electric shock from faulty wiring or equipment. Risk of injury from improper lifting techniques. Exposure to harmful fumes or gases in poorly ventilated areas. Risk of burns from handling hot materials or equipment.	Unlikely	Severe	Very high	Ensure to always wear all PPE gear. Follow all instructions given by the escort at the mine site at all times. Never travel around the site without someone to guide you. If any potential problem is witnessed, immediately alert someone. Always maintain clear communication with your team members Stay within designated safe zones unless explicitly authorized to enter restricted areas.	Rare	Severe	High
7	Isolation	Feelings of loneliness, depression, and anxiety. Decreased motivation and drive. Heightened stress resulting from a lack of support.	Almost certain	Moderate	Very high	Participate in weekly virtual social gatherings. Regularly share and acknowledge team member achievements through the "Praise" channel on Microsoft Teams. Always remain in regular contact with friends and ensure I am proactive in staying in touch with people	Possible	Moderate	High

Figure C.5 – Risk Assessment of Project and Mitigation Strategies

Appendix D

Potential Thesis Project Scope of Work Investigations

The following section contains seven different reports on potential areas of exploration for this project prepared and presented to Corehesion's management. From these reports, a decision was made to pursue the investigation of tyre maintenance management in mid to late May, with the project formally getting underway at the beginning of June.

D.1 Magnetic Plug Inspections

Magnetic plugs are commonly used in various industrial and mechanical settings, including mining, to capture metallic debris and indicate wear within machinery. Detecting the condition of these plugs can provide critical insights into the health of the equipment and indicate potential equipment failure. By accurately detecting and quantifying the metallic debris captured by magnetic plugs, it can provide early warnings of abnormal wear and tear or impending equipment failures. The insights gained from analyzing magnetic plug conditions are integrated with broader equipment maintenance processes, triggering alerts for specific maintenance actions and prioritizing maintenance tasks based on the condition of the equipment. By tracking changes in the amount and type of debris, organizations can analyze wear patterns, improve maintenance schedules, and make informed decisions on equipment management.

Implementation of this condition monitoring task commonly involved magnetic plug inspections being performed as a routine maintenance task by front line workers, however, there are various procedures deployed to collect, analyse and make decisions about the information, including:

- Visually inspect the magnetic plug and record the result without any guidance on what to look for or how to evaluate it. Maintenance planners or reliability engineers decide later what action to take based on the text description recorded on the inspection sheet.
- Visually inspect the magnetic plug, compare it to a guide (Figure 1) and record the result. Maintenance planners or reliability engineers decide later what action to take based on the rating recorded on the inspection sheet.
- Visually inspect the magnetic plug, compare it to a guide, that includes recommendations on what action to take based on the rating (Figure 2), and record the result and any action taken. Maintenance planners or reliability engineers decide later what additional action to take based on the rating recorded on the inspection sheet and the action taken.
- Replace the magnetic plug with a clean magnetic plug and provide the plug to the maintenance planner or reliability engineer to analyse and decide later what action to take.

MAGNETIC PLUG INSPECTION GUIDELINES

Caterpillar released a service magazine article (dated 17/01/2000) recommending the inspection of magnetic plugs for OHT front and rear wheels on a regular basis. The intention was to assist in the early detection of wheel bearing failures and reduce the system contamination and increase the salvageable components at repair. The very nature of rolling element bearing (wheel bearings, planetary bearings etc) failures means that they progress quickly from the first signs of fatigue flaking of the surface to a major failure.
To standardise on the reporting of magnetic plug ratings, the following guidelines should be followed when an assessment is carried out for recording on weekly inspection sheets and routine PM service sheets.

RATING A:
Little or no build up of material (paste) on a plug is desirable. Fine grey paste on a plug indicates normal wear. **There should not be any chips, flakes or slivers, only paste.** The quantity of paste will depend on the configuration of the component, i.e. non filtered rear axles will differ from filtered rear axles with hardened wheel spindles. **OK to return to work after plug is cleaned.**

RATING A:
Build up of paste for a non filtered rear axle would be significantly greater than the amount on a plug from a filtered rear axle with hardened spindles. The plug shown here would be acceptable for a non filtered rear axle, but would be suspect for a filtered rear axle with hardened spindles and would need to be monitored.
OK to return to work after plug is cleaned.

RATING B:
Any sign of shiny particles (chips, flakes, slivers, fragments etc) larger than paste (very fine dull grey) is not normal. This usually indicates the initiation of abnormal wear, however under certain circumstances (i.e. after component repairs or rebuild), this may be a "one off" event. This compartment needs to be monitored and plug debris should be kept for analysis. **OK to return to work after plug is cleaned.**

RATING C:
Further progression of abnormal wear would be an increase in the quantity and size of the particles (chips, flakes, slivers, fragments etc). Investigation into the source of the particles needs to be actioned as soon as practically possible. This may include compartment disassembly or more frequent monitoring of the plug. The plug debris should be kept for analysis. **THE MACHINE IS NOT TO BE RETURNED TO WORK UNTIL A SHORT TERM ACTION PLAN IS DEVELOPED.**

RATING X:
If a plug is fully covered in debris of significant size (larger than very fine dull grey paste), it is highly likely that a failure is in progress. **THE MACHINE IS NOT TO BE RETURNED TO WORK UNTIL FURTHER INVESTIGATION AND/ OR REPAIRS ARE CARRIED OUT.**

Figure D.1 – Magnetic Plug Rating Guide with Recommendations

D.2 Tyre and Rim Maintenance Inspections

Tyre and rim inspections are critical maintenance procedures in the mining industry, ensuring the safety and efficiency of heavy mining equipment such as haul trucks, loaders, and bulldozers. According to Galatia, "Tyres are one of the major cost drivers in mining operations and at the same time, a severe safety hazard due to their mass and stored energy" [41, p. 20]. The rigorous conditions in mines, characterized by rough terrain, heavy loads, and uncertain operating circumstances necessitate regular inspections to prevent catastrophic failures and costly downtime [41, 114].

Importance of Tyre Inspections

Mining tyres are a substantial operational cost for mining companies [41]. Their maintenance is essential for:

- Safety: Preventing accidents due to tyre failures, which can have catastrophic consequences, is a key driver of Rim and Tyre Inspections.
  - AS 4457.1: Australian Standard for Earth-moving machinery – Off-the-road wheels, rims, and tyres – Maintenance and repair [1]
- Cost Efficiency: Maximizing tyre life through early detection of issues like cuts, wear, and heat damage, reducing the frequency of expensive replacements.
- Operational Efficiency: Ensuring equipment runs smoothly and efficiently, as tyre issues can lead to increased fuel consumption, increase degradation on other mechanical parts, and an overall reduction in machinery effectiveness.

Key Aspects of Tyre Inspections

- Visual Inspections: Regular checks for signs of wear, damage (like cuts, cracks, or bulges), and incorrect inflation.
  - Visual inspections are often conducted by trained personnel before each shift.
- Pressure Checks: Tyre pressure is critical for optimal tyre performance and longevity. Underinflated or overinflated tyres can lead to increased wear or blowouts (which have serious safety risks attached).
- Tread Depth Measurement: Monitoring tread depth helps in assessing tyre wear and determining when a tyre should be replaced or re-treaded.

Importance of Rim Inspections

Rims also play a crucial role in the safety and efficiency of mining operations. Damaged or worn rims can lead to tyre failures and accidents. Inspections focus on:

- Cracks and Structural Integrity: Checking for any signs of stress or cracks, which can propagate and lead to failures.
- Bolt Integrity: Ensuring that all rim bolts are present, correctly torqued, and free of corrosion or damage.

Technological Advancements

The potential use of advanced monitoring and data management systems to increase cost efficiency and safety of tyre and rim inspections is substantial. Systems include:

- Data Analytics: Leveraging data collected from various sources, collected in one system, to predict tyre life, optimize replacement schedules, and improve overall tyre management strategies.
- Implementation of Visual AI Inspection: Use of Image recognition to conduct regular visual inspections, removing the requirement for specifically trained personnel to perform inspections.

Figure D.2 – Operator inspecting a truck tyre [59]

D.3 Excavator Bucket Inspection

In open-cut mines, excavators are, according to Minetek, “one of the most crucial pieces of equipment due to their versatility, manoeuvrability, and multi-functionality” [70, p. 1]. Therefore, inspections of the critical components of these assets are an essential area of focus due to their importance in operational efficiency and safety. However, like much of the mining industry’s maintenance practices, there has been little change in established practices despite considerable technological advancement in condition monitoring, data collection, and analysis tools [111].

Currently, bucket inspections on mine sites are carried out by an experienced operator using a pen and paper-based checklist [97], examples of which are displayed in Figure D.3 and D.4.

The implementation of these visual inspections focused on:

- Determining if there is any cracking occurring on the bucket, which can occur on the bucket itself or within welds and other joints
- Measuring the length of cracking
- Confirming that connections are secure
- Inspecting the wear on the excavator’s teeth

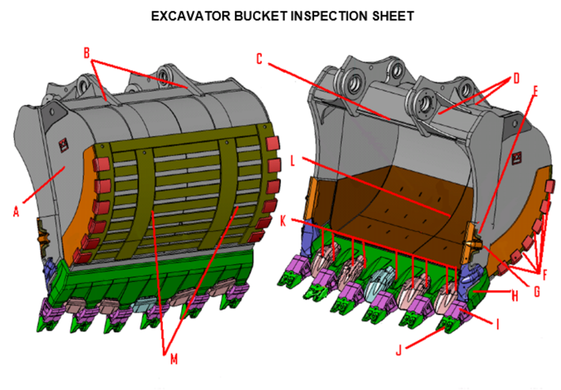

Figure D.3 – Bucket Visual Inspection Guide

EXCAVATOR BUCKET INSPECTION SHEET

Ref No	Defect Description	Length of Cracking	Comments
A	Visually inspect for washout area		
B	Visually inspect for cracking		
C	Visually inspect for cracking		
D	Visually inspect for cracking		
E	Inspect that sheer blocks are intact		
F	Visually inspect for wear and cracking on heel shrouds		
G	Inspect for loose adaptors		
H	Visually inspect for cracking on nose weld		
I	Inspect for loose adaptors		
J	Visually inspect for wear on teeth		
K	Visually inspect for cracking at welds. Inspect for loose lip shrouds		
L	Check for cracking		
M	Visually inspect for cracking at welds and washout		

Figure D.4 – Bucket Inspection Check List

Similarly, all other parts of the inspection of excavators almost must be conducted by qualified individuals, and inspection information is recorded on pen and paper forms. Figure D.5 shows the first page of an Excavator Inspection form.

	Anglo Coal (Capcoal Management) Pty Ltd Controlled Document	PREVENTATIVE MAINTENANCE INSTRUCTION	
		Revision: 2	Revision Date: November 2008
Excavator – Weekly Inspection			

No.	Task	Comment	OK	Defect
	Running Checks			
1.	Check the access steps for correct operation			
2.	Check the hour meter for correct operation and record the reading on the W/O job card.			
3.	Check the air filter restriction indicators for an active alarm. Clean or replace the air filter elements if required.			
4.	Check condition & function of cab gauges & controls			
5.	Ensure that no abnormal warning lights or alarms are active.			
6.	Check BCS function & check BCS error list			
7.	Run self test on Cummins Quantum Electronic Monitoring System			
8.	Check operation of two-way radio			
9.	Check the emergency stop switch in operator's cab for correct operation			
10.	Check the emergency stop switch in hydraulic cabinet (pump bay) for correct operation			
11.	Check the ground level emergency stop switch (on lube/ service tail) for correct operation.			
12.	Check operation of interlock - seat & hydraulic functions			
13.	Check operation of interlock - propel & brake			
14.	Check operation of interlock - hydraulic isolation valves & engines			
15.	Check operation of interlock - boarding ladder & hydraulic functions			
16.	Check operation of interlock - service leg & hydraulic functions			
17.	Check operation of travel alarm			
18.	Check operation of auto lubrication system. Move the auto-lubrication toggle switch to the manual position. Check that both pumps operate and the indicator pins retract			
19.	Check oil pressure on grease system pilot/supply oil gauge. Spec: 870psi (60Bar).			
20.	Check oil pressure on main grease pump gauge. Spec: 510 - 580psi (35 - 40Bar)			
21.	Check oil pressure on undercarriage grease pump gauge. Spec: 710 - 740psi (49 - 51Bar)			
22.	Check operation of engine oil centrifuge/Eliminator motors			
23.	Check operation of hydraulic cooler fans			
24.	Check operation of service leg			
25.	Check engine starter isolation switch condition & operation - check engines won't start			
26.	Check battery isolation switch condition & operation - check for dead			

Does sheet need updating /improving (Y/N) Item No. [ ] Initial [ ]

Page 2 of 5

Figure D.5 – Excavator Inspection Form Page 1

D.4 Slew Ring Deflection Inspection

The slew ring, also known as the slewing ring or slewing bearing, is a critical component in many types of machinery, including cranes, excavators, and wind turbines. It enables rotational motion between the upper structure relative to the base, handling combined loads that include axial, radial, and tilting moment loads. Slew rings consist of an inner and outer ring which are separated by ball or rolling elements [13].

Figure D.6 – Excavator Slew Ring [13]

Importance of Inspections

Within operation, slew rings usually wear at a linear rate [12]. Once this rate accelerates past a linear trajectory, it indicates that the bearing has reached the end of its service life. The industry "rule of thumb" dictates that once the measured deflection exceeds 1.5x the original value, plans should be set in motion to replace the ring. Once the measured deflection exceeds 2.0x, the ring should be replaced immediately [93]. Slew Ring deflection inspections are therefore critical for both ensuring the safety and efficiency of the asset and planning for part replacement.

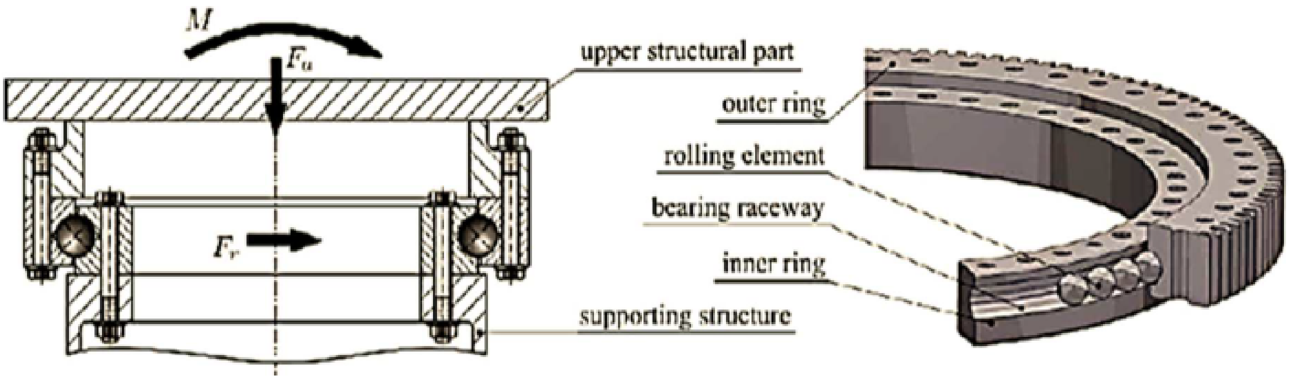

Figure D.7 – Diagram of a four contact point slew bearing [107]

Monitoring Methods

Rothsched highlights that maintenance guidelines provided by slew bearing suppliers emphasize the importance of regularly monitoring two key factors: axial movement variations, also known as tilting clearance or drop-height, and the condition of the lubricant used [98, p. 34]. The main inspection methods used for slew rings on mine sites are a Visual Inspection and a Measurement of Deflection.

Visual Inspection: Initially, inspectors look for signs of wear, corrosion, or mechanical damage on the slew ring. This includes checking for broken teeth in the gear, deformations, and any abnormal signs on the raceways and rolling elements.

Measurement of Deflection: Using dial indicators or more advanced electronic measuring devices, technicians measure the deflection of the slew ring under load. This measurement is compared against the manufacturer's specifications to determine if the deflection is within acceptable limits.

D.5 Conveyor Belt Inspection

Conveyor Belt systems are a common means of transporting bulk material long distances within the mineral industry due to their simplicity and cost-effectiveness. However, there are significant obstacles in ensuring their safe and efficient operation due to the range over which the equipment is extended. Even a small conveyor belt of 150 meters will have nearly 450 carrying rollers and 50 return rollers [81]. Given this, regular inspections across the total length of the belt are vitally important to prevent equipment failure, reduce downtime, and ensure safety standards are met.

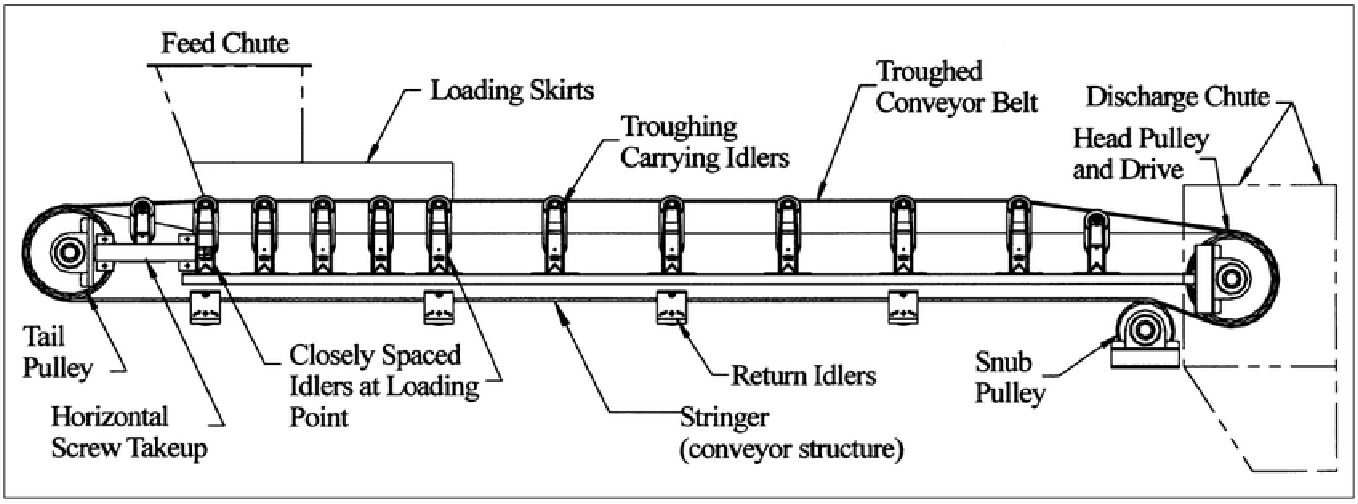

Figure D.8 – Diagram of a Conveyor Belt System [89]

Key Inspection Components

Historically, conveyor belt inspections have been carried out by specifically trained personnel using manual methods [106]. Inspections can be broken down into four main subsections [62].

Visual (Daily): Trained personnel will conduct visual inspections of the conveyor, looking for signs of wear, tears, and cuts on the conveyor surface, checking the edge of the belt for damage and ensuring that the belt is aligned.

Figure D.9 – Maintenance operator carrying out a visual inspection of a conveyor belt [24]

Operational (Weekly): Measurement of the tension in the belt and running the conveyor under loading while inspecting ensures that there are no misalignments, vibrations, or belt slippage occurring.

Mechanical (Weekly): Inspection of the rollers and idlers, bearings, and drive mechanisms (motors, gears, and chains) for signs of wear, damage, or insufficient lubrication.

Non-Destructive Testing (Monthly/as required): Techniques which include ultrasonic testing, radiography, and magnetic particle inspection are used to locate internal flaws in the belt or metal parts of the system.

Mechanical and some operational testing require that the system is idle while testing is performed. Given the amount of material that conveyor belts transport, any downtime is a major cost leakage for mining operations and therefore any improved methods of inspection can lead to significant efficiency gains [106, 62, 89].

Recent Technological Developments in Conveyor Inspection

Given the complexity and downtime cost involved in manual conveyor inspections, this has been an area of significant development and research within mining maintenance. There is currently a myriad of market-ready solutions including but not limited to; visually inspecting a belt using Unmanned Aerial Vehicles (UAV)s, installing sensors on key areas of the conveyor system or using a Distributed Optical Fiber Sensor (DOFS) system [1].

[1] DOFS systems use optical fiber cables as sensors, leveraging the properties of light within the wire to detect changes in the operating environment. They are used to monitor various physical parameters in equipment including; temperature, strain, pressure, and vibrations [56].

D.6 Problem

The methods used in the inspections investigated above have inherent problems in terms of efficiency, reliability, and availability of information, leading to sub-optimal decision-making and, consequently, increased instances of equipment failure. These failures not only disrupt production but also result in higher repair costs and increased downtime that could have been mitigated through timely and scheduled interventions.

Issues relating to information reliability and consistency:

- Inexperience: Operators and inspectors who lack sufficient training may not perform thorough inspections or might fail to correctly interpret the signs of wear and potential failure, leading to inappropriate or delayed actions.
  - Training workers to the required skill levels takes significant investment and time, without a guarantee of return on investment given the competitiveness of the industry.
  - The supply of specifically trained individuals is finite and in high demand.
- Undervalued Inspections: A cultural or procedural underestimation of the importance of thorough inspections can lead to inspections being rushed or neglected.
  - Neglect in inspection conduction can directly result in increased downtime, potential safety incidents, and decreased cost efficiency.
- Human Variable in Inspections: Based on variations in experience, diligence, and judgement, human workers will make inconsistent evaluations of the same information.
  - Implementation of standardized inspection procedures and training can only mitigate this problem to a certain extent.
- Documentation: Inspection reports are typically carried out by hand, resulting in potential inconsistencies as handwritten notes are often difficult to read or interpret.
  - Misinterpretation can result in incorrect follow-up actions and intervention actioned.
- Misalignment between manual inspections and automatic sensor data: Inconsistency and a lack of integration between manually collected data and automatic sensor data can lead to inconsistent maintenance decisions made without all the information available.

Issues relating to information availability:

- Delayed Reporting: The flow of information from the field to maintenance planners/strategists and decision-makers is often not streamlined. Paper-based reporting and manual entry systems lead to delays in data processing and communication.
- Availability Historical Data: In many mining operations, historical data from tyre and rim inspections are not systematically captured in a digital format that can be easily accessed or analyzed. This absence of structured historical data limits the ability to perform trend analysis, predict failures, and plan preventative maintenance effectively.

Issues relating to cost and time efficiency:

- Time-Consuming Processes: The time required for frontline workers to conduct thorough inspections and for maintenance planners and engineers to review and interpret the results can be significant, especially in operations with large fleets of machinery. This time investment is compounded by inefficient data handling and review processes.
- Data Management: Transferring handwritten inspection notes to a digital system that can be effectively used for tracking and analysis is not only time-consuming but also prone to errors. Manual data entry and analysis are inefficient and often lead to delayed decision-making. Establishing automated data capture and analysis systems could streamline these processes, reduce human error, and enhance the timeliness and accuracy of maintenance activities.

D.7 Objective

Reduce maintenance costs and increase availability and reliability of equipment leading to increased production by:

- Improving the efficiency of this condition monitoring process.
- Improving the accuracy of inspections.
- Providing immediate recommendations to decision-makers on what action to take.
- Providing transparency of current component condition for planning processes.
- Providing transparency of relevant correlations and patterns in condition monitoring data for problem-solving and proactive maintenance strategies.

Appendix E

Cost-Benefit Analysis of Proposed System

This appendix shows the working for the Cost-Benefit analysis performed on the operations of MAC, specifically with regards to their tyre maintenance costs. The explanation for these calculations can be found in section 4.1.

E.1 Scenario Comparison

This scenario analysis compares three different scenarios and the current operating conditions at the research mine

Current Operations

Figures	
Number of Trucks	69
Tyres per Truck	6
Cost of Replacement Tyre	80000
Operating Hours per year	7300
Minor damage repair	1250
major damage repair	5000
average lifespan	4700
average number of minor repairs	6
average number of major repairs	2

Number of tyres used per year	643
Cost of replacement per year	$51,441,702.13
Cost of minor damage repairs per tyre	$7,500.00
Cost of major damage per tyre	$10,000.00
Total repair cost per tyre	$17,500.00

Cost of replacement + repairs / year	$62,694,574.47

Realistic

Figures	
Number of Trucks	69
Tyres per Truck	6
Cost of Replacement Tyre	80000
Operating Hours per year	7300
Minor damage repair	1250
major damage repair	5000
average lifespan	4900
average number of minor repairs	4
average number of major repairs	1

Number of tyres used per year	617
Cost of replacement per year	$49,342,040.82
Cost of minor damage repairs per tyre	$5,000.00
Cost of major damage per tyre	$5,000.00
Total repair cost per tyre	$10,000.00

Cost of replacement + repairs / year	$55,509,795.92

Optimistic

Figures	
Number of Trucks	69
Tyres per Truck	6
Cost of Replacement Tyre	80000
Operating Hours per year	7300
Minor damage repair	1250
major damage repair	5000
average lifespan	5170
average number of minor repairs	2
average number of major repairs	1

Number of tyres used per year	585
Cost of replacement per year	$46,765,183.75
Cost of minor damage repairs per tyre	$2,500.00
Cost of major damage per tyre	$5,000.00
Total repair cost per tyre	$7,500.00

Cost of replacement + repairs / year	$51,149,419.73

Conservative

Figures	
Number of Trucks	69
Tyres per Truck	6
Cost of Replacement Tyre	80000
Operating Hours per year	7300
Minor damage repair	1250
major damage repair	5000
average lifespan	4800
average number of minor repairs	5
average number of major repairs	2

Number of tyres used per year	630
Cost of replacement per year	$50,370,000.00
Cost of minor damage repairs per tyre	$6,250.00
Cost of major damage per tyre	$10,000.00
Total repair cost per tyre	$16,250.00

Cost of replacement + repairs / year	$60,601,406.25

Figure E.1 – Scenario Analysis Tables

E.2 Present Value Calculations

This present value calculation, determines the current value of the money saved from each scenario over the next 6 years.

Present Value of Savings

Inflation	3.00%

Year	Current Operations	Realistic	Optimistic	Conservative
1	$62,694,574	$55,509,796	$51,149,420	$60,601,406
2	$60,813,737	$53,844,502	$49,614,937	$58,783,364
3	$58,989,325	$52,229,167	$48,126,489	$57,019,863
4	$57,219,645	$50,662,292	$46,682,694	$55,309,267
5	$55,503,056	$49,142,423	$45,282,214	$53,649,989
6	$53,837,964	$47,668,151	$43,923,747	$52,040,490

PV	$349,058,303	$309,056,331	$284,779,501	$337,404,379

	Current Operations	Realistic	Optimistic	Conservative
1	$62,694,574	$7,184,779	$11,545,155	$2,093,168
2	$60,813,737	$6,969,235	$11,198,800	$2,030,373
3	$58,989,325	$6,760,158	$10,862,836	$1,969,462
4	$57,219,645	$6,557,353	$10,536,951	$1,910,378
5	$55,503,056	$6,360,633	$10,220,842	$1,853,067
6	$53,837,964	$6,169,814	$9,914,217	$1,797,475

PV	-	$40,001,972	$64,278,802	$11,653,923

Figure E.2 – Present Value of Savings Calculations

Appendix F

Practical Experience Logbook

This logbook is a record of the work experience performed each week while working on this project with Corehesion. It documents my engagement with the company from the beginning in early February (onboarding occurred in the last week of January) through to my final meeting and presentation onsite.

Week	**Summary**
Week 1 (5/02/24 - 9/02/24)	• Completed onboarding of Corehesion systems. • Started to think about the gaps in Corehesion's current platform and develop ideas on where a thesis could be conducted. • Began familiarising myself with research articles about asset maintenance within the mining industry. • Reached out to my academic supervisor Guodong Shi to organise meetings.

Continued on next page

Table F.1 – continued from previous page

Week	Summary
Week 2 (12/2/24 - 16/2/24)	• Had an introduction to the forms component of the Corehesion system and began investigating what new capabilities could be introduced to this. • Began to put together a project proposal based on initial investigations. • Started working on smoke testing some new capabilities around the forms capability to better understand its operation (Work Items: 7081 & 7937).
Week 3 (19/2/24 - 23/2/24)	• Had a meeting with Corehesion's managing partner Brad Waldron to discuss the direction of the project and get a clear picture of the current industry problems. Introduction to RCM. • Sent a draft proposal to Guodong for review. • Had a meeting on Friday with Guodong to discuss my proposal and cement a clear direction for the project. • Continued to work through smoke testing new forms capabilities (Work Items: 7081 & 7937).
Week 4 (26/2/24 - 1/3/24)	• Travelled to Singleton this week to meet some of the team in person and stayed at the company accommodation. I was up there for 4 days from Monday to Thursday. • Finalised my thesis proposal for university and submitted it. • Began researching mining maintenance as Brad Waldron (Managing Direction) indicated this will likely be the area of exploration for my thesis project.

Continued on next page

Table F.1 – continued from previous page

Week	Summary
Week 5 (4/3/24 - 8/3/24)	• Once again travelled to Singleton this week and worked onsite (BHP's MAC) for 3 days. Stayed at the Singleton house for 4 days again. • Continued to work on the literature review, investigating maintenance procedures in other industries as well as maintenance theory. • Continued to work through smoke testing new forms capabilities (Work Items: 7081 & 7937). • Worked with Marcus Valastro (Industry Supervisor) to build a basic scope of work for the thesis, which is still open-ended. As yet, there is no specified area of exploration from Corehesion.

Week 6
(11/3/24 - 15/3/24)
	• Focused this week mainly on smoke testing for Corehesion (Work Items: 7081, 7937 & 8377).
	  ▶ This is important as it gives me an in-depth understanding of Corehesion's systems.
	  ▶ It also ensures that I develop a relationship with other members of the team through this work.
	• Continued to progress my literature review, further investigating maintenance practices in other industries.

Week 7 (18/3/24 - 22/3/24)	• Refined the Scope of Work for my thesis with Marcus, narrowing down the area of exploration to looking for inefficient/troubled areas within asset maintenance at open-cut mines where Corehesion's software could prove useful. • Continued smoke testing form functionality (Work Items: 7937 & 8377). This still takes up most of my time. • Began to research current AI platforms on the market and how they could be used.

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Week	**Summary**
Week 8 (25/3/24 - 29/3/24)	• Began having bi-weekly meetings with Guodong to discuss thesis progress and direction (He couldn't start these earlier due to prior commitments). • Continued to investigate current AI platforms that could be integrated into Corehesion's current system. Looking at Microsoft's Azure platform and potentially how it could be integrated given that Corehesion uses Microsoft already. • Continued smoke testing form functionality (Work Items: 7937 & 7931). • Had a meeting with Brad and Marcus to discuss developing multiple scopes of work for potential investigations (7-10) and how they would like those to be structured.
Week 9 (1/4/24 - 5/4/24)	• Built a clear timeline for the remainder of the project with Marcus. The first step is to complete the potential investigation scope of works for review by Marcus and Brad. • Completed smoke testing work (Work Items: 7937 & 7931). • Continued to research maintenance strategy this week and began writing the RCM section of the literature review.
Week 10 (8/4/24 - 12/4/24)	• Discussed current progress on the literature review with Guodong in the bi-weekly catch-up, and raised the issue of refining research areas due to the lack of a clear scope of work with Corehesion. • Continued to work on the progress report for the thesis. It is unclear what can be submitted given the lack of a clear project and the fact that I am still investigating exactly where the project will focus with Corehesion. • Continued to work on scopes of work for Brad and Marcus, currently have completed 4 with another 4 planned.

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Week	Summary
Week 11 (15/4/24 - 19/4/24)	• Began researching data-gathering methods for a potential project in maintenance areas. These methods need to be able to be implemented within the Corehesion application or online system. • Investigated how Corehesion stores and manages the data collected from its forms, which is accessed through SQL requests. • Reached out to Guodong to request an extension for my literature review to allow time to narrow down the scope of inquiry (which was granted) as there is still no clear problem.
Week 12 (22/4/24 - 26/4/24)	• Discussed the current progress of the project, including how to effectively narrow down the project investigation while maintaining its usefulness to Corehesion, with Guodong in the bi-weekly catch-up. • Continued to investigate data management, collection, and processing tools that could be integrated into Corehesion's platform. • Finalised scopes of work for Brad and Marcus, with 7 different investigations that will be reviewed and considered.
Week 13 (29/4/24 - 3/5/24)	• Met with Marcus to review the current progress made and outline a clear path forward, including: ▶ Detailing Corehesion's aims for my project. ▶ Potential industry partners that might be included. ▶ Next steps for the following few weeks of investigation and research. • The next steps for the project from Corehesion's side include finding an industry partner that can be brought in and determining which scope of work presented will most interest them. • Continued with research, now focused on how data gathered from Corehesion's system can be conveyed to key stakeholders, using Corehesion's current delivery method of an application or online website.

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Week	Summary
Week 14 (6/5/24 - 10/5/24)	• Met with Marcus to review the scopes of work prepared so they can be presented to potential clients. • Coordinated with Marcus about meeting with the BHP representative regarding partnering with them on the project. This discussion focused on their current tyre management system and its current shortcomings. • Continued with research and began investigating how the currently planned system could be adapted for use with BHP's tyre inspections. • Re-organised the meeting with Guodong to next week.
Week 15 (13/5/24 - 17/5/24)	• Had a meeting with BHP managers about potentially working with their tyre inspection company Otraco to develop a pilot program that integrates this project with their tyre maintenance strategy. • Began to build stories on the Corehesion Kanban board that would be required for the tyre inspection program. These revolve around making changes to the forms to allow for images and other useful data to be inputted into the Corehesion system. Much more specific information about the system is required. • Continued to work on the updated research area, including expanding the literature review in RCM.
Week 16 (20/5/24 - 24/5/24)	• Continued to build the stories required for the new system and began designing an implementation strategy based on the business requirements. This focused on strategising how our system could be used to streamline BHP's current tyre management system. • Worked on the required documentation for a new project for Corehesion, including a scope of work, shareholder register, risk assessment, work register, and workflow diagram. • Had contact with the Otraco tyre contractors at MAC and organised a meeting for next week.

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Week	**Summary**
Week 17 (27/5/24 - 31/5/24)	• Had a meeting with tyre inspection stakeholders from BHP to understand the current system, the problems experienced, and Corehesion's/my scope of work for the project. At this point, I was able to begin properly working on the project with some clear objectives in mind (Date: 28/5/2024). • From this meeting, it was Corehesion's understanding that the tyres at MAC were not lasting their full operating lifespan, and it was unclear why this was the case. • Continued work on the RCM literature review section.
Week 18 (3/6/24 - 7/6/24)	• Developed a complete design overview of the current tyre management system and began mapping out its weaknesses. • Continued to work on the thesis, including developing the context, motivation, and problem statement for the introduction. • Started to develop new forms within the Corehesion system that will form the basis of the tyre management system proposal. These forms still lack a lot of the software I believe will be required.
Week 19 (10/6/24 - 14/6/24)	• Continued work on the RCM literature review section of my thesis. • Worked on identifying the aims and objectives of the thesis based on the current weaknesses in the existing system. • Began working on a system design for the ATMS that will be proposed. • Did some more work on Corehesion's platform testing stories this week as well.

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Week	Summary
Week 20 (17/6/24 - 21/6/24)	• Completed the first draft of the final introduction section for the thesis, including context, motivation, problem statement, aim and objectives, and thesis outline. • Began research for Case Study 1 and Case Study 2 (ENGG5205 and AMME4710, respectively). Identified areas of investigation for each and mapped out how to ensure that learning objectives were met. ▶ For ENGG5205, given how closely it relates to the thesis, I have decided to conduct research for each learning objective. • Continued to work on the system design for the ATMS, still encountering some challenges in ensuring that the system can be quickly integrated with current operations. • Came up with an implementation plan to roll out the system in stages as new capabilities were developed and tested. This plan is based on an agile project management system
Week 21 (24/6/24 - 28/6/24)	• Re-established contact with BHP and Otraco stakeholders from Mt Arthur (Grant was away on long service leave for a couple of weeks). Organised to visit the site once again to meet with Otraco representatives in person, to gain a deeper understanding of their current operations and issues. • Had an extensive meeting with Brad to discuss how to structure the last month of the project and the deliverables to meet by the end of July. • Continued research for Case Study 1 and 2, spending time extensively investigating both areas and exploring how to apply the subjects to my current project.

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Week	Summary
Week 22 (1/7/24 - 5/7/24)	• Completed the RCM section of the literature review. • Organised with Otraco representatives to meet onsite at MAC on 8/7/2024. The reason for the delay was that I was unable to secure transport to the Hunter Valley this week. • Converted the OT-OP-OBP24 Otraco Best Practice Procedure Tyre Field Survey form into an online form on the Corehesion platform to demonstrate its capability to Grant and the other Otraco representatives. • Made updates to the project scope of work. • Developed a potential system design implementation plan and overview for review by Otraco representatives. • Presented my project's current progress to the entire Corehesion company.
Week 23 (8/7/24 - 12/7/24)	• Onsite visit with Grant and Dan (Otraco representatives). I had a detailed, multiple-hour discussion with both of them to understand the problems they are facing onsite with the current tyre management system. • From the discussion with Dan and Grant, it became clear that the direction of the project must once again change in order to satisfy their requirements. The situation onsite was different from what Marcus and I were led to believe during the Zoom call on 28/5/2024. • The form and other materials prepared are not what Otraco requires; they need a method for detecting issues and gathering visual data on tyre problems while they are onsite, without needing to perform in-person visits. • Spent the rest of the week brainstorming potential solutions and mapping out the current tyre management system in a process diagram.

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Week	**Summary**
Week 24 (15/7/24 - 19/7/24)	• Redesigned the system for the project based on updated requirements from Otraco. Developed process diagrams for the current system, phase 1 implementation, and phase 2 implementation. • Updated the scope of work document for the Corehesion project to reflect the altered area of focus. • Began building a prototype for the system using Corehesion's current forms capability and worked on modifying the work items prepared in June to align with the new project direction.
Week 25 (22/7/24 - 26/7/24)	• Returned to working on the thesis document for the week, as the draft report is due on 28/7. Finalised the introduction and inputted current progress for the methodology (including the process diagrams and introduction). • Completed the prototype in Corehesion forms and am now ready to demonstrate it onsite when Grant and other Otraco representatives are available. • Communicated current project progress, delays, and other issues to Guodong in preparation for resuming meetings next week following his time off. • Sent Otraco the complete process diagrams for review, along with several requests for information required for the results section of the thesis. • Submitted a draft report to Guodong for review, which includes the introduction, the RCM section of the literature review, a basic methodology section (process diagrams for the current system and phase 1), and a basic outline of the thesis.

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Week	**Summary**
Week 26 (29/7/24 - 2/8/24)	• Completed the following literature review sections of the thesis report: Mining Industry Background, AI and ML, Data Collection and Management, Project Management Styles, and the Summary of my Literature Review. • Continued to communicate with Otraco representatives at BHP's MAC mine to coordinate demonstrating a prototype of the proposed system. • Had several discussions with Marcus on how to finalise the project, including key deliverables and the timeline.
Week 27 (5/8/24 - 9/8/24)	• Completed Case Study 2 for ENGG5205: Professional Practice in Project Management. • Organised with Grant to travel to site on Wednesday, 14/8, to present the work, proposed solution, and workshop the prototype with the Otraco team.
Week 28 (12/8/24 - 16/8/24)	• Travelled to site on 14/8 to demonstrate the prototype to the Otraco team (Grant and Dan) with Marcus. • Handed the project over to Marcus for it to be continued at the conclusion of the thesis project. • From this point on, I will continue to work on my thesis while also managing my university studies. The plan is to be offboarded from Corehesion on the 20th of September and submit my thesis sometime after this.

Table F.1 – Weekly breakdown of thesis work