AN INVESTIGATION INTO THE SELECTION OF AN OPTIMISED MAINTENANCE STRATEGY FOR CONVEYOR SYSTEMS WITHIN THE PORT OF RICHARDS BAY

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DECLARATION

University of the Witwatersrand, Johannesburg

School of Mechanical, Industrial and Aeronautical Engineering

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ABSTRACT

This research aimed to use conveyor failure data from the PORB to: 1) Review and identify effects of the existing maintenance approach, 2) Highlight failure causes and consequences and 3) To determine the most suitable maintenance strategy for conveyors in the PORB that will reduce failures thereby reducing downtime and loss of revenue. The scope of research was narrowed to the routes which had experienced the most failures which was supported through use of the Pareto principle. The failure data was put through a logical sequence of failure analysis tools to identify cause-and-effect relationships and survey questionnaires were sent to key personnel which formed the basis for the selection of a maintenance strategy. The research has shown that a modified version of Reliability Centred Maintenance (RCM), with dominant predictive methods, will provide benefit to the business by applying the appropriate combination of maintenance strategies (RM, PM or PdM) and prioritising maintenance tasks based on the equipment and components that pose significant consequential risks.

DEDICATION

For my dear wife, Kimay Naidoo, for being the pillar of support and motivating me through this research process.

ACKNOWLEDGEMENTS

I would like to sincerely recognise and acknowledge the effort, support and guidance from my supervisor, Mr. John Jones, and co-supervisor, Professor Vishal Sharma, both from the School of Mechanical, Industrial and Aeronautical Engineering at the University of Witwatersrand.

I would like to thank Transnet SOC for allowing me the opportunity to conduct this research in utilising their data and resources.

CONTENTS **Page**

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CAPEX	-	Capital Expenditure
CBM	-	Condition-based preventive maintenance
FFOP	-	Failure free operating period
FMEA	-	Failure modes and effects analysis
FMECA	-	Failure modes, effects, and criticality analysis
KZN	-	Kwa-Zulu Natal
MCA	-	Multi Criteria Analysis
MCDM	-	Multi Criteria Decision Making
MFOP	-	Maintenance free operating period
MSG 3	-	Maintenance Steering Group 3
MTBF	-	Mean time between failures
Mtpa	-	Million tonnes per annum
MTTF	-	Mean time to failure
MTTR	-	Mean time to repair
PM	-	Preventive maintenance
PORB	-	Port of Richards Bay
RCM	-	Reliability Centred Maintenance
RTF	-	Run-to-failure
S&F	-	Search and Find
SRCM	-	Streamlined Reliability Centred Maintenance

TPH	-	Tonnes per hour
TPM	-	Total Productive Maintenance
WW2	-	World War Two

ETHICAL CLEARANCE

A memorandum and agreement have been signed by the relevant authorities to allow the transfer and use of data by the author for this research project. A non-disclosure agreement has also been signed by the author in obtaining and protecting the information and its use for this sole research report and publication. Ethics Clearance as per protocol number MIAEC 105/20 has been granted.

1 CHAPTER 1: BACKGROUND

1.1 Introduction

Bulk materials handling (BMH) operations perform a critical role in a great number and variety of industries worldwide, including South Africa (1). The Port of Richards Bay (PORB), located in the North of Kwa-Zulu Natal (KZN), is considered one of the largest export ports in Southern Africa when considering volumes handled (2). A network of conveyors within the port terminal, with the PORB conveyor layout shown in Figure 1.1 and the full network shown in APPENDIX A: CONVEYOR LAYOUT PORB, are the means of transporting bulk cargoes for storage, export and import (3). The port is currently a multiple cargo handling port conveying a variety of mineral bulk cargo with varying material characteristics (4). The conveyors were pre-dominantly designed and built between the 1970's and 1980's to operate for woodchips and subsequently coal with a design life of 25 years (5).

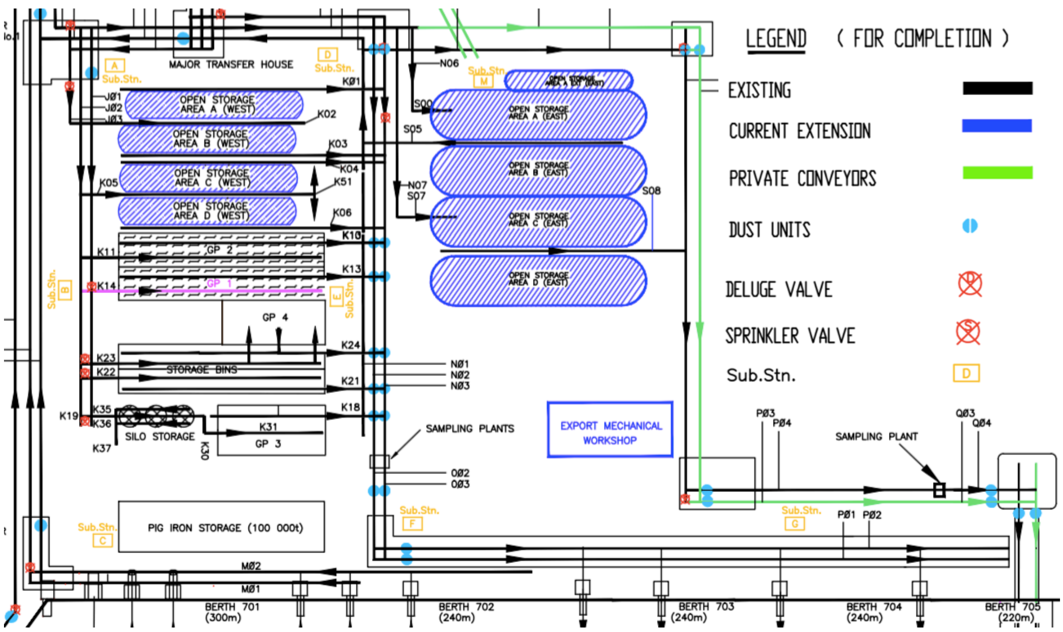

Figure 1.1: PORB Conveyor Layout (3)

The port has noted that the number of conveyor failures have increased within recent years and require frequent unplanned maintenance to ensure their operation (6).

Maintenance is the practice used to ensure equipment performance meets the end users’ expectations, in the case of this research, conveyor equipment performance (7). Maintenance of machinery and equipment has been needed ever since the development of machinery and equipment (8). The requirement of maintenance, and the management thereof, was triggered by the advancement in machinery, technology and complexity of equipment, systems and processes together with the advancement in specialist maintenance required for these pieces of equipment, e.g. vibration and oil analysis on lubricated components (8). The importance of regular maintenance on a conveyor system is largely second to that of revenue and profit, but consistent maintenance is an irrefutable approach to prolong the operating period of any conveyor and associated components which in turn can ensure steady operations and income generation (9,10).

Routine maintenance should ensure that the conveyor belt and associated infrastructure such as the idlers, chutes, pulleys, etc. remain in a useful operating condition adequate to ensure successful operation whilst disregarding maintenance activities will undeniably lead to damages and expenses that could have been avoided (9). Potential and existing difficulties which can increase downtime and maintenance costs can be detected through the conduct of routine maintenance. In addition to detecting impending issues, routine maintenance can also provide maintenance and technical staff with the prospect of identifying areas that can be improved to streamline operations. This leads to the importance of any plant or operation following a maintenance strategy and plan (11).

A maintenance strategy is a systematic approach to ensure facilities, equipment and components are operational. It involves the identification of an approach and plan to inspection, repairs and replacement specific to the operation, equipment and its components. It further involves the integration with other facets of the business such as planning and finance to ensure optimal usage of the plant (12). Maintenance plays a crucial role in achieving any organisation's goals and objectives with finding a balance between the maintenance cost and maximising production (13,14). The selection of an incorrect maintenance strategy can lead to improper maintenance activities being carried out on equipment which can pose serious risk to the safety of personnel and the operation, which directly impacts revenue (14). Improper maintenance activities could also reduce the life of machinery, equipment and components as they could be damaged or not adequately serviced or maintained through incorrect maintenance practices (15,16). Poor maintenance quality can dramatically decrease the reliability of equipment and may cause equipment to move towards a critical state and in many cases be operated to failure (17).

Optimised maintenance strategies provide organisations with various opportunities and challenges in the effort of improving performance through reduced failures and improved reliability (18). A structured maintenance approach and strategy plays an important role in the efficient running of a plant, particularly in the BMH environment where, roughly put, operational uptime of the plant directly equates to revenue. In the conveyor belt industry there are drastic consequences to failure ranging from downtime and the associated costs, to loss of life (19). With the evolution of maintenance, it has become critical to ensure alignment between business strategies and maintenance strategies (13,16). Therefore, maintenance optimisation through detailed planning of various maintenance actions provide an area of opportunity for improvement (18).

BMH industries generally adopt the traditional preventive maintenance (PM) strategy and techniques that utilise visual periodic inspection based on the expertise and experience of the maintenance staff (20). The dominant maintenance strategy within the PORB is that of inspection-based maintenance relying on the visual inspection skills of staff to determine when repairs or replacement of components or equipment are to occur (21).

1.2 Research Problem

The reliability of conveyor belts has always been of major concern within the BMH industry (22). The conveyor route reliability can be deemed as an integrated reliability of its components i.e. belt, pulleys, drive unit and idler rolls etc. (23). Figure 1.2 shows two typical conveyors within the PORB.

Figure 1.2: Typical Conveyor within the Port of Richards Bay (PORB)

The Existing Maintenance Strategy in the PORB utilises a system where the conveying routes are electrically interlocked and controlled to prevent product spillage under fault conditions. The port adopts a visual-based preventive approach, which they refer to as a Search-and-Find-principle, with the maintenance actions as listed below (21):

- The conveyors and their surrounds shall be kept clean at all times. Product spillages, accumulation of grease and other contaminants on the structural parts and walkways shall be immediately removed (24).

- Regular inspection of components and reporting as per maintenance plan (bi-annually),
- Lubrication at regular intervals, which involves greasing of components and filling of oil. In the case of abnormal noise or vibration, the drive shall immediately be stopped and the cause investigated and rectified (24).
- Adjustments to components such as scrapers, belt tracking devices, torqued bolts,
- Component change out on items such as silica gel moisture absorbers, idlers, redundant obsolete technology and equipment.

The existing maintenance strategy does not eliminate the failures, but it adopts a fault-finding approach to determine the cause of an occurrence through inspections. This is the least capital-intensive strategy, other than run-to-failure, with some sort of structure in ensuring operational uptime of the conveyors. It is heavily reliant on a substantial workforce with experience and knowledge in identifying worn components or parts as well as imminent failures. An example of this condition-based maintenance approach through visual inspection is seen on items such as wear liners used on hoppers and chutes, where the liners consist of a wear indicator, as shown in Figure 1.3, which changes colour to show the remaining product life. The existing maintenance approach can also result in failures, as can be seen in Figure 1.4, which shows an example of a pulley failure.

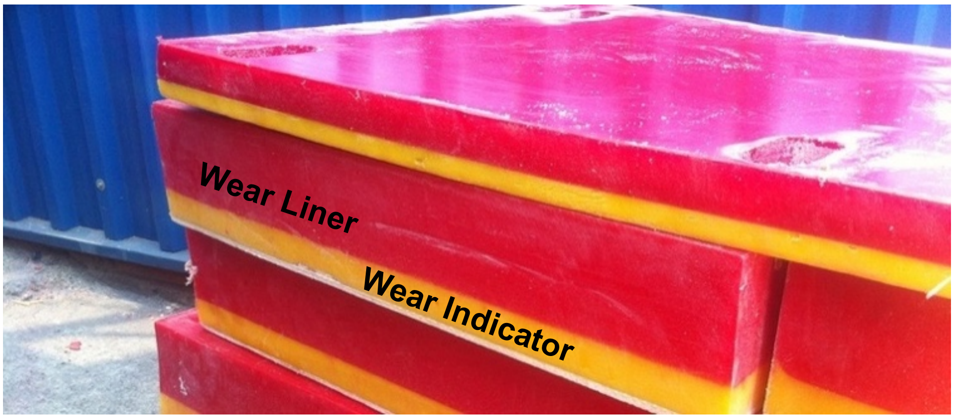

Figure 1.3: Typical PORB wear liners with wear indicators (25)

Figure 1.4: Pulley end disc failure

As discussed earlier, the PORB has experienced an increase in route congestion and failures over the past five years (6). The conveyors were pre-dominantly designed and built between the 1970's and 1980's to operate for woodchips and subsequently coal with a design life of 25 years (5). As a result, the BMH equipment has entered the maintenance intensive phase of its lifecycle and with Capital Expenditure (CAPEX) lean initiatives taken by the organisation to minimise costs, operational staff are managing the asset instead of end of life asset replacement. These initiatives aim at reducing already low maintenance budgets which in turn affects the reliability of the system. While investment in new infrastructure is vital in the long term, the need to review current maintenance strategies is critical to ensure system availability and uptime of operations (10).

The lifecycle of equipment or components generally trend to operate for a period of time before experiencing a decline of its operating capability that occurs toward the end of its useful life (26). The lifecycle of the equipment together with the introduction of difficult to handle cargoes such as magnetite and chrome ore have introduced new parameters that have not been accounted for in the maintenance procedures and intervals, which ultimately impacts the overall performance of the conveyor system.

This research project focuses on the conveyor systems in the PORB, its failures and the maintenance approaches adopted in order to investigate the selection of an optimised maintenance strategy for the conveyor systems at PORB and provide recommendations on implementing it. The use of PM cannot blindly be assumed to prevent failures and even if failures are prevented, it cannot be assumed that PM will provide the required results from the maintenance actions (20). Similar studies in analysing exiting maintenance strategies in order to select the most suited maintenance approach to conveyors were also conducted previously (14,27–30).

1.3 Motivation

A stoppage in a conveyor belt route means no production in bulk conveying applications resulting in a loss of revenue and an increase in maintenance and labour costs (31). On multiple conveyor routes the port was unable to perform at its installed capacity levels due to the unreliability of the equipment (32). On a single berth it was established that a throughput of 2.5 mtpa was achieved versus the installed capacity of 4.5 mtpa (32). Figure 1.5 shows the variations in planned tonnages versus the actual achieved tonnages for the period of December 2018 to May 2020. For the month of December 2018 it can be seen that the port obtained 12% of its planned target. In comparison, for the year of 2019 the port had achieved only 30% of its planned target whereas for the period in 2020, it can be seen that the port has achieved 27% of its planned volume target. This averages to an approximate 22% achieved of the planned targets, as shown in Figure 1.6, for the period of data obtained. These charts point to the dismal performance of the conveyors in the port.

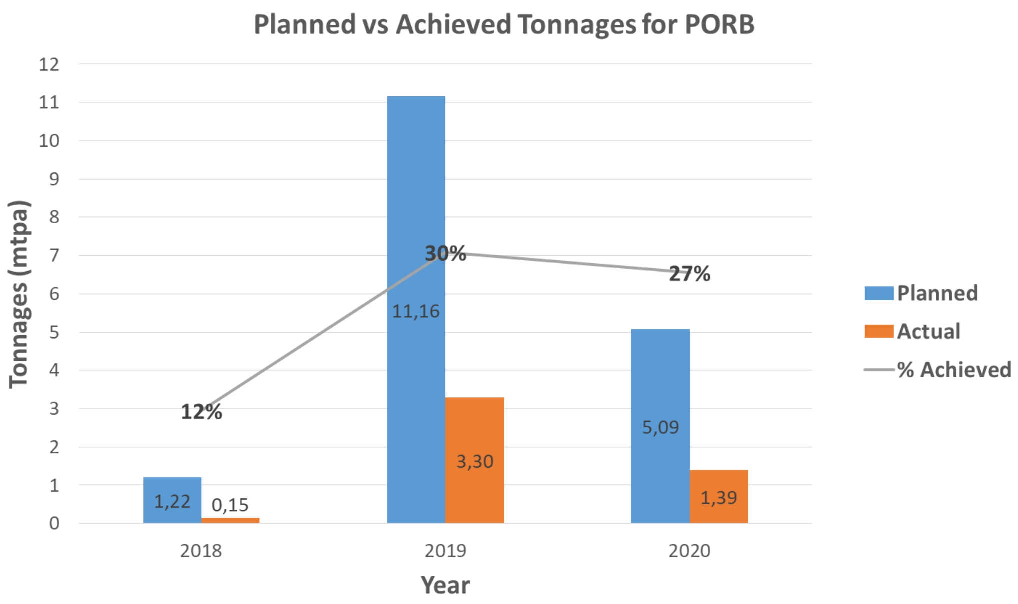

Figure 1.5: Planned versus Achieved Tonnages per year

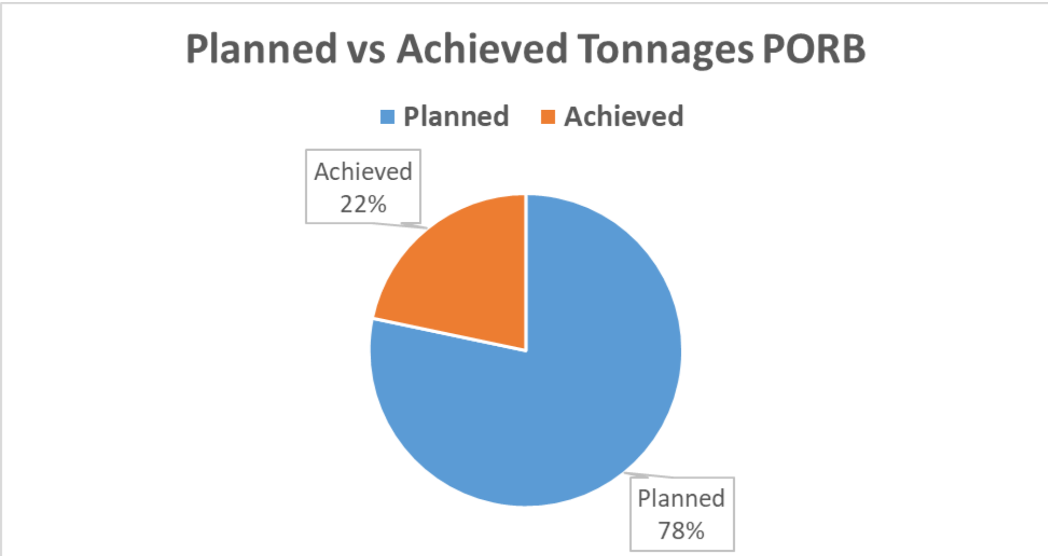

Figure 1.6: Planned versus Achieved Tonnages at the PORB

The specific failures and planned and achieved tonnages for each year and period are combined as shown on Figure 1.7. The number of failures experienced for the period of data obtained, December 2018 to May 2020, was 174 failures for all routes averaging approximately 11 failures per month. This represents an approximate 50% downtime per each month which, considering the port utilises on average 240 days per year for operations, equates to roughly 10 days a month downtime.

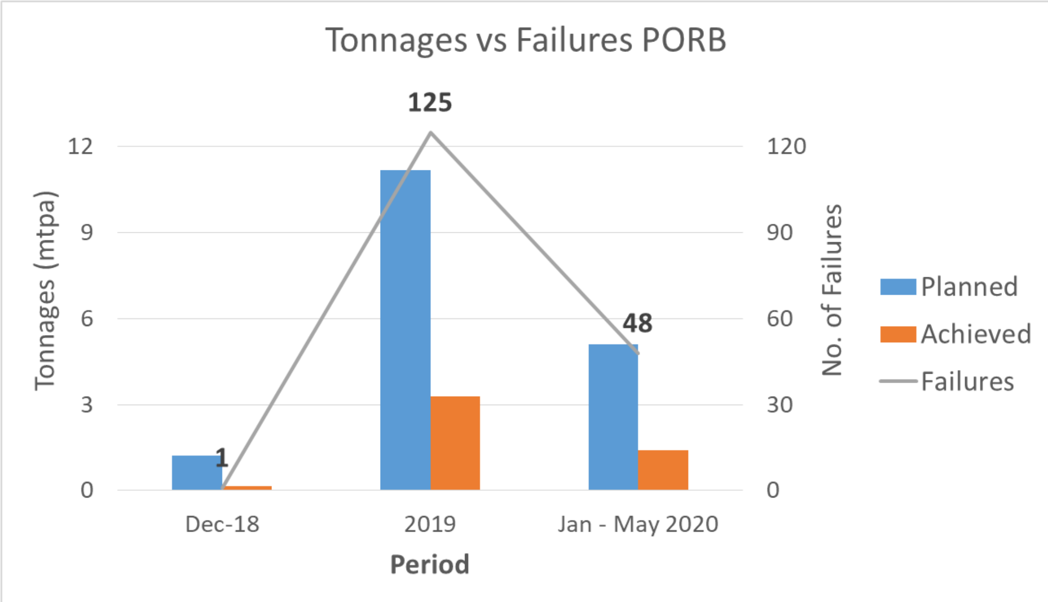

Figure 1.7: Tonnages vs Failures at PORB

1.4 Research Aim

The aim of the study is to investigate existing maintenance strategies applied to conveyor systems at the PORB and evaluate them against other maintenance strategies available in the literature. Conveyor failure data and maintenance plans will be gathered, analysed and compared to literature with the outcome of recommending an applicable and best suited maintenance strategy or strategies for conveyor systems within the PORB.

1.5 Critical Research Question

The conveyor failures experienced within the PORB leads to the following critical research question:

What is the most suitable maintenance strategy/strategies that can be applied to conveyor belt systems in the PORB?

1.6 Research Objectives

The overall objective of this study is to analyse and determine the most suitable maintenance strategy, principles and procedures that can be applied to conveyor systems in the PORB.

The specific objectives of this research study are to:

a. Identify, examine and analyse the existing maintenance strategies within the port and its impact on the business
b. Identify whether a new maintenance strategy/strategies or a change in maintenance approach is needed at the PORB
c. Identify possible new strategies and compare them against the current strategy
d. Provide recommendations on the most suitable maintenance strategy/strategies for the conveyors in the PORB.

1.7 Research Report Overview

Chapter Two encompasses literature on conveyor belts and its components, the principles of reliability and maintenance, the types of maintenance and optimised maintenance strategies, failure analysis techniques and tools and the varying research methods that can be applied to the project. The chapter concludes by selecting a research method that will be applied in this project. Chapter Three focuses on the detail of the research method and data analysis procedures and tools with Chapter Four representing the research context of the project highlighting routes for analysis. The results from the data and failure analysis procedures and tools utilised is covered in Chapter Five whilst Chapter Six concludes with a discussion, summary of the conclusions and recommendations based on selecting the most suitable maintenance strategy for conveyor systems in the PORB as well as any future work.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Conveyors are used in numerous applications, with belt conveyors particularly utilised to transport material commodity (33). The scale and nature of transporting materials and cargo may differ from one industry to the next, but the expenses involved in storing and conveying these materials and cargo are substantial (33). Thus the design, construction and execution of material conveying operations must be approached with the objective of achieving maximum productivity with minimal breakdowns (1). This literature review attempts to give an understanding on the maintenance involved in conveyor belts within the PORB and the general practice in the BMH field. It will cover literature on conveyors and their components, the maintenance strategies that exist and are applicable to conveyor systems, as well as maintenance and reliability procedures used to analyse failures of a system and components. It also entails literature on previous studies that aimed to select maintenance strategies for processing and manufacturing plants that utilise conveyor belt systems within their industry. It also covers multi-criteria decision making techniques in order to determine the go forward strategy or strategies for the plant. It will further explore the reliability and maintenance review processes used to analyse failures and identify relationships or patterns experienced with failures.

2.2 Overview of a Conveyor Belt

An overview of a conveyor's components is shown in Figure 2.1 and Figure 2.2. Troughed conveyors, as utilised in the PORB, are conveyors that form an angle to the horizontal to create a troughed shape in order to successfully convey its contents without spillage, with a cross sectional view shown in Figure 2.2 (34). It comprises a rubber belt, as shown in Figure 2.3, joined by means of a splice to become endless and is appended through a series of pulleys with a sequence of idler rollers equally spaced to support the belting along the conveyors length (35). The type of belt used in the conveyor system is dependent on the material conveyed, system tensions, desired loading capacity and the operating conditions and environment (36). The belt is driven via one of the pulleys, referred to as the drive pulley, which is connected to the drive system via a coupling (36). The tension within the system is sustained through the use of a take-up system, generally attached to the tail pulley, which comprises of a counterweight designed to maintain system tension (35). This is similar to the conveyors in the port.

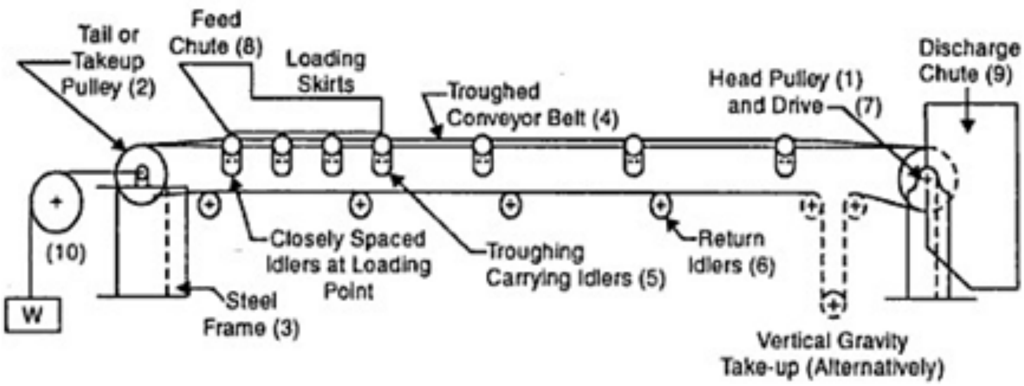

Figure 2.1: Conveyor Components (37)

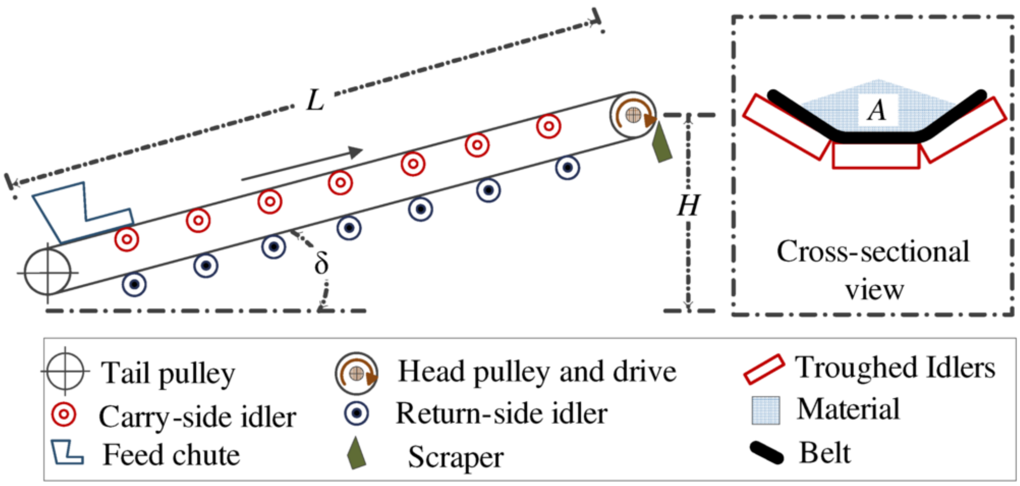

Figure 2.2: Troughed Conveyor Cross sectional view (38)

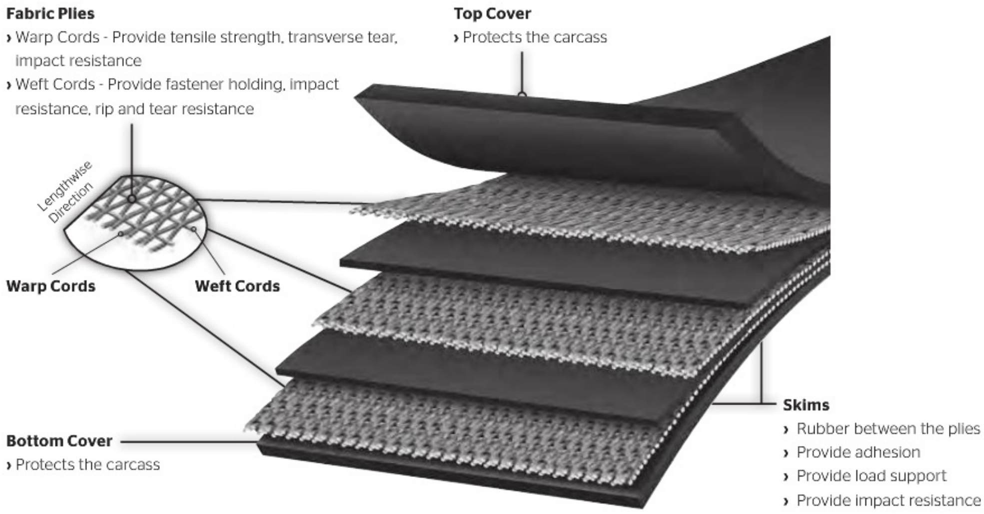

Figure 2.3: Exploded view of conveyor belting (39)

The conveyor systems in the PORB are operated from a central control room (CCR) which consists of a number of interlocks that run a series of conveyors to form a route to its final offload point. Conveyor systems and their equipment generally have a lifespan of between 10 to 15 years dependent on the operating conditions, maintenance efficacy and cargoes handled (35).

The rear of a conveyor is referred to as the tail-end and its front end is known as the head-end (40). The material is transferred onto a conveyor belt close to the tail-end with the actual feed referred to as the loading or feed point. The material is discharged at the head end of the conveyor onto receiving conveyors via a discharge chute which is referred to as the discharge or transfer point as depicted in Figure 2.4 (35). This is the process of material transfer that occurs in the port.

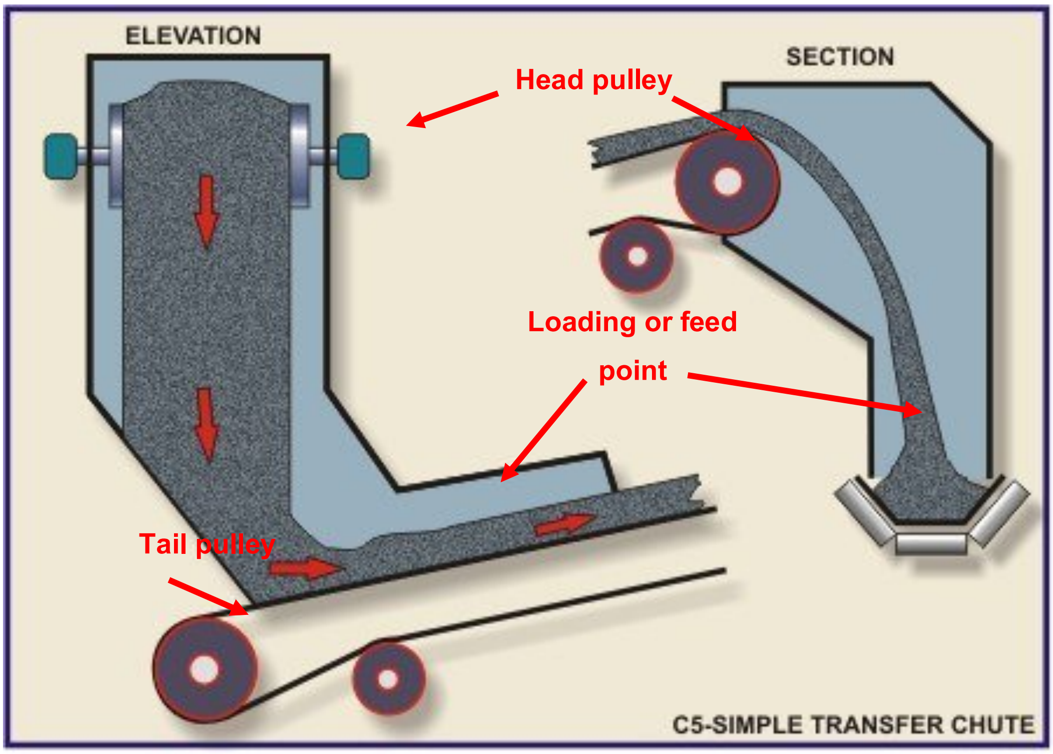

Figure 2.4: Transfer chute and material loading (41)

Impact loading is a frequent occurrence in the material handling industry due to the nature of the design and transfer chute arrangements, which does result in increased wear and could lead to possible failures in the critical conveyor components (42). Impact idlers are located at the loading point to provide additional support against the impact of the material whilst carry idlers support the belt and load along the length of the conveyor on the carrying side of the belt (35). Deflector plates are also found at the loading point and are used to guide the material centrally on the belt as shown in Figure 2.5 (34). The port utilises both impact idlers as well as the deflector plates to control loading impact and direct material flow respectively.

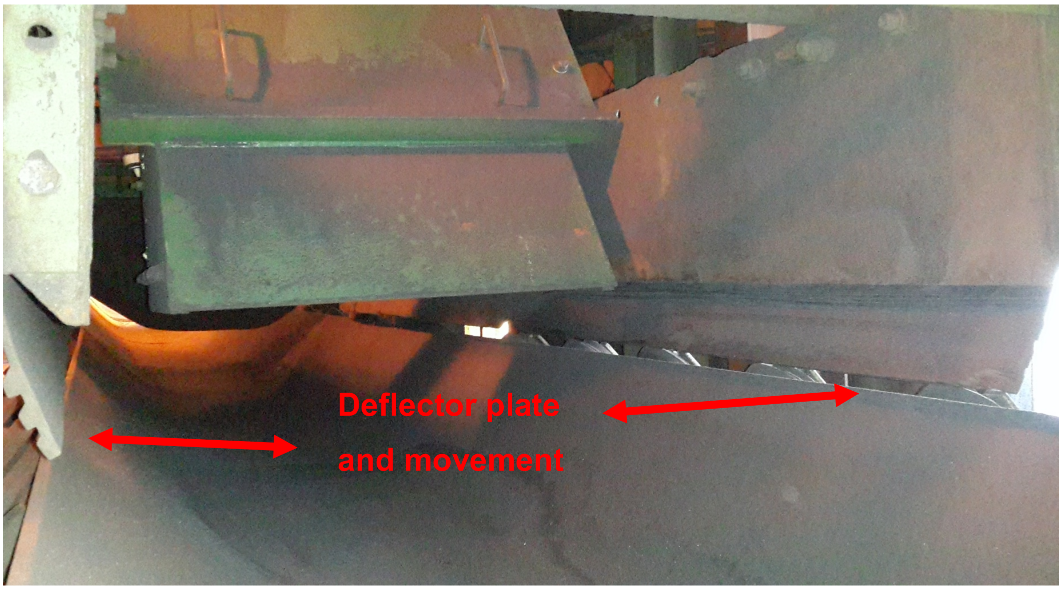

Figure 2.5: Deflector plates that guide material centrally

Once the cargo is discharged from the carrying side of the belt, the return belt, which is free of material, is steered toward the tail pulley on the return idlers (36,40). The return idlers are on the underside of the belt to support the load of the empty belt along the length of the conveyor (36,40). An exploded view of an idler is shown in Figure 2.6.

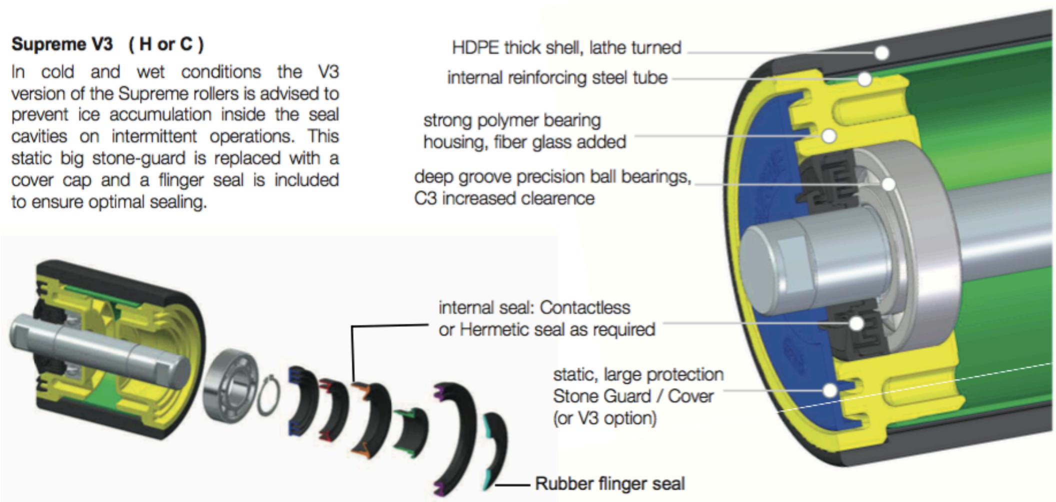

Figure 2.6: Conveyor idler exploded view (43)

The port also makes use of a chain conveyor on import routes from berth 609 for commodities such as pet-coke and alumina. The simplest chain conveyor system uses a single endless chain to carry cargo from the vessel to clients external to the port (44). Sprockets power the chain, unlike rollers, which are used with belt conveyors (44).

2.3 Reliability and Maintenance

Reliability can be defined as the probability that a process, function or system will run for a defined operating period under a defined environment (26). Maintainability can be described as the probability that a process, function or system can be restored in a given time and environment after failure (26). In this context, the conveyor components should operate for their specified design life under their specified operating conditions without breakdown.

Reliability is frequently measured by the mean time between failures (MTBF), the mean time to failure (MTTF) and the maintenance free operating period (MFOP) of a process, function or system (26) whilst maintainability is measured by the mean time to repair (MTTR) or restore the system, process or function to its original state (45). Complex systems generally tend to have in-built reliability (26). The reliability of the system can be reduced if maintenance planning and activities are not given equal importance as the design (11). Increasing intervals and maintenance tasks could also increase failures as a result of incorrect maintenance or excessive maintenance resulting in the equipment reliance on frequent maintenance (11). The principle rule with regard to maintenance is “Know your plant and keep it good as new” (26).

The beginning and end of correct conveyor maintenance is good housekeeping. This does not mean cleaning up the roads and conveyor pathways monthly or every second month. It means maintaining a clean conveyor system and route at all times through regular inspections scheduled periodically. The maintenance team on the conveyor system must be made responsible for conducting swift site inspections and investigations to detect dangerous conditions. All emergencies should be reported immediately so that the conveyor can be locked out and repaired. Improper maintenance may result in conveyor fires. Good maintenance is necessary not only from the standpoint of reducing breakdowns, but also from the standpoint of safety and continuity of operation (46).

2.4 Maintenance Strategies

Maintenance is the practice used to ensure equipment performance meets the end users' expectations, in the case of this research, conveyor equipment performance (7). A strategy is something that reflects the organisations ideals and concepts highlighting the pathway to achieving its long term goals and objectives (13,47). It is often found that strategies are formulated at a senior management level and when filtered down the hierarchical ladder, provides an abstract view of the strategic goal (48).

Maintenance strategies are a means for transforming business priorities and goals into maintenance policies. By addressing existing flaws or impending gaps in maintenance activities, a maintenance strategy and plan can be developed. The relationship between maintenance and business strategies are required to be coherent, unifying and integrated in order to ensure a successful operation of the plant and to generate revenue (48). There are various maintenance strategies that can be applied to plant and machinery to achieve the optimal reliability and availability (45). Higher availability comes from building stronger components with longer MTTF, ease of operation with shorter MTTR and having fewer components that can fail (45).

Different types of machinery and equipment demand different approaches and methods to maintenance, and by distinguishing between the right maintenance activities to use, the maintenance and operations personnel are able to select or develop the most suitable maintenance strategies to use for different type of machinery and equipment (49).

There are six different maintenance strategies that can be applied in any manufacturing concern, namely (11,13,15,50–52):

1. Reactive Maintenance
2. Preventive Maintenance (PM)
3. Predictive Maintenance (PdM)
4. Reliability Centred Maintenance (RCM)
5. Total Productive Maintenance (TPM)
6. Maintenance Steering Group 3 (MSG 3)

These six strategies will be discussed in the proceeding sections. As described earlier, the port utilised the preventive maintenance which they term as the search-and-find principle (S&F).

2.4.1 Reactive Maintenance

Reactive maintenance can be described as maintenance that occurs only once a failure has occurred (50). This is also known as run-to-failure (RTF) or corrective maintenance (53). Reactive Maintenance is fundamentally the base from which all preventive maintenance strategies have been developed (50). Reactive strategies have several risks and can lead to expensive maintenance due to subsequent failures that may result from a single component failing (50). The result could further lead to longer duration of downtime depending on the spares holding capacity of the company concerned which can result in higher operational costs, increased standing time and no movement of commodity which can result in a loss of revenue, reputational damage and penalties to the company from their clients (50). Reactive strategies are suitable for applications where the consequences of failure are low to non-existent and the costs associated with implementing this strategy outweigh the costs of the consequences of the failure (50,54). In the Researchers view this seems to be the approach at the port with maintenance activities or schedules not being followed. This will be elaborated further in the report.

2.4.2 Preventive Maintenance

Preventive maintenance (PM) undertakes maintenance actions prior to any failures in order to prevent them from occurring (50). Maintenance actions in accordance to pre-determined frequency and schedule to replace or repair any components, irrespective of their condition, can be classified as time-based PM (50). PM was founded in arms organisations during the WW2 period with the original premise focusing on component age and replacement after a specific time period (53). Conveyor belts are dependent on various different components, with the majority of them being serviceable (26). The serviceability of these parts is defined by the usage of the component since new or since repaired. The principle of infant mortality characterises how this philosophy can be flawed (50). New conveyor components (belting, pulleys, idlers, bearings, etc.) are susceptible to early-life failure due to installation errors or supplier quality and the replacement of this new component will not necessarily improve the reliability of the conveyor system or reduce functional failures (50). Infant mortality, as a result of installation errors, can be rectified with a maintenance team performing assessments and safety checks on the works conducted to ensure that the installations are correct (26,50). Quality issues from the supplier would require management intervention in the appointment of suppliers and development of the specification documents (26).

PM that considers the actual condition of the equipment or component through visual assessment and inspection in order to determine the required maintenance action is referred to as condition-based preventive maintenance (CBM) (19). CBM points to maintenance actions required on equipment or components that show signs of imminent failure or deterioration in performance characteristics failure (19). CBM aims to identify imminent failures so that the required maintenance actions can be implemented proactively and not prematurely or post failure (19). This method relies on experienced personnel with a background and knowledge in spotting imminent failures (19,52). For this approach, conveyor components or equipment (idlers, pulleys, belting, etc.) must be able to display distinct wear characteristics that would allow the maintenance team to predict when the equipment or component would fail or be worn out (50). Although this is an improvement on the reactive or RTF approach, CBM cannot promise enhanced improvements in uptime and reliability as components and equipment wear in an unpredictable way (50). It is however important to note that during any visual assessment or inspection, naturally other imminent or active problems or issues can be identified and resolved prior to any breakdowns and hence, reliability can somewhat be improved (50). As described earlier, the port utilised the preventive maintenance which they term as the search-and-find principle (S&F).

2.4.3 Predictive Maintenance

Predictive maintenance (PdM) aims to reduce failures and the consequent impact to operations whilst also factoring in scheduled maintenance (50) through the use of measurements and tools that detect and monitor equipment and components for any sign of wear that could lead to failures, thus eliminating the underlying possibility of failure (53).

Many types of components use sensors to monitor and capture live data relating to the condition of the equipment (19). This data can be analysed to evaluate the serviceability and predict potential future failures based on the previous failure data recorded. This, proves the basis of predictive maintenance (26). The quality and accuracy of the data used with the predictive maintenance approach is crucial to ensure the effectiveness of this strategy (50).

Predictive maintenance is a stringent inspection and monitoring regime that does not include the act of physically monitoring equipment as is the case in preventive maintenance. Examples of predictive maintenance are (50):

- Vibration analysis
- Infrared Thermography
- Oil analysis
- Visual inspections
- Belt thickness monitoring

PdM differs to PM through its use of monitoring equipment to measure the actual deterioration and wear of a component to determine the required maintenance actions, whilst PM utilises a pre-determined schedule to conduct inspections and maintenance (50). PdM proves a quantifiable method to determine the required maintenance actions based on the actual condition of the component or equipment, and with an efficient and well-coordinated plan it can theoretically reduce significant failures and downtime (50). The port make use of this approach on drives solely with temperature monitoring devices. The existing strategies and operating procedures will be compared to the strategies discussed in this literature review in order to identify similarities, issues and possible amendments that can ensure its suitability to conveyor belts.

2.4.4 Reliability Centred Maintenance (RCM)

Reliability Centred Maintenance (RCM) is a systematic process that separates out equipment components of a plant that will respond to some sort of scheduled maintenance action from components that will not (26). The scheduled maintenance according to (8,26) can be divided into three categories: schedule inspection, schedule rework and scheduled replacement. If an item does not respond to one of these three approaches, there are two options left: run to failure or redesign. Redesign often means replacing the item with a part that will respond to scheduled maintenance (26).

For schedule maintenance to work, the following five conditions must apply (26):

1. The failure rate must be increasing which will be investigated during the failure analyses
2. The total cost to replace before failure must be less than the total cost to replace after failure, meaning run to failure must not be more cost effective. In total cost, we must include labour, materials, and outage costs.
3. The failure rate after replacement must be lower than the failure rate before replacement meaning the maintenance activities must not have a negative effect on the system
4. One must be able to predict, at least approximately, when failure is likely to occur. This requires accurate data recording of past failures
5. The maintenance or replacement operation must not induce failures

There are several forms and variations of RCM such as RCM II and Streamlined Reliability Centred Maintenance (SRCM). RCM II is a form of RCM developed by John Moubray (7). It addresses environmental concerns by including a question on possible environmental damage. The wording is also simplified when compared to the RCM process. SRCM was developed by the electrical power research institute for analysis of electrical transmission and distribution systems (26).

The key focus of the RCM process is to ensure optimal uptime and operability of the equipment and components by identify modes of failure specific to each component before prioritising those failure modes through a ranking analysis (7). Preventive actions are then taken based on the ranking of the failure modes which identifies possible risk of safety and health related consequential failures or failures hidden to operators (7). RCM considers the individual component together with its desired life and operational environment (7,55). The RCM process provides the end user with a maintenance plan that highlights scheduled maintenance and failure-finding tasks for all components within the system (7,55).

The RCM process includes the following steps (26,56):

1. Description and selection of equipment and components to probe focusing on critical components
2. Describing the functions each component performs
3. Preparing a failure modes and effects analysis (FMEA) for each component and identifying failures of each
4. Performing the RCM for each failure using a decision diagram
5. Determining the remedial maintenance action required

The RCM process, in some instances, as stated by Moubray (7), can incorporate a further two questions, namely; “What can be done to predict or prevent each failure?”, and “What should be done if a suitable proactive task cannot be found?”

RCM differs from PM or CBM approaches by focusing on the condition of an item and attributing maintenance actions based on that actual condition (57). The approach further distinguishes between the various function failures that exist and its detection probability (57). RCM also considers potential hidden and consequential failures that could arise and aims to avert it (57). This approach of identifying the consequences allows the maintenance actions to be tailored to the specific components and its functional failures experienced (7). The principle of RCM allows it to be adapted to a variety of failure modes and types that consider the operational and process based environment (58).

RCM can be considered to have been widely used for numerous years and is frequently found in maintenance programmes and plans in order to improve the operational uptime and reduce failures in organisations. The challenges of RCM are that many management executives believe that RCM will resolve all problems and the equipment will instinctively improve reliability, which is not the case (58). In some cases, an RCM analysis may not be the best fit in that the environment and efficient operation could call for a single maintenance strategy (58). In other instances, RCM cannot be enforced in its full theoretical form, but adaptations or modified forms can ensure the main aim of any maintenance strategy, which is to keep the equipment running with optimal maintenance costs and time. This modified approach typically costs less and may show more benefits for organisations (58).

2.4.5 Total Productive Maintenance

Total Productive Maintenance (TPM) is a strategy that considers and utilises human resources in its approach. TPM's focus is set on the staff and improving their capability and skillset required to conduct their roles which is believed to ultimately improve the overall quality of work produced. TPM is considered to have been developed within the Japanese process industry with factories that utilise assembly lines (7,26,55,59). TPM aims to grow productivity by investing in applicable maintenance to reduce losses (60).

TPM's centric is to ensure the resources are well equipped and trained within the overall production process with the intention of creating a failure free environment (16). The aims of TPM are to maximise equipment effectiveness, optimise the maintenance system to achieve this, make sure the entire company is involved and to make sure that all employees are involved, by developing autonomous small group activities (26,61). The strategy requires involvement from top management to ground staff. This type of involvement tends to be time-consuming, expensive and is often met with resistance from operational and maintenance employees (26).

TPM can be said to be the Japanese Total Quality approach applied to maintenance. It is very much a people-driven approach, in contrast to RCM which is hardware approached (26).

The aims of TPM are (26,60,62–64):

- Maximise equipment effectiveness

- Optimise the maintenance system to maximise equipment effectiveness
- Make sure the entire company is involved
- Make sure that all employees are involved, by developing autonomous small group activities.

The pillars of TPM, as shown in Figure 2.7, are defined as (65):

1. Increase equipment effectiveness by eliminating the major losses
2. Train operators to do low-level maintenance (Kaizen principle)
3. Planned maintenance must be in place
4. A maintenance prevention plan must be in place
5. There must be training of operators in plant fundamentals
6. Office TPM must ensure productivity and efficiency levels are increased whilst also considering administrative functions while identifying losses
7. Emphasis on creating a safe workplace that is not hindered by the procedures and practices.

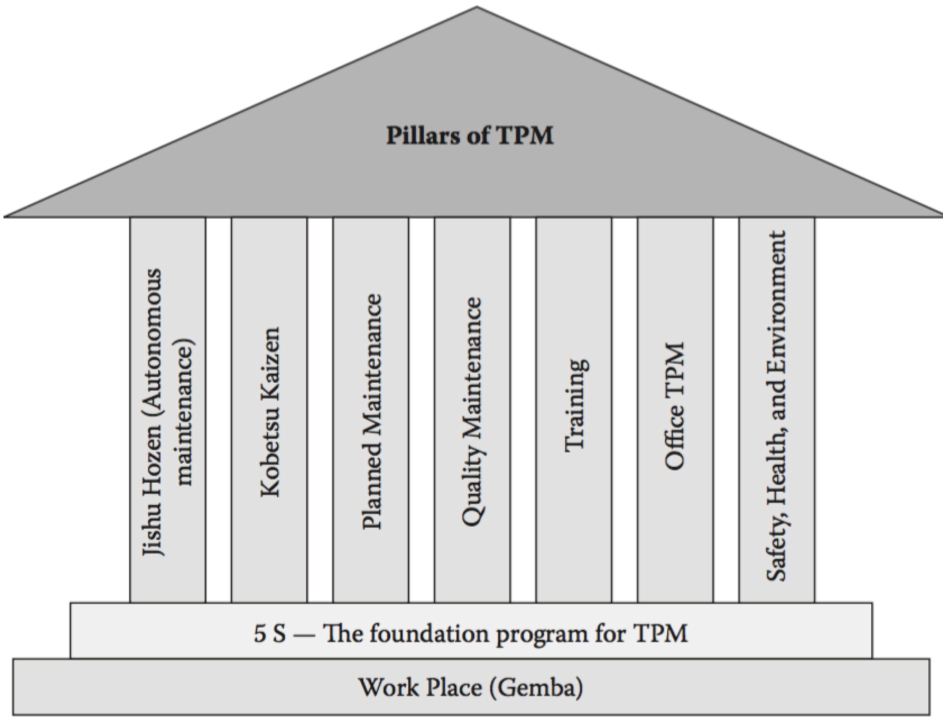

Figure 2.7: Pillars of TPM (60)

The final TPM metric is a measurement of the overall equipment effectiveness (OEE) which is determined as the multiple of the plant availability, rate of production and the quality of the works produced in relation to total discard works (26,62,64). The goals of TPM can be summarized and achieved by the four “zeroes” as described below.

- Zero Breakdowns –achieved by cleaning of the plant, adherence to operating conditions, restoration of plant to original condition, correct design flaws, Increase operator and artisan skills and training (26,63).
- Zero Adjustments - This step will only proceed once zero breakdowns phase has been achieved and encompasses the operations of the system, plant or equipment. (26)
- Zero Idling and Zero Defects - These steps aims to minimise idling conditions and reduce stoppages by installing relevant alarms, ensuring operator vigilance, measurement of time lost due to idling and avoiding overproduction or quality defects (26,63).

2.4.6 Maintenance Steering Group 3

Maintenance Steering Group 3 (MSG 3), which adopts a similar approach to that of RCM, is a methodology that maps out the organisation structure and processes in order to determine scheduled maintenance actions. MSG 3 was developed and pioneered for use in the airline and power generation industries with a view to sustain a high level of safety and reliability (66). MSG-3 is a detailed methodology that’s core focus area is on maintaining and improving maintenance regimes in the aircraft industry (67). This strategy is similar to RCM except questions are focused around lubrication of components and equipment (26). The MSG method of determining initial maintenance strategy is as follows (67):

- Determine the operationally important items.
- Utilising OEM supplied data and information
- Determine failure modes and effects.

- Determine suitable and operative maintenance tasks (Repair, replace, monitor);
- Determine intervals for all tasks.

2.4.7 Maintenance Strategy Selection

Failure prevention is the key driver behind any maintenance regime or plan, which is particularly true for conveyor belt systems. Regular actions and tasks to maintain equipment will firstly ensure safety of the personnel and plant but will also prolong equipment life and improve profitability. Lack of proper maintenance may result in increased downtime, costs and labour with reduced revenue. These provide a great motivator to consider the use of an effective and suitable maintenance strategy or strategies on the equipment (68).

Some of the challenges faced by maintenance teams are as follows (11):

1. Selecting and applying the most suitable and effective strategy and techniques
2. Identifying and conducting maintenance tasks to deal with each independent failure mode and type
3. Conducting and implementing maintenance tasks with least financial impact
4. Ensuring asset owners, staff and all relative stakeholders' expectations are met

A common thread in many previous studies indicate the importance of the alignment between business strategies and maintenance strategies (13,16,49,59,69). The first step in maintenance strategy selection as prescribed by similar studies (15,47,70–74) suggest a maintenance plan and objectives be retrieved from business goals and objectives. By considering maintenance objectives it becomes simpler to identify, prepare and develop maintenance plans and schedules for a particular maintenance strategy (13). These objectives aim to achieve increased levels of performance through efficient maintenance planning and actions (75). The understanding of the operation and its link to the commercial market are critical in ensuring profitability of the business. This feeds into the concept of feeding maintenance objectives from the business vision and goals (13).

The selected maintenance strategy is required to be supported by logical sequencing and plans that realistically can be implemented (8). Furthermore, it is important to ensure that the maintenance strategies undergo a periodic review process due to the changing environment and business requirements. The important items to consider in developing and selecting a maintenance strategy are as follows (8,13):

- Maintenance strategy development begins with a philosophy or goal that bests describes the maintenance practices and the development of maintenance objectives.
- The maintenance strategy selected must ensure that the maintenance goals and objectives are aligned and obtained from the business goals and vision
- Assess and evaluate the maintenance actions, tasks and challenges as and when issues and maintenance failures are experienced.

A theoretical framework in selecting a maintenance strategy for plants and processing plants presented by McAllister (75) describes that maintenance must integrated with business objectives and goals in order to ensure the overall goal of the organisation can be achieved with acceptable revenue. Therefore it is critical to ensure that any maintenance approach, plan or policy is directly derived and aligned with the business strategy (75).

The maintenance strategy should act as a pathway for maintenance that allows for agile and flexible adaptation with clear direction to adjust to any environment and scenario. This pathway should be developed from historical data within the organisation and its own goals as well as benchmarked against international standards (13). The implementation of maintenance strategies is a difficult task for maintenance management personnel in many industries and organisations. Every company or organisation has its own challenges and face different problems dependent on the objectives, that is business and maintenance objectives (13,47).

2.5 Previous studies

In this section some of the previous studies that have been conducted to identify a method for maintenance strategy selection are reviewed and analysed in order to guide the steps forward for this research project.

Based on previous studies by Bevilacqua, Fredriksson, Mungani, Rashidpour and Velmurugan (13,15,47,51,59), it has been noted that the maintenance strategy selection in any organisation, plant or system in varying fields are typically a Multiple Criteria Decision Making (MCDM) problem. To overcome this problem the authors used multi-criteria decision-making tools such as Analytic Hierarchy Process (AHP) and Multi-Criteria Analysis (MCA).

Alsyouf (76) identified a MCDM methodology for selecting the most informative maintenance approach for a paper mill industrial firm (76). The study described the role of cost-effective maintenance in achieving competitive advantages and conducted a survey in its initial stages to determine the current maintenance practices used and how they were selected. The study further developed a model to select the most suitable maintenance policy in terms of cost to implement and actual maintenance costs, as well as improving the effectives of the decision making in maintenance tasks. The main results from this study showed the utilisation of the FMECA to categorise and prioritise areas of concern, together with the need to select a practical approach to maintenance tailored to the system or subsystem at hand. This in the view of the researcher points to an RCM approach (76).

Salonen (16) formulated a maintenance strategy procedure for a processing and manufacturing plant based on three important aspects; company mission and vision, company strategic goals, and the strategic goals of maintenance (16). This research considered the manufacturing industry in developing a cost effective and simple approach to develop, implement and assess maintenance strategies. The research developed a process to select maintenance strategies (16).

Zaim (73) attempted to develop a method for maintenance strategy selection using AHP and ANP methods (73) for a local newspaper printing facility in Turkey. The purpose of this paper was to illustrate two methods utilised in general decision making to select the most suitable maintenance approach for companies or industries. The two methods, AHP and ANP, proved effective in selecting a suitable approach to maintenance for printing machines. The two methods resulted in very similar results. The research showed that these methods and techniques can be applied to varying industries and companies to select maintenance strategies (65).

El-dogdog (77) describes RCM as the integrated approach that links the work of FMECA and Ishikawa Fishbone diagram in its process which was adopted in a Toshiba glass factory (77). It was found that the FMECA and Ishikawa Fishbone methods can assist maintenance personnel of any plant or industry by decreasing the risk of severe failures. This research identified failure modes, risk priority numbers (RPN'S) and the revised RPN's when the remedial actions were applied (77).

Deshpande (18) applied the concept of RCM to a medium scale steel industry through systematically applying RCM techniques by analysing failures, failure causes and effects on the system (18). The study acknowledged the need for different and varying maintenance approaches for the different pieces of equipment. The study found that RCM can be applied to the manufacturing industry to improve overall performance and reduce maintenance costs (18).

Vishnu (14) stated that RCM selects the most suitable maintenance strategy for equipment and components in the industry based on its criticality score and reliability parameters which was based on a case study conducted on a titanium oxide plant (14). The plant conveys titanium oxide through use of a feed screw conveyor. This paper proposes a broad approach to implement Reliability Centred Maintenance (RCM) in process plants. The study highlighted the importance of surveys and considering expert personnel opinions from the maintenance and production departments. The model developed in the study was validated against the maintenance historical data of the titanium oxide plant. The plant had shown signs of following a combination of planned and reactive maintenance strategies. The implementation of RCM was justified through simulation results which indicated poor availability and performance of equipment with the existing maintenance approach (14).

Carretero (20) investigated scenarios in applying RCM to large scale railway infrastructure to achieve an effective and structured maintenance approach and found RCM to be promising technique due to its introspective approach with regards to technical areas, its multidisciplinary approach to conduct analyses and its requirement of detailed and structured documentation and reporting (20).

Fore and Msipha (78) conducted a case study on a ferrochrome processing plant where preventive maintenance techniques were investigated through application of RCM (78). This research had determined the neglect of preventive maintenance measures which directly affects the operations of the plant. This formed the basis of the research paper's RCM approach which was used to create a maintenance strategy to address the majorly failing equipment. The result was a maintenance initiative that focuses limited resources in areas of high risk and concern that would cause the most severe damage and consequential damage (78).

Gerike (28) conducted a study at a coal mine with a significant number of conveyors in operation. The study encompassed determining failure causes and failure rates through use of actual failure data and investigating predictive tools, vibration monitoring, to monitor equipment. The research concluded that the use of vibration monitoring equipment had reduced failures to the equipment by prompting maintenance activities (28).

Yuan (30) conducted a case study to select a maintenance strategy for a blast furnace conveyor belt. This paper presents a reliability simulation to assess and link different maintenance strategies. The study had defined systems and sub-systems before evaluating and categorising failures, functions and failure modes. The study utilised a MCDM tool, namely pairwise MCA tool, to select an appropriate maintenance strategy. This study found that maintenance conducted on individual components based on its own characteristics improves reliability and performance, which points to a tailored approach to maintenance, i.e. RCM (30).

Kumar (79) conducted a study to analyse the operating parameters, maintenance procedures and the plant availability for a critical conveyor system in a coal mine in India. The research utilised existing failure data to conduct analyses. The scope of this research had considered seven subsystems that make up the critical conveyor system. This research paper prioritises areas of concern through ranking of failures according to severity, similar to that of an FMECA. It further measures the criticality of each component based on the failure data which deduced the downtime, repair time and availability of that component and subsystem. The study had concluded that plant parameters such as the reliability and availability can be improved by introducing proper maintenance techniques and strategies but it did not allude to what strategy would be the most effective (79).

Zimroz (80) developed a research paper which intended to provide the status quo on existing research practices focused on maintenance of belt conveyors. The study concluded that simply applying predictive maintenance initiatives through fully automated methods poses many challenges and may not be the final solution with further research required ascertain the most suited maintenance strategy or combination of strategies. This leads the researcher to believe a tailored maintenance approach is required (80).

Ojha (27) conducted a research study that focused on belt conveyors in a coal handling plant. The study utilised the Fishbone technique to briefly identify failure causes. It further prioritised failures in a process similar to the FMECA. It identified the importance of determining root causes prior to selecting a maintenance approach. The research concluded that there are early stage improvement in reducing costs and improving efficiency when following the approach of identify failure causes and scenarios prior to maintenance strategy selection (27).

It can be noted that there have not been many studies that consider maintenance strategy selection for conveyor belt systems. However, it is noted from the previous studies that that the procedures encountered in maintenance strategy selection can be applied to other industries, i.e. conveyor belt systems.

2.6 Research Method Types

The purpose of any research or study is to investigate and identify patterns, sequences, trends or possible responses to a predetermined set of questions. The key aim when conducting any research is to uncover layers of data to reveal the answer to the objectives (81).

The research process generally follows the below steps (81):

1. Formulating the research problem;
2. Detailed literature survey and developing the hypothesis or CRQ;
3. Preparing the research design and methods;
4. Collecting, collating and analysis of data;

5. Results interpretation and presentation, and
6. Formal conclusions and recommendations.

The objective of research is to arrive at an answer for a defined problem or set of questions, with the use of available data in order to provide possible solutions and recommendations. With this in mind, research methods can be put into the following three groups (81,82):

- Data collection methods. These methods will be utilised in scenarios where the actual data available is insufficient to arrive at a solution
- Analytical methods. That is the statistical techniques which are used for establishing relationships between the data and the unknowns;
- Results Comparison. These approaches are utilised to are used to gauge the accuracy of the results obtained.

The latter two methods above are considered as the analytical tools of research. Research can be conducted using various methods with the most common being qualitative and quantitative research methods. Qualitative studies do not enable the researcher to deduce cause–and–effect relationships (83). Quantitative research can be defined as a process using statistical procedures to analyse data in order to examine the cause-and-effect relationship (84).

Qualitative research methods are commonly linked to the study and investigation of social and cultural aspects. Qualitative methods generally provide results that can be termed as open-ended, based on ideas and concepts that have been utilised in the research. Qualitative methods are able to deduce relationships and conclusions based on the feelings and thoughts of personnel, which allows flexibility in the structure of the report (84,85). The qualitative method allows for fluidity in the research development. This approach is suited to investigating and exploring the nature of problems without quantification. The foremost objective in qualitative studies are to define the changes between any phenomena or scenario. Qualitative research methods were established in the social aspects of research to study and examine socio-cultural occurrences (82).

Quantitative research is a method that measures objective hypotheses drawn on the relationships and link between quantifiable information and data. The data can be measured and analysed utilising statistical techniques or tools. This provides the final report to have a more rigid structure than that of the qualitative process in that the structure would generally consist of chapters such as introduction, literature, research approach and methods, results and discussion, and conclusion and recommendations (86). Quantitative methods are most suited to understand the extent of problems and challenges by identifying and grasping relationships and changes between them (82). The techniques used in quantitative research include random selection of respondents, questionnaires and surveys, as well as statistical analytic tools to test and identify relationships of the outputs. The researcher in quantitative methods is external to the actual research and the results (86).

Mixed methods research is a research approach that involves the use of both quantitative and qualitative information and data, which are integrated to draw conclusions and recommendations in the social and theoretical frameworks. The main assumption in this mixed methods approach is that the integrated use of qualitative and quantitative data and analysis tools provide a complete view and understanding of the research problem and objectives (84,85,87,88).

Table 2.1 shows the comparisons between qualitative and quantitative research.

Table 2.1: Comparison of Qualitative and Quantitative Research Methods (87)

Qualitative	Quantitative
Induction **Purposes** • Develops notion based on studies. • Focused on finding or unearthing principles. **Procedures** • Developing design. • Combines and collates information for analysis.	**Deduction** **Purposes** • Proves data and theory through investigations. • Focus on determining measured results **Procedures** • Fixed scope and area of works. • Distinguishes between information collected and analysis methods and results
Subjectivity **Purposes** • Highlights the descriptions, behaviours and understandings • Attempts to comprehend views and standpoints **Procedures** • Researcher closely associated with information collected. • Researcher acts as the "research instrument."	**Objectivity** **Purposes** • Highlights items which are measurable or can be calculated • Outcomes are independent of opinions or views **Procedures** • The academic is divorced from the information collected • Reliance on measures, procedures and standards to deduce results
Context **Purposes** • Focuses on precise detail • Evaluates complete structures. **Procedures** • Considers life-like methods and tactics • Dependent on low volume of data	**Generality** **Purposes** • Focuses on simplified approach and repetitive patterns • Considers numerous settings (Environment, people, etc.). **Procedures** • Utilises statistical and measured methods • Focuses on a higher volume of information and data.

The author decides on the type of study that is to be undertaken when considering and selecting the research methods approach, be it a qualitative, quantitative, or mixed methods study (84). Research studies and designs are types of analyses and investigations within these research methods procedures that give the researcher guidance in terms of the direction the research design or study will take (84).

2.6.1 Data collection

The undertaking of data collection starts at the definition or understanding of a research problem. The type of data forms an integral part in setting and planning out the research. There are generally two types of data that can be collected, that is primary and secondary data. The primary data consists of information that are new and have not been seen or published before, appearing as original data. The secondary data consists of information that has already been published in previous studies or journals and has been put through a series of statistical and analytical processes. Data collection for primary and secondary differ in that primary data is original and must be collected for the first time whilst secondary data can be considered a compilation of works that have already been conducted (81).

Primary Data

Primary data can be collected in the course of experiments during experimental research and can also be obtained through direct or indirect communication with research participants. It is represented as the actual data received. This research makes use of the actual failure data and maintenance logs from the port (81).

Secondary Data

Secondary data refers to information and data that are available through previous research and studies. With the use of secondary data, it is important to investigate the multiple sources to corroborate the information. Secondary data may take the form of either circulated and published data or uncirculated and unpublished data (81,84).

Surveys and Questionnaires

Surveys are a widespread technique used to collect and analyse data from primary sources using various collection methods that involve a series of questions tailored to obtain relevant and pertinent information from respondents. Surveys provide flexibility when requesting information and dependent on the structure and types of questions posed, can result in both qualitative and quantitative information (81,85). Surveys are flexible and can easily be combined with other methods to give detailed insight into the data (89). Survey design involves determining the sample population and determining the method/s of approach, i.e. interviews, questionnaires, online platforms etc. It also entails identification of an accepted response rate and level of accuracy which is highly depended on the subject of the survey (90).

When conducting a survey, it is important to understand what format of survey is required. There are two survey formats (85):

- **Cross-sectional surveys** are surveys that obtain relevant information a group at a particular point in time and attempts to investigate and determine correlations between two distinct factors
- **Longitudinal surveys** are surveys that obtain information over a specified duration. This method will allow analysis of changes within the actual group of respondents and attempt to draw relationships and conclusions from that. A longitudinal survey also attempts to determine correlations between distinct factors but this is done considering the change in factors over the specified duration as opposed to the distinct difference between them, e.g. relationship between the wellbeing of an employee and the employment period of that employee.

2.6.2 Research Validity and Reliability

Some method that are utilised to ensure validity and reliability of the research are as follows (81,84):

- Triangulate various sources of data and information by scrutinising the data, comparing relevant studies and data to each other and utilising it to develop a logical process flow for achieving research objectives
- Utilise peer reviews to verify and confirm accuracy levels when conducting qualitative research by giving research participants the opportunity to review the final report findings.
- Use a rich, thick description to convey the findings. This approach will elevate the peers to provide a detailed perspective of the research process and its findings.
- Identify and discuss any subjectivity that may arise or exist from the researcher. This presents a transparent view to the reader
- Expend sufficient time on site in the surroundings relevant to the research. This provides the researcher with detailed first-hand experience in understanding site conditions, problems and possible remedies. This also improves level of accuracy in that the researcher is able to identify and communicate directly with the relevant personnel.

2.7 Analysis tools

A variety and assortment of statistical procedures and tools can be utilised to analyse research data and information. These statistical methods or tools may be split into descriptive or inferential statistics. Descriptive statistics refers to those that are used to illustrate and describe the information whilst inferential statistics are those that are utilised to conduct the actual analysis of the data to draw relationships. There are various ways that data can be analysed but ultimately that is based on the study objectives and the data available (91).

2.7.1 Pareto Principle

The Pareto principle is a statistical tool that enables its user to identify and select a specific item or number of items that result in the most significant effect. It utilises the principle of determining the top 20% of causes that result in 80% of failures or issues. The numbers do not have to be 20% and 80% exactly, but must show a distinct view between the causes in order to identify the causes with the greatest impact. The purpose is to ascertain the items accounting for the majority of the results, then introduce tools such as the FMECA, Ishikawa diagram or Five Whys to identify the root causes of the problems (92). Generally, in maintenance practice the Pareto analysis is used to prioritise maintenance activities. A Pareto histogram is a graphical representation of the results from a Pareto analysis and can be used for successful identification and ranking of failure events contributing to downtime (93).

2.7.2 Failure Modes, Effects and Criticality Analysis

A failure modes, effects and criticality analysis (FMECA) is a reliability assurance technique with first official use recorded from the late 1940's (26). The FMECA is used to categorise and evaluate any probable failure modes of critical components of a system, the consequences or effects these failures may have on the system and how to circumvent the failures, and/or alleviate the failure consequences or effects (56). The FMECA is an adaptation and progression from the originally developed FMEA (Failure modes and effects analysis) with the addition of the C for the criticality (or severity) of the various failure effects which are now factored into the analysis (56). The objective of FMECA is to determine possible remedial actions that need to be implemented in order to reduce failure effects and consequences. The fundamental intention is to induce actions that will reduce the likelihood of failures. The severity, probability of occurrence and detection probability are scored and ranked to determine a risk priority number or rating (RPN).

The basic questions asked in an FMECA are the following (26,56):

- How will each component or item possibly fail?
- What causes or events lead to these failure modes?
- What are the consequences or effects of the failures?
- How can the failures be detected?
- What existing measures or provisions are made to prevent failure?

The failure modes, consequences and effects for critical components are typically detailed on schedules. The documentation involves the following (7,26):

1. Description of the different components and their intended functions that ensure operability of the equipment or plant.
2. Description of the failures which involves highlighting the various modes of failure, causes and events that give rise to these failure modes, and the numerous methods and probability of detection for the failure modes
3. Detailing the failure effects on the system and possible consequential effects the failure could have on the system and other components
4. The severity, probability of occurrence and detection probability of the failures are detailed and scored in line with a weighted scoring criterion to determine a ranking referred to as a Risk Priority Number (RPN). The RPN ranks the failure modes in the order of which failure will require action first. The higher the RPN the more serious the failure.

2.7.3 Weibull Analysis

Failure can be defined as the inability of a component or system to continue to function, rendering it unable to perform to its specified performance requirements (56). They can be divided into two main types; catastrophic failures which occur suddenly and completely, and degradation failures in which the system or component gradually loses ability to function (94).

The Weibull analysis is a model commonly used in statistics to detail the failure distribution and operating life of equipment and components in a variety of industries such as aircraft and aerospace, automotive manufacturing and assembly, materials handling, process industries, electronics, etc. (95). The use of Weibull analysis technique allows the researcher to determine the failure distribution pattern from which reliability conclusions can be presumed, such as the failure pattern and types (26).

There are three common failure patterns i.e. infant mortality, random and wear-out failure. Infant mortality are failures that occur prematurely and are generally a sign of a quality issue within the system (26). Random failure, also referred to as constant failure rate, occurs in a pattern within a specific period (94). A very different type of failure is wear-out failure, which occurs toward end of life of a component after providing its useful life or design life with appropriate maintenance actions (26).

2.7.4 The Five Whys

The Five Whys technique is an ingenuous problem-solving methodology used to unravel any difficulty or issues by repeatedly asking the question "Why", to unpack the various layers of signs that can lead to the root cause of a problem. The Five Whys adopts similar principles to that of systematic problem solving (96). The Five Whys methodology was pioneered within the automobile industry, specifically at Toyota by Sakichi Toyoda (26). This approach is commonly used to identify underlying problems and root causes in equipment failures and safety related incidents (97). The intended use of this technique is to, on the surface, briefly identify the root cause of the failures (96). This method of root cause may appear simple and often gets used incorrectly. Caution must be given when conducting a Five Whys to ensure that when asking questions, the real root cause is identified. The five in the "Five" Whys analysis is a rule of thumb and more or less Whys can be asked before finding the root of a problem (97).

2.7.5 Ishikawa Diagram

Ishikawa diagrams, also referred to as Fishbone diagrams, are diagrams that depict the possible causes of a specific event. The process first starts with the failure event or problem that has occurred within the equipment or component which forms the main bone of the fishbone diagram (98). Distinct categories related to the component or equipment branch off forming further bones and depict the primary causes to the failure event with further secondary causes identified within each distinct category (98). Typical categories of the diagram include (26):

- People: Staff involved in the maintenance of the conveyor belts
- Methods: Maintenance procedures, plans and requirements
- Machines: Any equipment, computers, tools required to complete the works successfully
- Materials: Raw materials, splices, steel, idler brackets, etc. required to maintain operation
- Measurements: Data generated from the conveying that are used to evaluate its throughput and uptime, (no condition monitoring in PORB)
- Environment: The conditions within the PORB; location, temperature, etc.

The components of a conveyor system, environment of operation, maintenance procedures and operational staff generally form part of the primary cause with external influence such as the commodity changeovers forming part of the secondary causes (27).

2.7.6 Multi Criteria Analysis (MCA)

A Multi Criteria Analysis is a logical process to determine a "most favourable" option across multiple criteria. When considering how "good" any solution or option is, many factors or criteria need to be considered. The MCA aims to score the options independently against a set of criteria to deduce the single best go forward option or combination of options to meet project requirements (99,100). The general process followed during an MCA is shown in Figure 2.8.

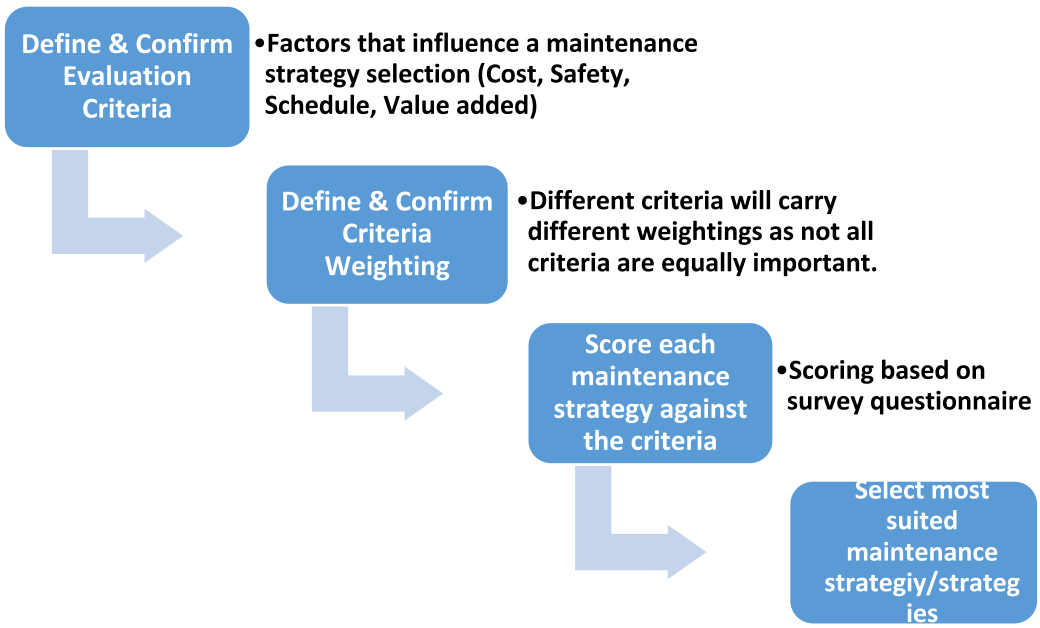

Figure 2.8: Flow diagram of MCA process (99)

MCA Scoring Methodology

Each option is given a score between 1 and 10 where a 1 is a flawed but possible solution, and a 10 is ideal. The scores are related to the approach particular to that specific criterion (99).

The 1-10 scale is described as follows:

- 9-10 –Ideal
- 6-8 – Acceptable
- 4-5 – Can be improved
- 1-3 – Possible but has many challenges

The scores received are then weighted and tallied to provide a percentage. The percentage is then compared to the other options and ranked accordingly to determine and select the most suited option across all the criteria (99)

2.8 Literature Review Summary

This literature review aims to capture the essence of the analysis methods to be followed during the course of this research project. It follows a methodical sequence beginning with literature providing an overview of a conveyor belt and its components before defining reliability and maintenance. It is followed by literature on the different maintenance strategies describing the approaches taken during reactive or corrective, preventive and predictive maintenance strategies. The introduction of new maintenance strategies is then discussed which encompasses strategies such as TPM, RCM and MSG-3 which streamline the existing maintenance strategies. Literature of maintenance strategy selection is then covered to understand the procedures undertaken in previous studies. The FMECA failure analysis tool was utilised in previous studies to determine the failure causes, modes and effects from the varying components within any system. The outputs were then used to develop a remedial action for the failure modes which reduced the overall risk and effects of that failure, which was a similar process followed in this research (11,27,47,77,79). Maintenance strategy selection occurred in previous studies via varying MCDM tools such as the AHP, ANP and the MCA, with the use of an MCA utilised in this study due to its objective approach by conducting a sensitivity analysis on the MCA results (13,15,30,47,69,73).

These studies also utilised cause-and-effect tools such as the Ishikawa diagram in order to narrow down failure causes and their effects (27,77). The Five Whys tool was utilised as a failure cause-and-effect tool by Bradley (26) in his maintenance investigations and tasks (26). The various research methods and data analysis procedures are captured to provide an oversight into the methods of approach to this research project.

Failure analysis tools are detailed in the literature highlighting the steps, theory and how the analysis tools will be used for this study. The failure analysis tools first consist of the Pareto principle which the researcher used in order to determine which route contains majority of the failures. The FMECA is then described and the steps followed within the process. The Weibull analysis tool is then discussed highlighting its purpose and expected outputs from a Weibull. Literature regarding the cause-and-effect analysis tools, namely the Five Whys and the Fishbone diagram tools were covered to highlight the process and its intention. Literature on the MCDM tool used for this project, MCA, was covered to describe the process taken to develop, distribute and populate an MCA.

The literature review shows that previous studies have initiated research into maintenance strategy selection for conveyor systems (13,15,30,47,69,73). It further highlights the gap that exists with maintenance strategy selection and effective maintenance within conveyor systems with a limited amount of studies previously conducted (13,15,30,47,69,73). There are various maintenance strategies developed that can be adapted to conveyor systems which has been discussed in the literature. This links to the overall objective of this study, which is to analyse and determine the most suitable maintenance strategy, principles and procedures that can be applied to conveyor systems in the PORB.

3 RESEARCH DESIGN AND METHODS

A research design can be classified as the development and formation of systematic research from the first to the last step to guide the researcher in collecting, analysing and interpreting factual data (101). Velmurugan (13) stated that maintenance optimisation is considered as a science within operational research and it may be considered as an effective tool for maintenance strategy selection and optimisation by maintenance managers (13).

3.1 Research and Data Analysis Method and Overview

This research project utilised historical failure data of the conveyor routes. It represents a quantitative approach to the project and somewhat resembled an ex post facto design. In an ex-post facto study the events that have already occurred are identified and relevant data pertaining to those events are collected in order to investigate and determine the possible scenarios or sequences of the events and its subsequent effects (83). The significance of maintenance planning and initiatives has increased due to the role it has on improving the reliability, uptime, budget and safety of the plant. Accordingly, maintenance strategy selection has become one of the most critical and strategic decisions to take in industry (14,20,77).

The researcher was able to identify existing maintenance strategies through conducting a survey questionnaire and through existing failure data as well as data retrieved from maintenance personnel in the PORB describing their maintenance procedures, i.e. visual-based preventive approach which the port title as the Search and Find principle. The justification to conduct the study to understand whether a new maintenance approach is needed or not was done through the investigation and analysis of the actual failure data received from the port regarding the planned and actual tonnages achieved, as well as the breakdown schedules. The failure tools applied to the data were utilised to support the requirement for change in maintenance approach and strategies in the port.

The researcher has opted to utilise the survey questionnaire and MCA in order to select an appropriate maintenance strategy for conveyor systems in the PORB (28,30), similar to research conducted by Gerike (28) and Yuan (30). The researcher will compare the results of this study against that of previous literature in order to support the selected maintenance strategy, however it must be noted there are not many previous studies with relation to maintenance strategy selection for conveyor systems (27,28,30,74,79). The research will attempt to provide in-depth insight into the failures experienced within conveyor systems and possible scenarios and methods to alleviate them through the selected maintenance approach. The failure analysis tools will be used to provide a set of results regarding the failures experienced and will support the adopted methods. An overview of the research process is shown in the flow diagram in Figure 3.1

3.2 Research Design

This research is concerned with the evaluation of existing maintenance strategies in conveyor systems at the PORB. The overall objective of this study is to analyse and determine the most suitable optimised maintenance strategy, principles and procedures that can be applied to conveyor systems in the PORB.

The sequence of activities conducted by the researcher in order to fulfil the objectives of this study are summarised as follows:

- Determining the relevance of data and possible research scenarios.
- Developing a project proposal inclusive of the research objectives and critical research question (CRQ).
- Defining the scope, context and limitations for the research project utilising Pareto principle.

- Raw data collection via literature and conveyor failure data (APPENDIX B), operation schedules, maintenance plans as received from the PORB.
- Sorting of raw data and definition of analysis tools and methods.
- Conducting the Research Methods and Analysis utilising Failure analysis tools (FMECA, Weibull, Five Whys, and Fishbone) and Questionnaires in order to perform a Multi Criteria Analysis (MCA).
- Review, discussion and recommendations based on results from research analyses. Selecting a maintenance strategy and comparing against previous studies.

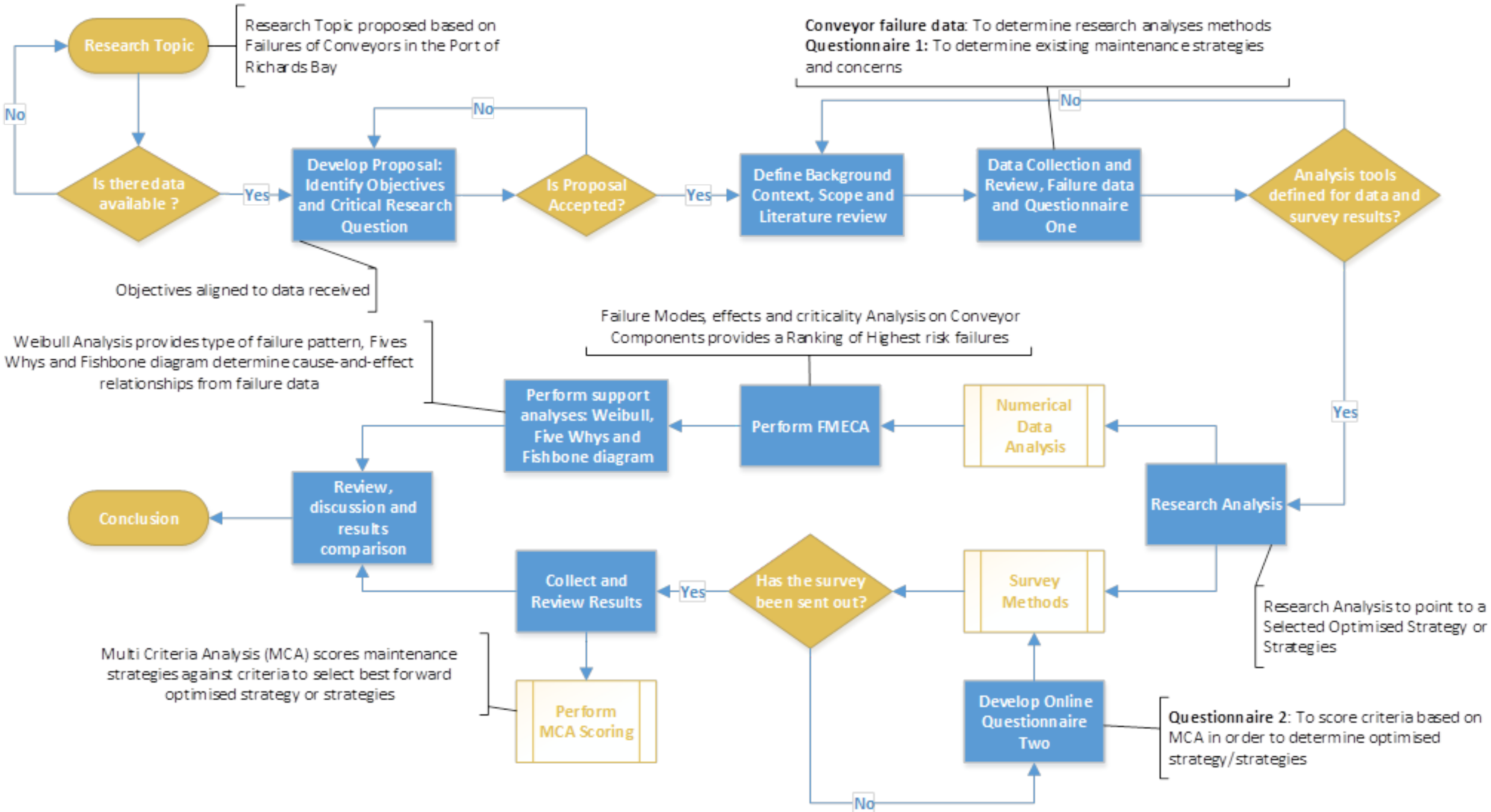

Figure 3.1: Research process flow diagram

3.3 Data Collection and Analysis Methods

The analysis of any system or subsystem requires knowledge of the system and the relationship between the system and its components. To evaluate the consequences of a functional failure it is necessary to envisage the different failure possibilities in terms of the basic function of the entire system (26).

3.3.1 Data Collection techniques

Quantitative data collection consists of gathering numeric and objective data (84). Data collection techniques involve sourcing of primary and secondary data. Primary data in the form of conveyor failure data in excel format was collected from the maintenance manager in the PORB as shown in a snapshot in Figure 3.2. Primary data was also gathered from maintenance personnel which included existing maintenance approaches and equipment maintenance procedures. The secondary data was collected from relevant literature and the critical review thereof.

DATE	DESCRIPTION	Actual Time (Minutes)	BERTH	SECTION	Product 1	Product 2
12/19/18	K10 SPEEDSWITCH DUE TO CARGO ON RETURN CONVEYOR	45	703	Export	Magnetite	Chrome
1/4/19	H03 conveyor booked out by mech	50	703	Export	Magnetite	Chrome
1/4/19	Takraft boom conveyor run skew	30	801	Export	Magnetite	Chrome
1/4/19	FUSABLE PLUG POPPED/Invisible thing stuck in cross conveyor	32	804	Export	Woodchips	
1/6/19	cross conveyor tripped	40	804	Export	Woodchips	
1/7/19	repair splice on E01 conveyor	220	703	Export	Magnetite	Chrome
1/8/19	M02 conveyor running skew	20	702	Import	Coal	Sulphur
1/9/19	M02 conveyor running skew	20	702	Import	Coal	Sulphur
1/14/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	205	801	Export	Magnetite	Chrome
1/15/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	170	801	Import	Magnetite	Chrome
1/17/19	K21 PLOUGH AND CONVEYOR NOT STARTING	70	704	Export	Magnetite	Chrome
1/21/19	MECH CUT FLAP ON N06 CONVEYOR	30	Tippler 2	Storage	Magnetite	Chrome
1/24/19	CUTTING FLAP AT C02 CONVEYOR	5	Tippler 2	Storage	Magnetite	Chrome

Figure 3.2: Snapshot of Failure Data

The primary data collection also consisted of the researcher using the email system to distribute a survey link containing questions pertaining to general maintenance actions with a follow up survey detailing maintenance selection criteria and associated scoring based on the Multi Criteria Analysis (MCA). This research utilised the cross-sectional approach as it aimed to determine relationships between the current maintenance actions and failures experienced with the objective of reducing selecting the most suited maintenance strategy or strategies for conveyor belt systems (85). The researcher also opted to approach different experts to broaden and diversify the feedback input to the maintenance strategies in the port and in the MCA model. The researcher also utilised data regarding the operational periods and uptime of the routes as well as data on achieved versus planned tonnages in the research analyses.

Research survey team

The researcher opted to select maintenance, maintenance management and engineering staff that work with conveyor systems in the port to respond to survey questionnaires as these individuals have significant experience in performing, planning and determining the maintenance strategies (102).

The first round of questions was sent to general maintenance and engineering staff in an attempt to gain an insight into the existing strategies within the port and to understand what maintenance activities staff believe they have conducted. The second questionnaire was sent to colleagues believed to be experts in the field of working on conveyor systems and maintaining them.

Maintenance management staff are familiar with the planning of maintenance activities and thus have expert knowledge on grouping activities to minimise cost, reducing risk and improving safety (102). Maintenance management staff work closely with the operations and maintenance staff to ensure that opportunities to conduct maintenance are optimised. Engineering staff conduct critical inspections and verifications to ensure that the plant is maintained and operating within its operational and design capabilities. Engineers have the overall accountability to sustain and improve the reliability of the plant with the help of maintenance and operating departments. The use of maintenance, maintenance management and engineering experts provide a balanced view in the survey (102).

Questionnaire

The researcher conducted two sets of questionnaires. The first survey questionnaire, found in APPENDIX E, contained 9 questions around the current strategies to gain an understanding of what type of maintenance strategy staff believed they have conducted. The second questionnaire, found in APPENDIX F, details the MCA criteria in an attempt to score and select a combination of optimized maintenance strategies. The second questionnaire consisted of 10 questions related to the MCA criteria and sub-criteria and was used as an input to the MCA scoring sheet to determine the best go-forward maintenance strategy or strategies for this research study.

3.3.2 Level of Analysis

Careful consideration is needed to determine the level at which analysis will be performed in order to provide the most beneficial outcome. Clear definition of the asset and its process is needed (7).

The main advantages of starting using a top down approach are:

- Operability and required functioning levels are simpler to outline
- Failure effects or consequences are easier to evaluate
- There is less repetition of functions and failure modes

The main disadvantage of this approach is that at a specific level, there could be failure modes that may be overlooked (7). The research level of analysis was constrained to the level that was obtained from the conveyor failure data as well as to the components that are critical in the operability of a conveyor belt as shown on Figure 3.3 (34).

3.3.3 Critical Item Selection

The conveyor belts can undergo a critical item selection task in which the major items that are required to ensure the operability of the conveyor are selected (34). The critical items were driven by the available failure data found in APPENDIX B and appropriate literature covered in the literature review. The critical equipment in a conveyor are the (34,74):

- Drive made up of the motor, couplings and gearbox,
- Pulleys which consist of a shaft, bearings and end disks,
- Idlers which consist of a shaft, bearings and end caps,
- Belting which are made up of different ply's and joined by means of a splice and,
- Take-up mechanism consisting of the trolley, sheaves, winch, rope and counterweight.

These items formed part of the failure analysis methods and were further broken down into individual components that ensure the running of the critical equipment as shown in Figure 3.3. These were also used in determining failure modes in the FMECA process (103,104).

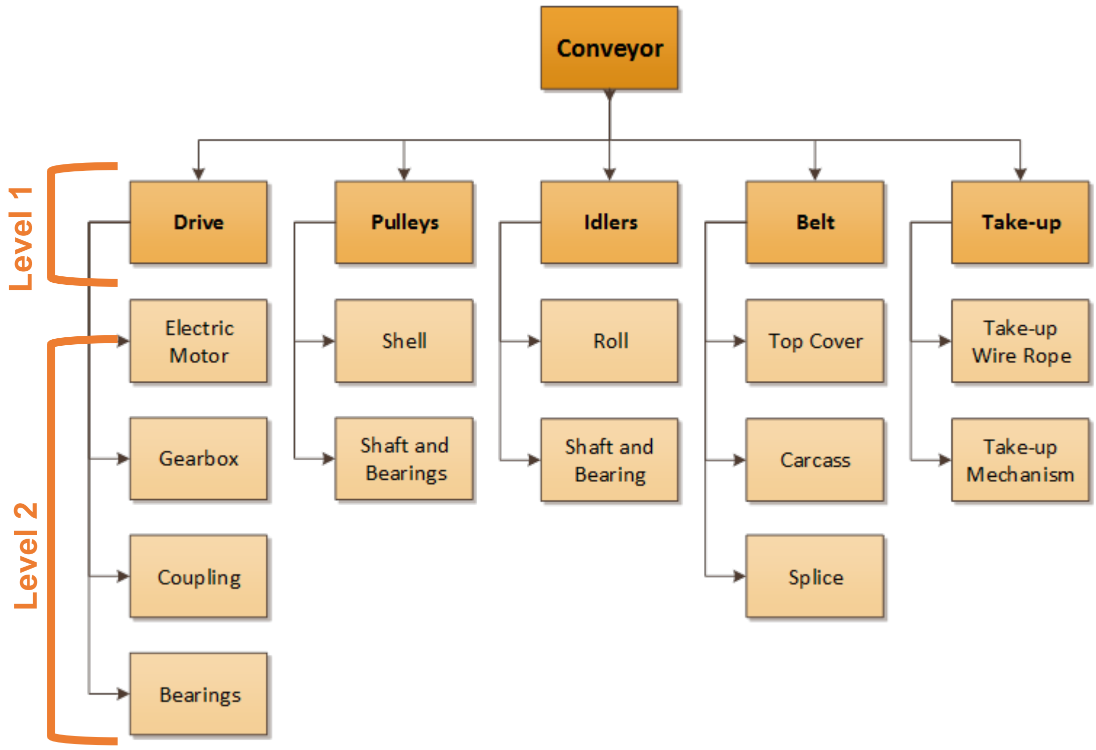

Figure 3.3: Conveyor critical components and failures modes

3.3.4 Data Analysis

This research project utilised historical failure data of the conveyor routes. It represents a quantitative approach to the project and somewhat resembled an ex post facto design. In an ex-post facto study the events that have already occurred are identified and relevant data pertaining to those events are collected in order to investigate and determine the possible scenarios or sequences of the events and its subsequent effects (83). The significance of maintenance has risen exponentially due to its part in ensuring uptime of the plant, managing quality of the outputs, maintaining safety standards and balancing costs in the operation of the plant. Accordingly, maintenance strategy selection has become one of the most critical and strategic decisions to take in industry (14,20,77). The quantitative data used in the study comprised of failures experienced on all conveyor routes within the port from December 2018 to June 2020.

The analysis methods discussed in the literature review were applied to the failure data. The ports maintenance approach and policy were also obtained and reviewed to determine a base to measure the research against. The port utilises reactive and preventive maintenance measures which they deemed as a search-and-find principle. There were no evidence of maintenance tracking or traceability. An online questionnaire was then developed to understand perceptions of staff within the port regarding existing strategies, training and shortfalls. The Pareto principle was then applied to the failure data in order to understand which components and areas of the conveyor routes experience the most failures, which is covered in the next chapter, Chapter Four.

Using the failure data and output of the Pareto analysis; a failure modes, effects and criticality analysis (FMECA) was conducted on critical conveyor components to prioritise failure modes in order of risk. Appropriate maintenance, design and management actions were developed in order to address each respective failure mode. Failure software was used to conduct a Weibull analysis which plotted failure data points and allowed the researcher to interpret and determine the failure type and support the recommended remedial actions in the FMECA.

Having determined the failure type and developed the FMECA table, a Five Whys investigation and Ishikawa “Fishbone” diagram was developed to determine primary and secondary causes and effects of the failures. The Weibull, Five Whys and Fishbone diagrams were reviewed and conducted in order to provide appropriate remedial actions on the FMECA and aid in recommending an appropriate maintenance strategy to support the data in the FMECA table.

Subsequently, to determine and select an appropriate strategy, a second questionnaire was sent to key experienced maintenance and engineering personnel in order to conduct an MCA to select the most suited strategy or strategies for conveyor systems. This process of maintenance strategy selection and the selected strategy itself was compared to previous studies. Based on this selection and the failure analyses conducted, recommendations and discussions on maintenance actions will be made.

3.4 Failure Analysis Tools

The failure data was analysed using the Pareto principle to identify the routes that experience the majority of failures. The failure data are also analysed using the Weibull method to determine the different failure types and failure rates. The failures experienced on the conveyors are broken down to the components and analysed using The Five Whys method to understand the causes and effects on the conveyor system. The Fishbone diagram is also used as it is a more structured approach to cause and effect determination when compared to the Five Whys method (105) and will determine the possible causes of failures on equipment on the conveyor routes (104). The FMECA process was conducted to determine failure causes and remedial actions which are supported by the Weibull, Five Whys and Fishbone diagram. The research study will point to a maintenance strategy that is most suited to conveyor systems through the utilisation of a survey questionnaire and multi-criteria analysis (MCA), together with the abovementioned analysis tools (99).

3.4.1 Failure Modes, Effects and Criticality Analysis (FMECA) Method

The FMECA scoring criteria used in the RPN's were modified and adapted to conveyors operated in the PORB as shown in Table 3.1, Table 3.2 and Table 3.3. These were used in order to evaluate the risk associated with the failure modes (26,104). The FMECA was conducted utilising the conveyor failure data that appears in APPENDIX B as well the use of literature on common failures experienced on conveyor belts. Considering the severity of the failure's effects, a score or value of 1 denotes no effect or severity whilst a score or value of 10 depicts inability to meet safety requirements and is extremely severe as shown in Table 3.1. The effects of a conveyor component failing is based on the ports failure data and historical data gathered from literature (26,103,104).

Table 3.1: Severity ranking used in FMECA (26)

Effect	Severity of Effects on Process	Rank
Failure to meet safety requirements	May endanger operator or personnel in vicinity without warning	10
Failure to meet safety requirements	May endanger operator or personnel in vicinity with warning	9
Major disruption	All conveyor routes to berth shutdown	8
Significant disruption	Partial shutdown of conveyor routes to berth	7
Moderate disruption	Complete rework required when during shutdown	6
Moderate disruption	Partial rework required during shutdown	5
Moderate disruption	Complete rework possible during operation	4
Moderate disruption	Partial rework possible during operation	3
Minor disruption	Slight disruption to operator or process	2
No effect	No disruptions or effects	1

Occurrence is related to the actual failure data received from the port based on the number and type of failures that have occurred. A value of 10 is assigned for 15 and greater number of failures that occurred. A value of 1 is assigned for 0 failures that have occurred. The occurrence ranking is detailed in Table 3.2.

Table 3.2: Occurrence ranking used in FMECA (26)

Probability of Failure	Occurrences	Rank
Very High	>15 per route	10
High	Between 13 and 15 per route	9
High	Between 10 and 13 per route	8
High	Between 8 and 10 per route	7
Moderate	Between 6 and 8 per route	6
Moderate	Between 4 and 6 per route	5
Moderate	Between 3 and 5 per route	4
Low	2 per route	3
Low	1 per route	2
Very Low	0 per route	1

Detection is related to the actions taken to detect the respective potential failure causes. When considering detection, a score or value of 1 indicates that operations are under control by the operating staff with detections measures in place. A score or value of 10 indicates that no existing measures are in place and detection is almost near impossible. The detection ranking is detailed in Table 3.3 with scoring conducted utilising failure data and existing maintenance strategy (21,106).

Table 3.3: Detection probability ranking used in FMECA (26)

Probability of Detection	Criteria	Rank
Almost impossible	No current process control	10
Very remote	Not easily detectable. Random inspections	9
Remote	Detection post operations by Visual inspection	8
Very low	Tripwire activation by Operator	7
Low	System lockout by Operator	6
Moderate	Automated failure identification to Operator	5
Moderately high	Automated failure identification post operations	4
High	Automated failure identification and stop during operations	3
Very high	Automated controls prevent operations	2
Almost certain	Operations under control	1

The RPN value, as mentioned earlier, is used as a quantitative measure to prioritise maintenance actions in accordance to the most consequential failures (26,107). The failure modes were ranked using the risk priority number (RPN). The RPN is critical in proposing accurate solutions and maintenance actions. The RPN is calculated as a multiple of the Severity, Occurrence, and Detectability (108). Maintenance and corrective actions are prioritised based on the numerical value of the RPN (104). The higher the RPN, the higher the risk and failure effects of that failure mode and the more urgent it is to resolve (26,107). It is important to note that the FMECA table was looked at with a two-pass view by first analysing the severity independently from the occurrence and detectability for each failure mode in order to understand if immediate remedial action is needed, as a severity of 9 and 10 are linked to the safety of personnel. The occurrence and detectability were subsequently scored to determine the ranking (26).

3.4.2 Weibull Method

The Weibull Analysis is applied to the conveyor failure data to identify the failure pattern, that is, whether the failures are infant mortality, random or wear-out failures, which will assist in determining appropriate remedial actions. The Weibull analysis can only be used for one failure mode at a time (26). The conveyor failure data was accordingly split per component in order to conduct the Weibull analysis and determine failure patterns. This split data enabled the researcher to link results between each analysis conducted, i.e. the failure modes from the FMECA were inputted to the Weibull analysis and results were used to verify to the remedial actions developed in the FMECA. The results of the Weibull analysis is presented in Chapter 5.

3.4.3 Ishikawa “Fishbone” Method

Ishikawa diagrams, also referred to as fishbone diagrams, are diagrams that show the possible causes of a specific failure event, in this case the event is a conveyor belt failure. This analysis tool was used to determine primary and secondary causes of the conveyor failure modes. It is a more structured approach than the Five Whys and is used to support the remedial actions developed in the FMECA (105). The categories in the fishbone diagram have been split into distinct areas that play a major part in the successful operation of a conveyor belt (104). The categories are; people/staff, environment, machinery/equipment, materials and operations (27,109). The categories were then evaluated to determine primary and secondary causes adding further "fish bones". The outcomes of the Ishikawa Diagram are discussed in the next chapter.

3.4.4 The Five Whys Method

The Five Whys analysis is an investigative tool used to determine causes of failures. This tool was used to aid in determining the failure causes on conveyors and support the information inputted to the FMECA. This analysis was conducted using failures based on the critical component selection mentioned under Section 3.3.3. The Five Whys was conducted using the conveyor failure data, failure modes and literature discussed earlier. This failure analysis tool was used to determine causes for failures on conveyor routes to support the results and outcomes from the FMECA and to provide the most suitable remedial actions. The analysis was done in line with the failure types obtained from the failure data. The bar chart shown in Figure 3.4 displays failure types against commodity and is used in the analyses which will be discussed in the next chapter.

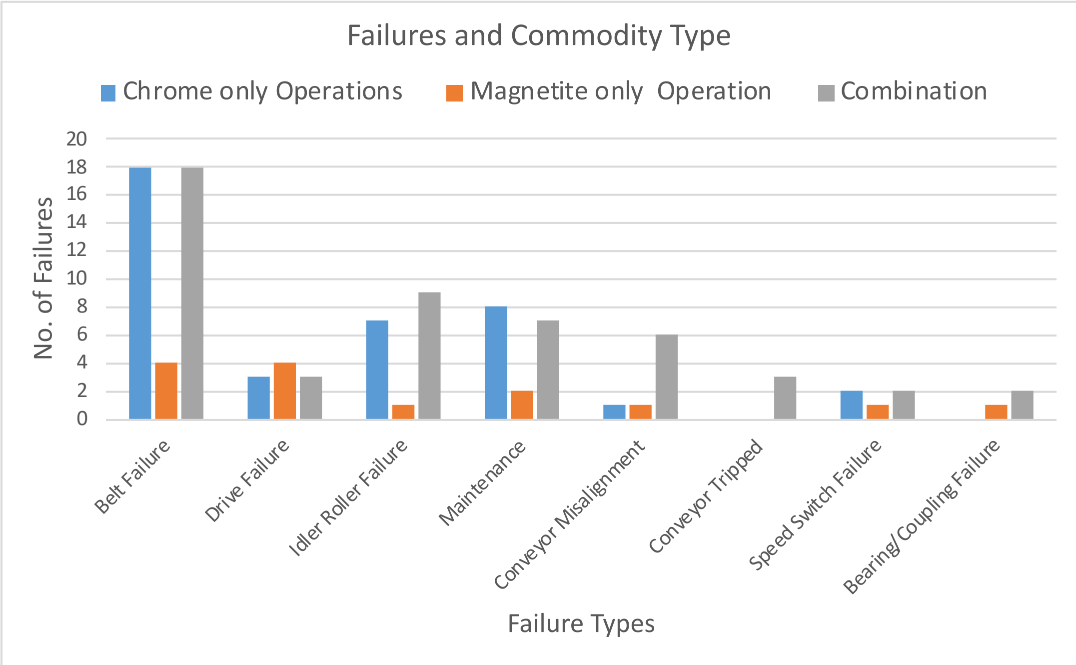

Figure 3.4: Failure types and commodity in operation

3.5 Research Validity and Limitations

Kothari (68) indicates that the review and scrutiny of information should be thorough and adequate enough to enable the researcher or author to reveal its significance and suitable methods of analysis. The validity and consistency of the information must be verified prudently (81). Research validity considers the degree to which the research paper can be measured whilst reliability considers the accurateness and precision of the manner in which the research is measured (81). Research validation may occur throughout the process of conducting the research study and validity presents itself as a strength in qualitative methods where the findings are to be verified for accuracy from the view of the researcher, research participants and the reader (84). Data will be collected through multiple sources which include actual failure data, surveys and questionnaires regarding maintenance in the port, site visits and monitoring of conveyors which feeds into the principle of data triangulation (81,84).

3.5.1 Assumptions and Limitations

The research was conducted using the factual data from site. It is assumed the data collected by maintenance staff was true, correct and free from error. The MCA carried out during the research considered expert opinions in its process and it is assumed that all questionnaires were answered with an objective standpoint. The commodities conveyed on the selected routes are assumed to be correct and as presented by the obtained data. The limitations for the research was that it was constrained by the information available, i.e. conveyor failures only.

4 RESEARCH CONTEXT

The conveyor routes in the PORB are broken down into storage, export and import as shown in the flow diagram in Figure 4.1. Storage routes receive products from wagons via offloading equipment such as tipplers and (T1 & T2) and a bottom dump out station (BD) and are destined for stockpile areas via the conveyor network. Import occurs at berths 609 to 702 with cargoes destined for storage and for transfer to clients outside the port boundaries. Export is transfer of cargo from the stockpile areas by front end loaders onto conveyors, ship-loaders and vessels at berths 703 to 804. The conveyor network comprises of a series of conveyor belts that convey cargo and change direction through numerous transfer points up to the point of final offload.

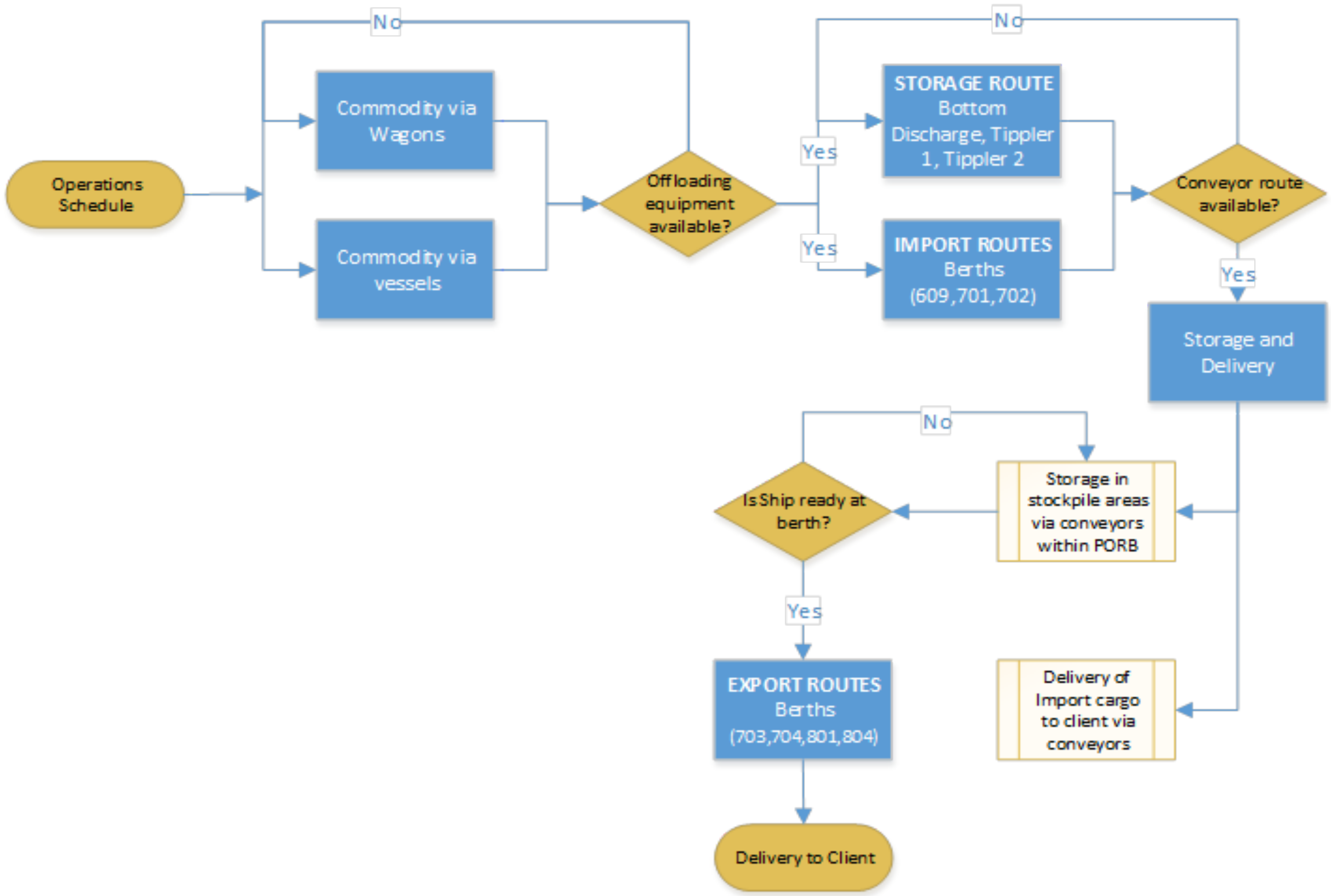

Figure 4.1: Process flow block diagram of conveyor routes and berths

4.1 Boundary Definition

Accurate boundary definition is essential to ensure that all critical functions of the conveyor system are captured to enable a greater understanding with regards to the process flow of the system (11). The tipplers, ship-loaders, unloaders and front-end loaders are outside the scope of this investigation as they act as an independent medium of transfer to and from the conveyor belts and their operation is independent to that of the conveyor belts and conveyor failures experienced on the routes. Furthermore, the loading and offloading machinery and equipment were originally designed with the highest density cargo as an input. These large machines also undergo specialist maintenance tasks by external companies making it challenging to obtain data and usage rights (110). Therefore, the system boundary for this project is from the point of cargo transfer on and off the conveyor routes. It is further narrowed down to the failures experienced on the export routes as these routes accounted for 65% of the failures, as shown in the pie chart in Figure 4.2 for the period of data obtained, which is between December 2018 to May 2020.The storage conveyor routes accounted for 21% of the failures whilst the import route accounted for 14% of the failures.

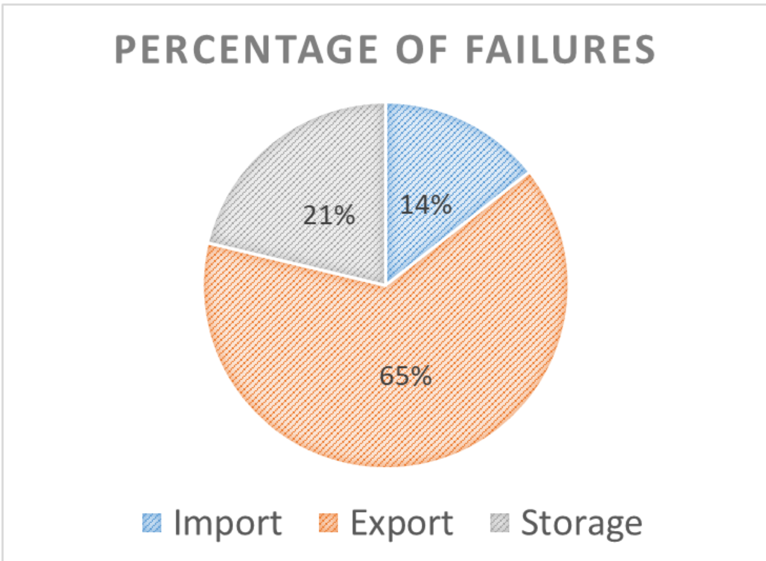

Figure 4.2: Pie Chart showing percentage of failures per area

4.2 Conveyor Berth Selection

This research will cover conveyor export routes which handle two cargoes with outputs that can be adopted port wide. The research scope was further narrowed down, through the use of the Pareto principle, to uncover three berths (703, 704 and 801) which accounted for the majority of the failures experienced on the export routes as shown in Figure 4.3. Figure 4.3 shows the selected berths accounting for 59% of failures across all ten berths, i.e. 30% of berths accounting for 59% of failures. These berths alternate between two commodities; namely magnetite and chrome. The routes to berth 801 were originally designed for woodchips with berths 703 and 704 originally designed for coal and woodchips. Minor modifications have been made in an attempt to handle the heavier material, but no calculations were conducted to verify these modifications (5).

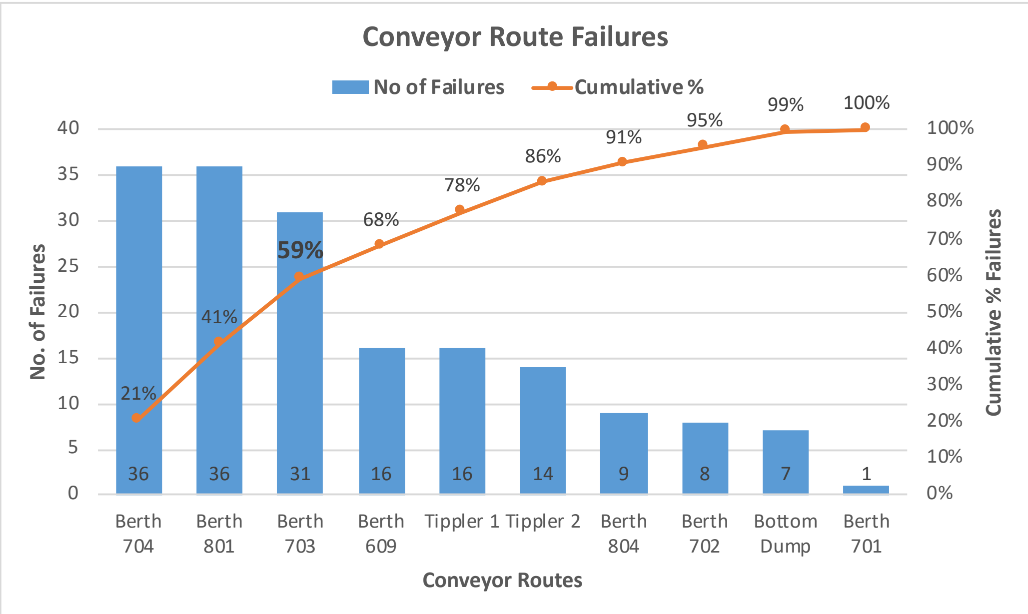

Figure 4.3: Bar Chart showing ranked conveyor route failures

On multiple conveyor routes to berth 801, the port was unable to perform at its installed capacity levels due to the unreliability of the equipment (32). A throughput of 2.5 mtpa was achieved versus the installed capacity of 4.5

mtpa (32). Figure 4.4 shows the variations in planned tonnages versus the actual achieved tonnages for the period of December 2018 to May 2020. For berth 703 the actual tonnages achieved was 26% of the planned target with 704 and 801 achieving 45% and 28% respectively. This chart points to the dismal performance of the conveyors on the selected routes and berths.

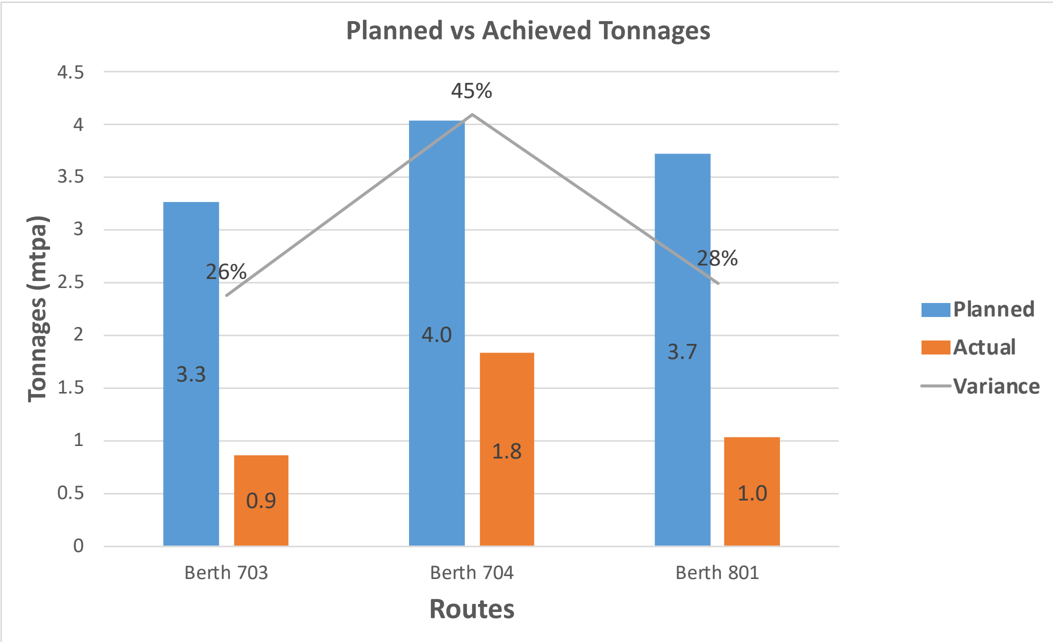

Figure 4.4: Bar Chart showing Planned vs Actual tonnages

4.3 Common Failures in Conveyors at the PORB

A stoppage in a conveyor belt route means no production in most bulk conveying applications resulting in a loss of revenue, increase in maintenance spares and increased labour costs (31). Common failures and failure modes experienced by belt conveyor components are described in the following sections.

4.3.1 Pulleys

Bearing collapses contribute to majority of pulleys failures due to the immense tension load on the pulley, as shown in Figure 4.5 with a failure experienced on a conveyor route to berth 704. These failures can cause resultant damage to the drive of the conveyor and the supporting structure in the vicinity. Heated or seized bearings as a result of lack of lubrication could lead to fires accelerated by dust ingress (21). This is shown in Figure 4.6 with spillages and dust having resulted in a layer of material form on the pulley bearings in the PORB on a conveyor route to 703. The cargoes handled in the port are also combustible, providing further cause for concern regarding this failure mode (31,111).

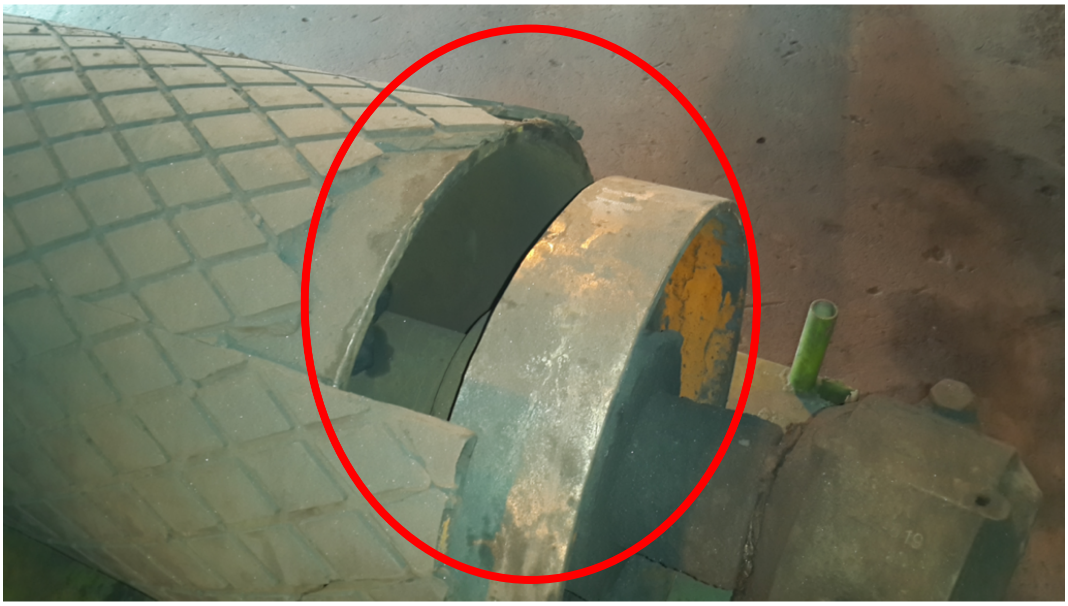

Figure 4.5: Pulley end disk failure

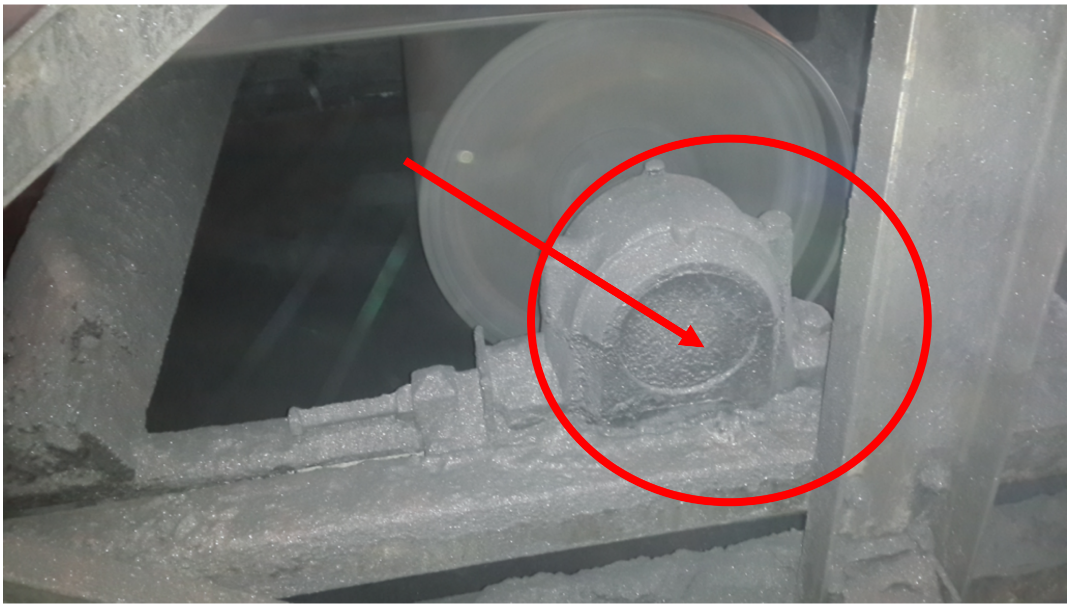

Figure 4.6: Spillage and dust ingress resulting in seized pulley bearing

Common failure detection on bearings can be conducted utilising temperature monitoring. Temperature monitoring provides early detection for maintenance staff to conduct repair or lubrication actions. A newer and more detailed method of failure detection is that of vibration or frequency analysis (31).

4.3.2 Idler failures

Idlers are a critical component of the conveyor providing support of the belting and cargo throughout the conveyor's length. Normal practice dictates regular inspection on idlers as they emit a sound alerting to their failure. Handheld infrared scanners can be used to monitor idler bearing temperatures under operating conditions (31). Figure 4.7 displays an example of idler bearing and end cap failure experienced in the PORB on a conveyor route to berth 703.

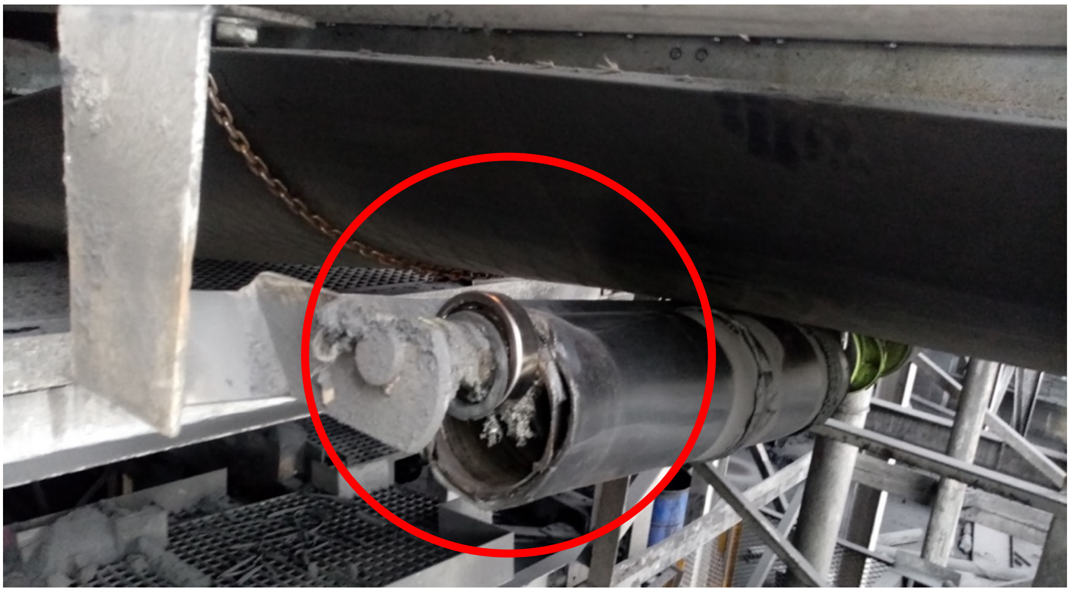

Figure 4.7: Idler bearing and end cap failure

4.3.3 Electric Motor and Gearbox failures

Motors normally fail through overheating or a collapse in the internal bearings. Motors currently have built-in temperature monitoring on the windings and provide an early detection monitoring for the motor. Temperature sensors on the motor casings and cages will provide additional monitoring to prevent bearing failures. Vibration and frequency analysis can also be adopted on gearboxes to monitoring the loads experienced on the gear teeth (31,111).

4.3.4 Belting damage

Conveyor belting is a capital-intensive component within the conveyor and holds substantial costs in relation to procurement and installation of the entire system. Belting failures are experienced as follows:

Belt rip

Belting may split longitudinally by various causes, such as foreign objects on belt, overloading the belt as experienced in the port, and chute blockages (21). Magnets can be used to detect foreign objects that are ferrous with a trap sort of design at chutes to prevent non-ferrous material from causing belt rip failures (31). Belt monitoring is a relatively new field with the introduction of a “figure 8” loop antenna like device embedded in the belt being developed by Belt manufacturers (112). This type of device does not prevent the belt rip from occurring but protects against further damage that could result from belt failure (31).

Splice failure

Splice failure cannot be detected but consequential damage as a result of a splice failing can be prevented. The take-up travel can be monitored by means of limit and positional switches. If the splice fails, the take-up trolley will reach its end of limit range which will trip the limit switch and shut off the conveyor belt preventing further damage (31).

Belt edge damage

Edge damage of the belt is caused when the belt edge rubs against the support structure as shown in Figure 4.8 where the off-centre loading has created belt drift resulting in edge damage and spillages. Edge damage can limit the amount of cargo that is run on the belt and lead to spillages. It can also reduce the life of the belt by allowing moisture into the plies of the belt. Careful installation of the belts is needed as well as alignment of the splices to ensure the belt tracks centrally.

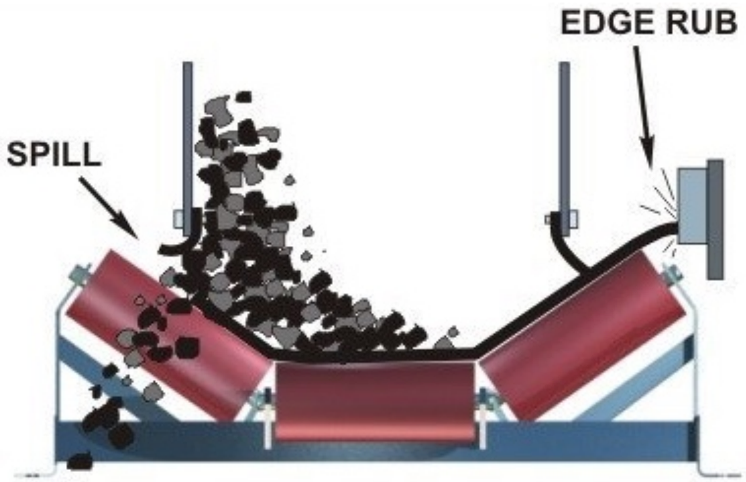

Figure 4.8: Effects of loading off-centre (41)

Belt drift switches can also be used to trip the conveyor should it run skew. The PORB utilised this approach for belt alignment with the use of belt drift switches that shut the conveyor off should the belt edge trigger the switch (21,31). This does not determine the root cause of the belt misaligning but it does alert maintenance staff to perform a fault-finding exercise and it prevents secondary damage. An example of belt edge buckling experienced at the port due to overloading is seen in Figure 4.9.

Figure 4.9: Belt edge buckling under load

Carcass damage

Carcass damage is as a result of a high impact load or overloading on the conveyor belt as is experienced in the PORB (21). The port uses predictive type monitoring in chutes with a vibrating fork probe that sends a blocked chute signal to the control room when it is triggered (21). This does not determine the root cause of the blocking of the chute but it does alert maintenance staff to perform a fault-finding exercise and it prevents secondary damage. Chute designs need to ensure smooth transition of cargo onto the belt at the loading point as is shown in Figure 4.10 highlighting an engineered chute in a discrete element model (DEM) simulation (31).

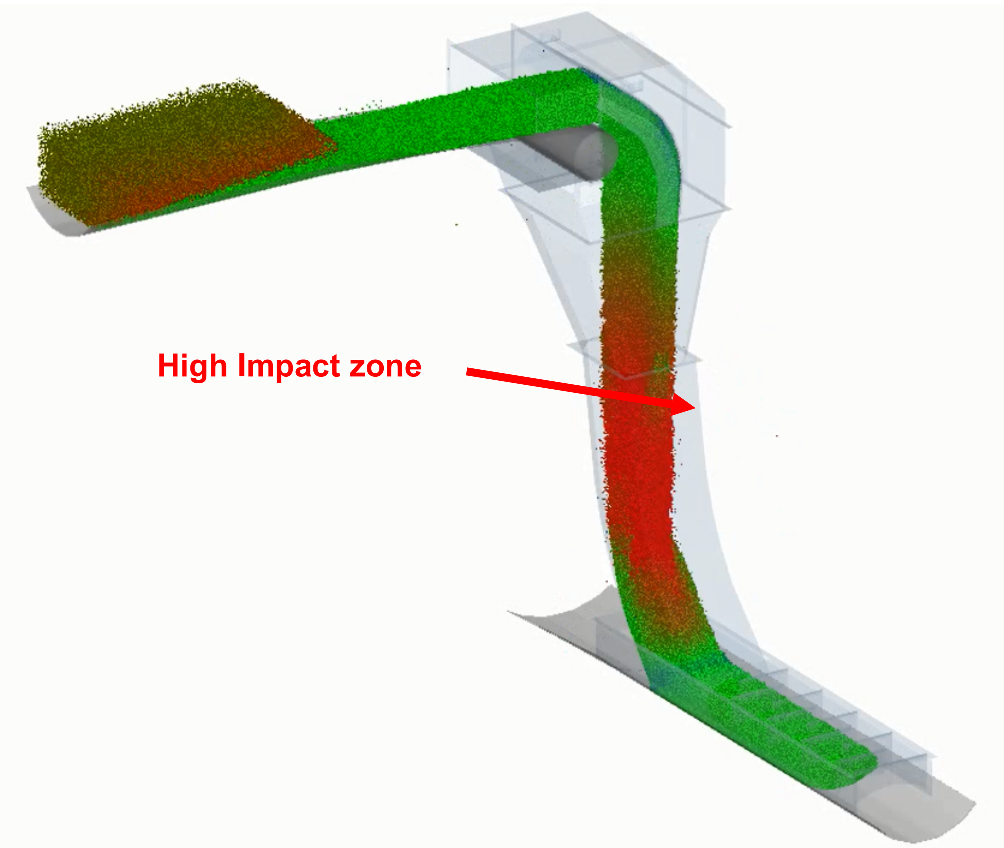

Figure 4.10: Engineered flow Chute DEM (113)

4.3.5 Take-up failures

Take-up towers are generally low maintenance equipment, but travel monitoring on the take-up trolley and counterweight provides insight into the conveyor belts performance. Positional switches will provide an insight into the amount of stretch that is experienced under full load and with an empty belt. There are components within the take-up arrangement that could fail, such as the winch failure as seen in Figure 4.11 experienced on a conveyor route to berth 703, rope breakage, limit switch failure due to overloading and abrupt start-up conditions (21,31).

Figure 4.11: Take-up winch failure

4.4 Existing Failure Effects

Every failure occurrence has an impact on the port in some form. Failures can affect throughput tonnages, equipment handling, customer service and increase operating costs. Others may appear to have no direct effect at all if they occur on their own, however, they may expose the port to the risk of much more serious failures at a later stage. If these failures are not prevented, the recovery effort and cost in correcting them has a subsequent undesirable effect because repairing failures expends resources which could be better used elsewhere. The nature and severity of the failure determine the way in which the failure is viewed and responded to by maintenance staff. The consequence of each failure mode depends on the operational environment, functional performance requirements and the physical effects of the failure modes. If the consequences are drastic, then significant efforts will be made to prevent the failure or to anticipate the failure in its early stages prior to failure (7).

4.5 Ishikawa Diagram

Ishikawa diagrams, also referred to as fishbone diagrams, are diagrams that show the possible causes of a specific failure event, in this case the event is a conveyor belt failure. This analysis tool was used to determine primary and secondary causes of the conveyor failure modes. It is a more structured approach than the Five Whys and is used to support the remedial actions developed in the FMECA (105). The categories in the fishbone diagram have been split into distinct areas that play a major part in the successful operation of a conveyor belt (104). The categories are; people/staff, environment, machinery/equipment, materials and operations (27,109). The categories were then evaluated to determine primary and secondary causes adding further "fish bones". The complete Fishbone diagram is shown in Figure 4.12.

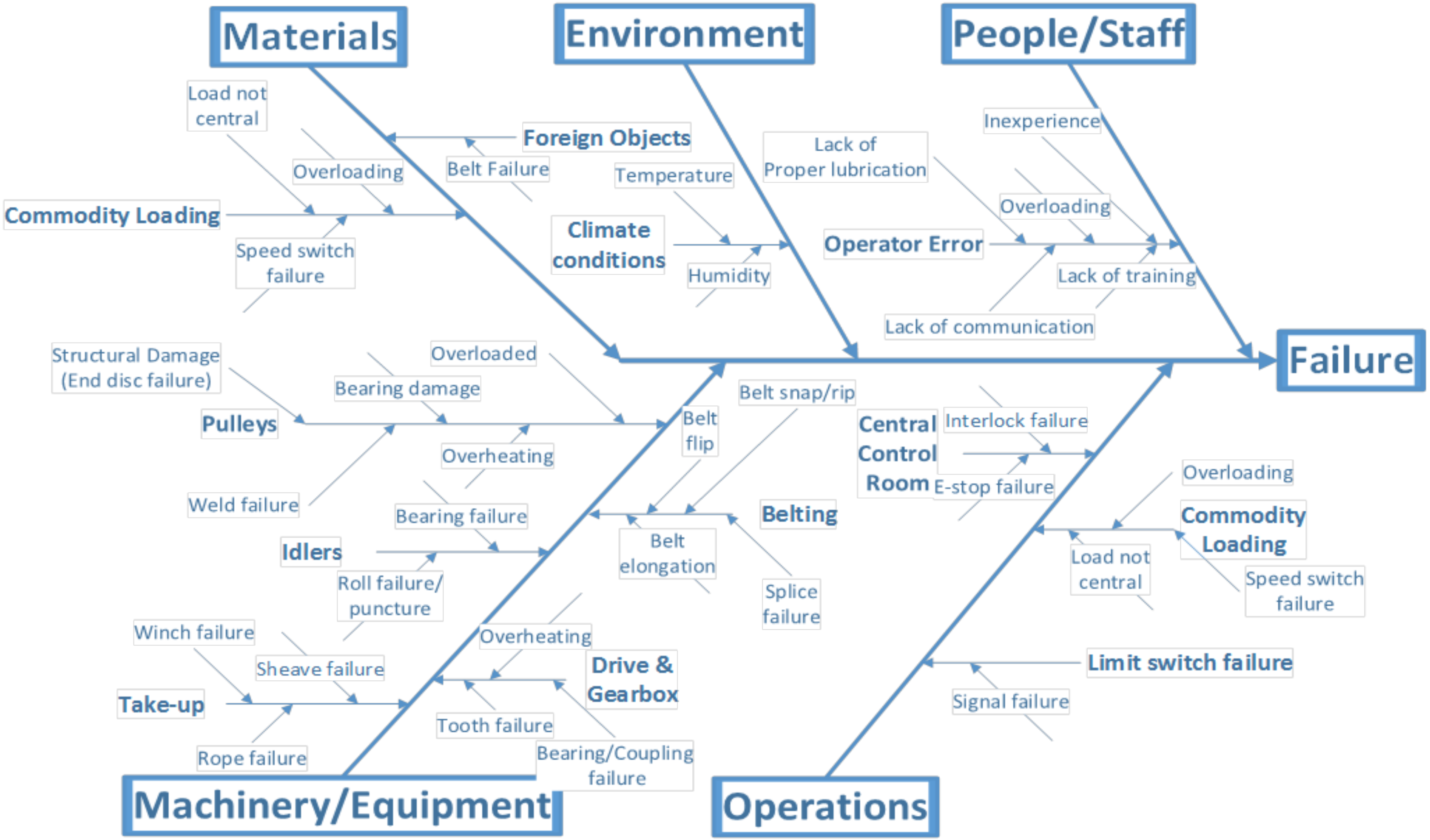

Figure 4.12: Conveyor failure fishbone diagram

4.5.1 People/staff

Operator error during loading, maintenance and running of the conveyor belts was classified as the primary cause in the failures obtained from analysis, review of the failure data and literature. Operator error is expanded under secondary causes which are; signs of inexperience in conducting maintenance and operational tasks (27), negligence with incorrect or lack of maintenance on components (21), overloading of the conveyor belt as the flow is controlled by deflector plates, and lack of communication with the control room staff who control route starts and stops (27).

4.5.2 Operations

Under the operations category it was noted, through review and analysis of the failure data and literature, that the primary contributing factor to the conveyor failures was the commodity loading operation onto the conveyor belts with overloading of the belt, load not central and speed switch failure listed as secondary causes. Overloading is expanded in the FMECA table and is as a result of incorrect position on the deflector plate or running higher density cargoes without a proper design verification (5,21). Loading commodity off-centre from the belt centreline occurs via belt tracking issues and the operator not correctly aligning the deflector plate that controls commodity flow onto the belt (21,104). Speed switch failure leads to possible overloading of the next belt with no speed control (21). Limit switch failure, as obtained from the failure data, was also listed as a primary cause in the operations category with signal failure identified as the secondary cause. The limit switches on the belt protect against belt drift and trip the conveyor when triggered (21). These switches can be turned off and on occasion have been found to be switched off by operational staff (21). The final primary cause, uncovered from the failure data and operational procedures, was the operation and feedback from the central control room with emergency stop and interlock failures mentioned as secondary causes. Conveyor loading routes are interlocked to each other for a given berth and commodity. This interlock provides a safety measure and engages a start-up procedure prior to loading. Interlock failure can result in severe spillage, blocked chutes and a major loss in revenue due to standing time experienced from the client's vessel docked at the berth (21).

4.5.3 Environment

Through analysis of the available failure data and literature, it is noted that the climatic conditions of the environment in the Richards Bay area serve as the major contributing cause under this category for conveyor equipment failure with secondary causes listed as the temperature and humidity proving harsh operating conditions for the conveyors (42,104). Richard's Bay is a generally humid environment exposing the equipment to harsher conditions than other ports in South Africa (42). The PORB is also a dusty environment due to the multitude of dry bulk cargoes handled and poses further risk to the equipment (114).

4.5.4 Materials

The primary contributing factor to conveyor failures from analysis of the available failure data and literature under this category was the loading of material onto the conveyor belt as well as the type of material being loaded. Secondary causes to arise from these primary factors were overloading of the belt, load not central, variable load and speed switch failure. Overloading is expanded in the FMECA table and occurs at the transfer points as a result of incorrect position on deflector plate or throughout the conveyor length as a result of running higher density cargoes without a design verification (5,21). Loading commodity off-centre from the belt centreline occurs via belt tracking issues and the operator not correctly aligning the deflector plate that controls commodity flow onto the belt (21). Speed switch failure leads to possible overloading of the next belt with no speed control. Foreign objects are further listed as a primary cause under this category leading to secondary cause being belt failure (21). Foreign objects failures occur as depicted by its name, foreign objects making its way onto conveyor belts during offloading or loading. These foreign objects arrive from source mines, wagons and at times are scooped up by the loaders and fed onto the conveyors during operations (27).

4.5.5 Machinery/Equipment

The critical item selection conducted earlier, to select components essential to ensure operation of the conveyor belt, was used together with the failure data and literature to determine the primary and secondary causes that could contribute to conveyor failures under the machinery and equipment category of the Fishbone process. The primary and secondary causes were as follows:

- Primary Cause: Pulley failure:
    - Secondary causes: Structural damage on the pulley shell, weld failure between the shell and end disk, shaft and bearing failure, overheating of the bearings, conveyor overload causing excessive force on pulley shell, shaft and bearings (104,111).
- Primary Cause: Belting failure,
    - Secondary causes: Belt flip due to uneven loading; belt rip or snap due to overloaded conveyor, foreign object or excessively worn belt;, belt elongation due to incorrect belt specification or conveyor overload, splice failure due to inferior workmanship (21,103,104).
- Primary Cause: Idler failure,
    - Secondary causes: Shaft, Bearing or Roll failure as a result of conveyor overload, incorrect sizing and specification, overheating, lack of lubrication, incorrect transition distance (21,104).

- Primary Cause: Take-up failure,
    - Secondary causes: Sheave, rope or winch failure due to incorrect specification and sizing, belt elongation beyond allowable limit (111,115).
- Primary Cause: Drive and gearbox failure
    - Secondary causes: Motor, bearing or coupling failure due to excessive vibrations, overloading, overheating or gear teeth failure due to contamination, misalignment, lack of lubrication, incorrect specifications and size (21,104).

4.6 The Five Whys

The Five Whys analysis is an investigative tool used to determine causes of failures. This tool was used to aid in determining the failure causes on conveyors and support the information inputted to the FMECA. This analysis was conducted using failures based on the critical component selection mentioned under Section 3.3.3. The Five Whys was conducted using the conveyor failure data, failure modes and literature discussed earlier. This failure analysis tool was used to determine causes for failures on conveyor routes to support the results and outcomes from the FMECA and to provide the most suitable remedial actions. The analysis was done in line with the failure types obtained from the failure data. The bar chart shown in Figure 4.13 displays failure types against commodity and is used in the analyses under this section.

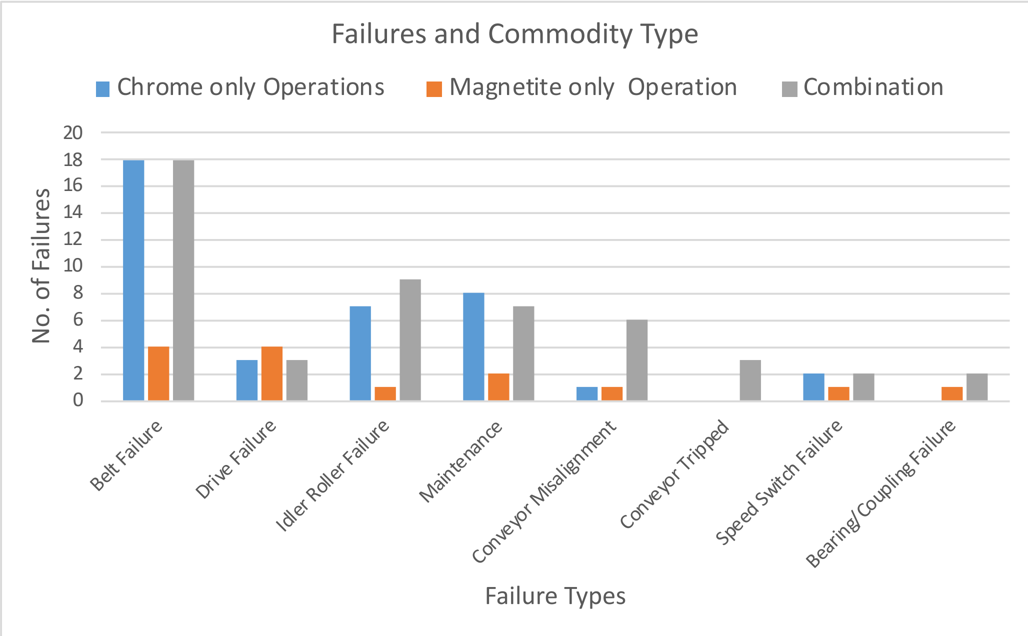

Figure 4.13: Failure types and commodity in operation

4.6.1 Conveyor drive failure

The Five Whys evaluation on a conveyor drive failure, shown in Table 4.1, filtered the root cause down to the lack of lubrication due to negligence. Additionally, it was established that the initiative from senior management to achieve higher tonnages had resulted in an overloaded conveyor belt through higher loading capacities (21). The number of conveyor drive failures were approximately equal when running Chrome, Magnetite and a combination of both as is shown in Figure 4.13. It was also found that the lack of a maintenance through negligence by staff and inferior workmanship by maintenance team during repairs or replacements has resulted in the failures (21).

Table 4.1: Five Whys – Conveyor drive failure

The Five Whys: Conveyor Drive Failure (21,111)	
Why	**Because:**
1. Why did the conveyor drive trip or fail?	→ Excessively high temperature, → Conveyor overloaded, → Belt drift, → Operations team activated tripwire
2. Why was the: → Temperature excessively high? → Conveyor overloaded? → Belt drifting? → Tripwire activated?	→ Bearings seized → Excess material on belt → Conveyor overloaded → There was excessive belt flap
3. Why did the: → Bearings seized? → Excess material runs on belt? → Belt flap?	→ Bearings not lubricated/greased → The operations increased deflector plate opening → Idler transitions incorrect
4. Why were the: → Bearings not lubricated/greased → Deflector plate opening increased by operations? → Idler transitions incorrect?	→ The maintenance staff did not apply lubricant → To achieve a higher tonnage per hour rate → Change in cargo
5. Why did the: → Maintenance staff not apply lubricant? → Operations team need to achieve higher tph rate? → Cargo change?	→ Lack of maintenance (negligence), manual log and tracking → To meet targeted volumes (Management, Asset sweat) → Business demand

4.6.2 Belting failure

The belting Five Whys review seen in Table 4.2 determined the change in cargo without design verification as a root cause in that the original designs for routes to 801 catered for lower density cargoes (5,21). The poor quality and inferior workmanship was identified as the root cause resulting in splice failures (21)..

Table 4.2: Five Whys - Belting failure

The Five Whys: Belting Failure (21,34)	
Why	**Because:**
1. Why did the conveyor belting fail?	→ Belt edge buckling, belt flap, → Conveyor overloaded, load not central → Splice failure → Foreign objects on belt,
2. Why did the: → Belt edge buckle or the belt flap? → Conveyor become overloaded or loaded unevenly? → Splice fails? → Foreign objects land on the belt?	→ Overloaded belt, incorrect transitions, incorrect radii → Excess material on belt or material flow diverted? → Quality of workmanship inferior → The wagons/loaders offloaded onto conveyors,
3. Why were the: → Transitions or radii incorrect? → Excess material on belt or material flow diverted? → Quality inferior? → Foreign objects on the wagons/loaders?	→ Cargo changed without design check → The operations adjusted deflector plate opening → Inexperienced contractor → Foreign objects from source at mines
4. Why was the: → Cargo changed without design check? → Deflector plate opening adjusted by operations? → Contractor inexperienced? → Foreign objects found at mines?	→ Operations team instructed to run new cargo → To achieve a higher tonnage per hour rate → Tender requirements lowered → Foreign objects filtered into commodity during operations
5. Why were the/their: → Operations team instructed to run new cargo? → Operations team required to achieve a higher tonnage per hour rate? → Tender requirements lowered? → Foreign objects in the commodity during operations?	→ Business need to run new cargo → To meet higher volume demand and tonnage targets → Business need to meet social objectives (SMME's, local labour) → Lack of housekeeping

The causes need to be addressed by management through introducing stringent control measures to monitor and sign-off on hold points during all works. A lack of house-keeping also results in foreign objects landing on belting caused damage or tearing of the belt (21). The number of belting failures were 4.5 times greater when running chrome only or a combination of chrome and magnetite than when running solely magnetite as shown in Figure 4.13. This leads to the assumption that chrome has a greater impact on belting than magnetite

4.6.3 Idler Failure

The idler failure Five Whys analysis seen in Table 4.3 resulted in the sole root cause related to the change in cargo from low to high density without a full design verification on existing conveyor belt, and the drive by management to achieve higher tonnages per hour to meet targeted volumes for magnetite and chrome which are both high density cargoes (21). The running of both cargoes has shown a greatest number of idler failures followed by chrome only with magnetite only experiencing one idler failure as is shown on Figure 4.13.

Table 4.3: Five Whys - Idler failure

The Five Whys: Idler Failure (21)	
Why	**Because:**
1. Why did the conveyor idler fail?	→ Roll wear and failure, → Idler shaft and bearing failure → End disk failure
2. Why did the: → Idler roll wear or fail? → Idler shaft and bearing fail? → End disk fail?	→ Overloaded belt, incorrect transitions, → Overloaded belt, incorrect design, → Weld failure
3. Why was the: → Belt overloaded, transitions incorrect? → Belt overloaded or design incorrect? → Weld between end disk and shell failing?	→ Operations team changed cargo without design check → The operations adjusted deflector plate opening → Design load of idler exceeded,
4. Why was the: → Cargo changed without a design check? → Deflector plate opening adjusted by operations? → Design load of idler exceeded?	→ Operations team instructed to run new cargo → To achieve a higher tonnage per hour rate
5. Why was/did the: → Operations team instructed to run new cargo? → Operations team need to achieve a higher tonnage per hour rate?	→ Business need to run new cargo and achieve targets (Management to resolve and manage a design verification process)

4.6.4 Pulley failure

The Five Whys review of the pulley failures, shown in Table 4.4, have shown the root causes to solely be the change in cargo from a low to high density material without a detailed design verification on all conveyor routes and associated infrastructure. This proved to be the ultimate cause in the excessive loads on the shell, shaft and bearings on the pulleys (21).

Table 4.4: Five Whys - Pulley failure

The Five Whys: Pulley Failure (21)	
Why	**Because:**
1. Why did the conveyor pulley fail?	→ Bearing failure, → Shaft or shell failure → End disk failure
2. Why did the: → Bearing fail? → Shaft/shell fail? → End disk fail?	→ Overloaded belt, → Incorrect design, → Weld failure
3. Why was the: → Belt overloaded? → Belt overloaded or design incorrect? → Weld between end disk and shell failing?	→ Operations team changed cargo without design check → The operations adjusted deflector plate opening → Design load of pulley exceeded,
4. Why was the: → Cargo changed by operations team without design check? → Deflector plate opening adjusted by operations? → Design load of pulley exceeded?	→ Operations team instructed to run new cargo → To achieve a higher tonnage per hour rate
5. Why was the: → Operations team instructed to run new cargo? → Operations team needed to achieve a higher tonnage per hour rate?	→ Business need to run new cargo and achieve targets (Management to resolve and manage a design verification process)

4.6.5 Take-up failure

The Five Whys review of the take-up failures shown in Table 4.5 have indicated the root causes to be; design error where the designer had not considered sheave position, change in material specifications by the contractor without proper change process followed and a change in the business to run higher density cargo at higher tonnages per hour without a detailed design verification (21).

Table 4.5: Five Whys - Take-up failure

The Five Whys: Take-up Failure (21,115)	
Why	**Because:**
1. Why did the conveyor take-up fail?	→ Take-up trolley, counterweight, rope, winch or sheave failed,
2. Why did the: → Take-up trolley, counterweight, rope, winch or sheave fail?	→ Misaligned trolley and winch, → Winch mounting platform failure, → Belt overload, tension limit exceeded
3. Why was the: → Trolley and winch misaligned? → Winch platform failing? → Belt overloaded?	→ Contractor mounted sheave incorrect on trolley → Winch platform sheared from concrete based → Operations team changed cargo without design check, the operations adjusted deflector plate opening
4. Why was the: → Sheave mounted incorrectly by contractor? → Platform separating from the concrete? → Cargo changed by operations team without design check?	→ Design drawings stipulated position → Incorrect epoxy used on hold-down (HD) bolts → Operations team instructed to run new cargo, to achieve a higher tonnage per hour rate
5. Why was the: → Positions stipulated incorrectly in design? → Epoxy incorrect on HD bolts → Operations team instructed to run new cargo? Operations team needed to achieve a higher tonnage per hour rate?	→ Error by Designer (Contractual process to address) → Contractor utilized different epoxy from the one specified on drawings without notification (Contractual process to address) → Business need to run new cargo and achieve targets (Management to resolve and manage a design verification process)

5 RESULTS PRESENTATION AND DISCUSSION

This chapter focuses on the outputs from the analysis tools and methods conducted during this research study. The sequence in which it is presented is directly linked to the order in which the works were conducted. This was previously highlighted in Figure 3.1 which shows the Research process flow diagram. The chapter introduces the various failure types as analysed from the failure data. It is followed by introducing the results of the first survey questionnaire, which is conducted to determine and understand status quo conditions and procedures that are applied in the port. The chapter subsequently covers the FMECA results highlighting all failures and their respective remedial actions. The Weibull results are then discussed to highlight failure patterns. The second survey questionnaire results follow, which are analysed through an MCA process. The final section of the results chapter encompasses discussion points surrounding the results from each method and analysis conducted, where the outputs from each method and/or analysis are critically assessed.

5.1 Conveyor Failure Types on Selected Berths

The failures experienced across the selected berths were classified according to conveyor components (74,104), guided by the available conveyor data shown in APPENDIX B and the literature covered in this research report. The failure types are shown in Figure 5.1 and are as follows:

- Conveyor misalignment,
- Belt failure,
- Idler failure,
- Conveyor overload,
- Conveyor drive failure.

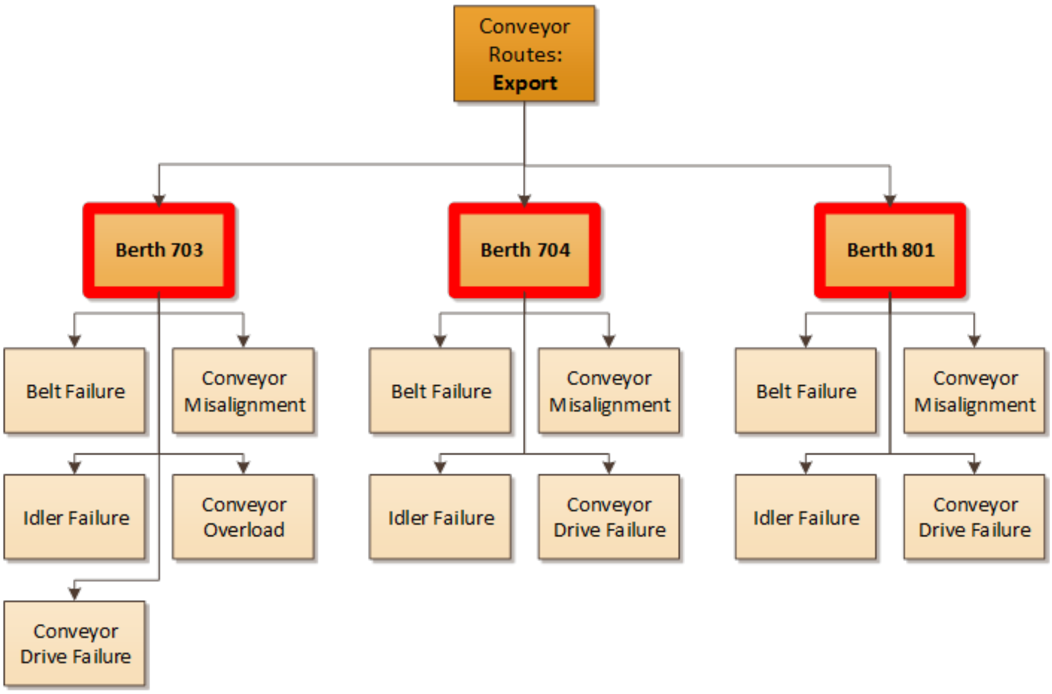

Figure 5.1: Selected berths failure types

The failure types and maintenance activities experienced on the respective routes are depicted on the bar chart in Figure 5.2. The chart compares the failures experienced on the selected routes (berths 703, 704 and 801) against the failures experienced on the seven remaining routes. From Figure 5.2, it can be seen that the selected routes account for a 59% of the failures experienced in the port for the period of data obtained, December 2018 to May 2020. The selection of berths 703, 704 and 801 were also supported by the fact that these berths account for 89% of all planned and unplanned maintenance activities that take place on the conveyor routes. This points to the continuous maintenance required to keep the selected routes operational. Belt failures account for 75% and idler roll failures account for 85% of its respective failures on the selected routes which heavily outweigh the other seven routes. It is concerning to note that these two components are designed to endure wear out failure over their lifespan but over a period of one and a half years have accounted for a considerable amount of failures. It must also be noted that the selected routes do not comprise of any chain conveyors which resulted in a zero rating.

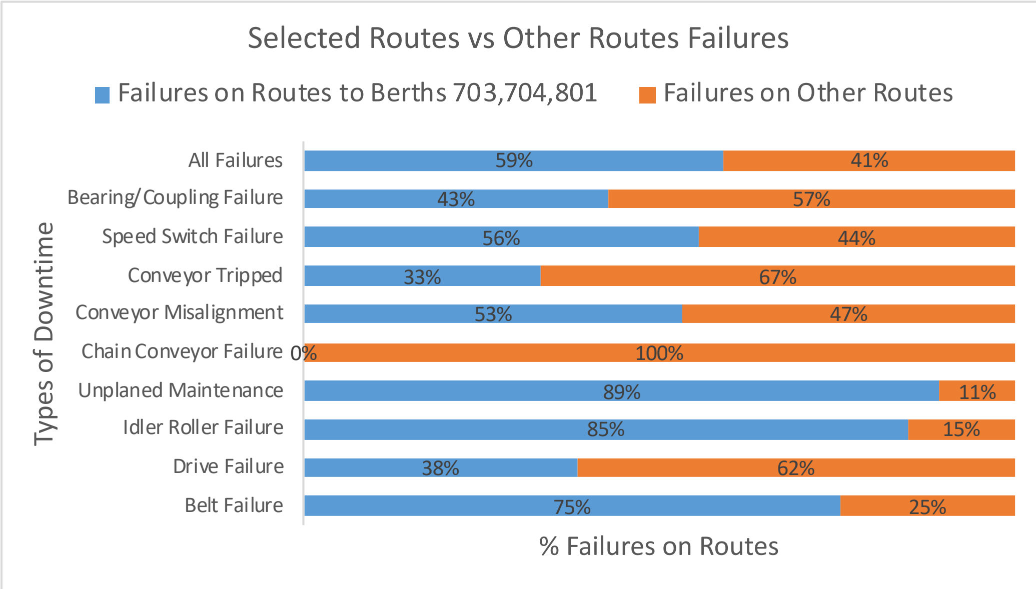

Figure 5.2: Bar Chart showing percentage of failures on selected routes vs other routes

In order to ensure unbiased results, the failures experienced on the individual selected berths were tabulated. This is shown in Table 5.1 which aims to highlight the majorly failing components and the variance in each failure type and occurrence. The failures on routes to berth 703 contained an approximately equal split, with majority of the failures resulting from belting, unplanned maintenance and misalignment breakdowns. The conveyor routes to berth 704 experienced roughly half of its breakdowns due to failures in the belting with idler roll, drive failures and unplanned maintenance accounting for the other half. Similarly, belting failures accounted for nearly half the breakdowns experienced on routes to berth 801, with idler failures and unplanned maintenance accounting for the second most frequent failure.

Table 5.1: Failure type split on selected berths

Failure Type	703	704	801
Belt Failure	26%	44%	44%
Drive Failure	6%	14%	8%
Idler Roller Failure	16%	19%	14%
Maintenance	23%	14%	14%
Conveyor Misalignment	23%	0%	3%
Conveyor Tripped	3%	3%	3%
Speed Switch Failure	3%	6%	6%
Bearing/Coupling Failure	0%	0%	8%

The bar chart in Figure 5.3 shows the failure type against the number of failures experienced for each of the selected conveyor routes. The pie chart in Figure 5.4 shows the percentage split in failure types experienced across the three selected berths. In review of both these charts, it can be established that belting failures account for the maximum of the failures experienced on the selected berths with 39%. It is also recognised that the top three factors that contribute to downtime across berths 703, 704 and 801 are belting failures, idler roll failure and unplanned maintenance. The routes to berth 703 appeared to have the most alignment failures which will be investigated. Belting failure will require further investigation to determine the root causes and problems with belt supply and installations (21,27).

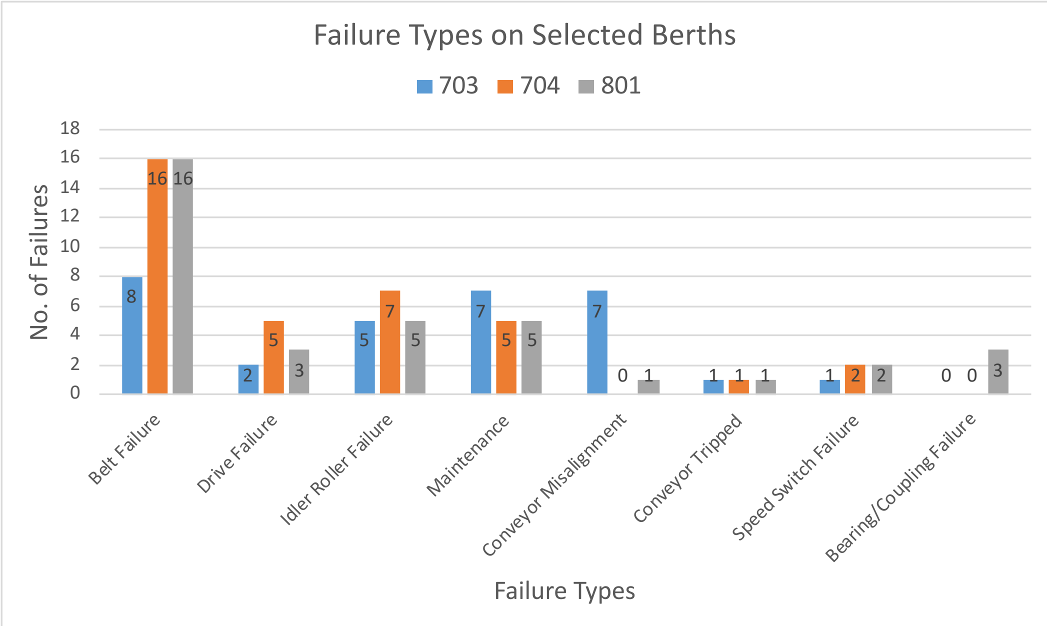

Figure 5.3: Bar chart showing no. of failures and type per berth

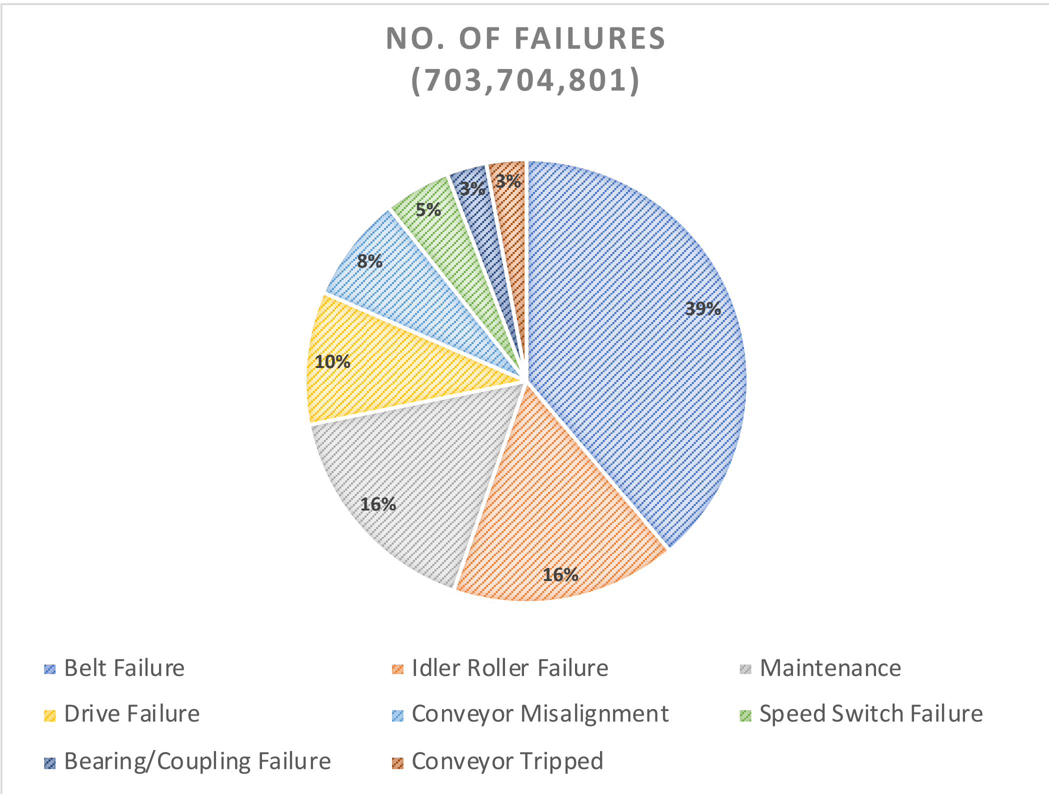

Figure 5.4: Pie chart showing percentage failure types on selected routes

The failures experienced on the conveyor routes could possibly be linked to the change in commodities with the failure types and commodity type in operation for chrome and magnetite shown in Figure 5.5. This shows that both chrome and a combination of magnetite and chrome have an approximately equal impact on the belting failures. The changeover of cargoes involves dry running the conveyor belts for the designated time before loading the different material. The time for changeover between commodities is approximately 30 to 60 minutes per changeover, dependent on the length of the route. Material flow testing had been conducted by the company on chrome and magnetite, with results indicating a higher coefficient of adhesion for magnetite than chrome and both commodities showing similar abrasive characteristics with similar coefficients of rolling and static frictions (113). Figure 5.5 also shows that when chrome is solely in operation, there are more failures than when magnetite is solely conveyed. The researcher could not identify the exact split in operations between the two cargoes, chrome and magnetite, and hence the effect of the combination of the commodities on the route may not accurately be established.

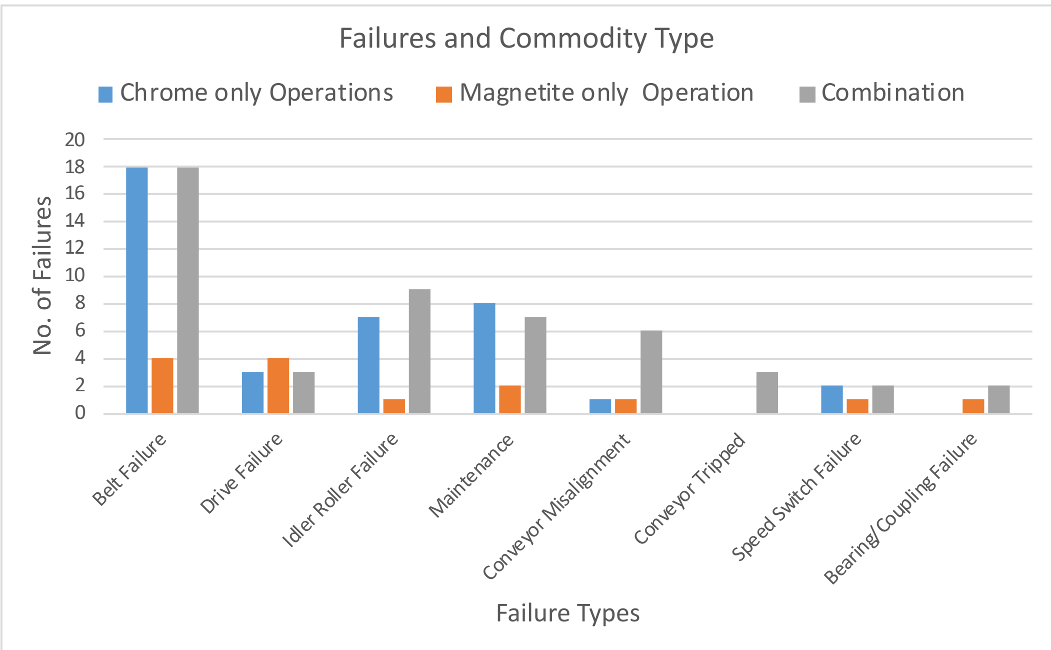

Figure 5.5: Failure types and commodity in operation

5.2 Existing Failure Effects

The effects failure have on the port are shown in this section. The bar chart in Figure 5.6 shows the variations in planned tonnages versus the actual achieved tonnages. The planned versus actual tonnages were extracted from the operational data received and summarised as found in Table B.2 in APPENDIX B. For berth 703, the actual tonnages achieved was 26% of the planned target with 704 and 801 achieving 45% and 28% respectively.

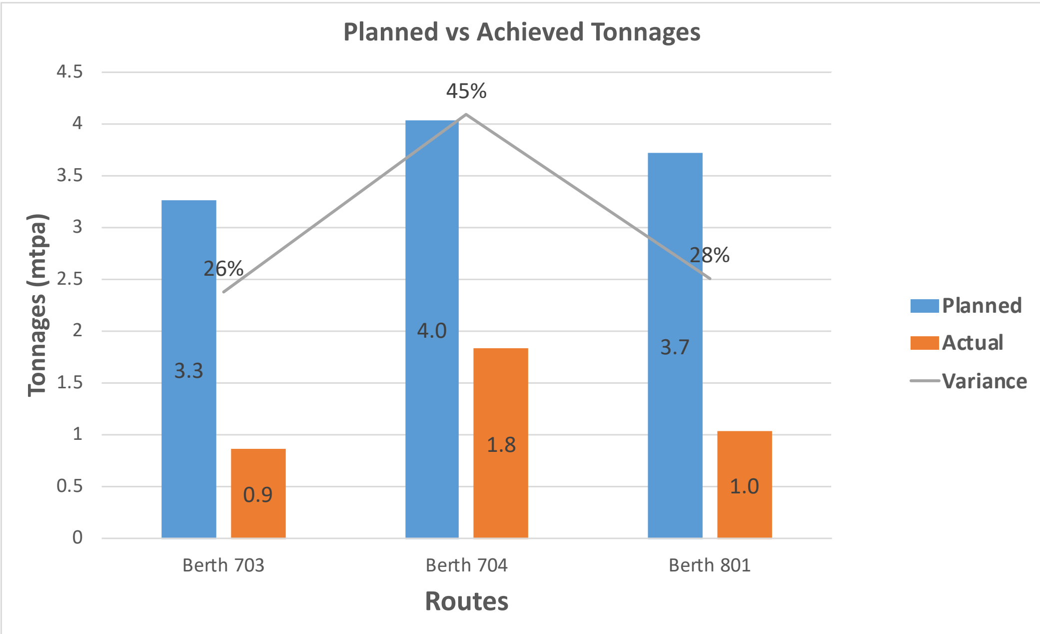

Figure 5.6: Bar Chart showing Planned vs Actual tonnages

The planned and actual tonnages, as shown in Figure 5.6 were plotted against failures experienced on each selected berth over the same time period as depicted on the bar charts in Figure 5.9, Figure 5.10, Figure 5.12 and Figure 5.13. The charts also consider the annual planned maintenance intervals for the routes, as shown in Figure 5.7 which contains search and find (S&F) principles and refurbishment tasks. The charts also plotted the months that had been affected by the national lockdown due to the COVID-19 outbreak which are captured on the individual failure correlation charts for the nominated routes. The planned maintenance for routes to berth 703 were for periods in September and January, routes to berth 704 in November and March/April and routes to 801 during December and May. These intervals were planned maintenance shutdowns with the actual planned and unplanned maintenance periods obtained from the operational schedules with an example shown in Figure 5.8.

	Month	June				July					August					Sep				Oct					Nov				Dec				Jan					Feb				March				April				May			
Berth	Week	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Alesa 01																																																				
609	Alesa 02																			S&F																																	
701	LHM 550													Refurbishment																																							
	Caillard 7							Refurbishment																																													
702	Caillard 8											Refurbishment																																									
703	Caillard Loader															S&F																		Refurbishment																			
704	IMG Mann Loader																								S&F																			Refurbishment									
705	Sandvik Loader																																					S&F															
801	Man Takraf Loader																												S&F																					Refurbishment			
804	Elmec WC Loader																			S&F																			Refurbishment														
PRT	Tippler 01		Refurb																							S&F																											
	Tippler 02						Refurb																				S&F																										
	Stacker			Refurb																						S&F																											
	K51		S&F																							Refurb																											

Figure 5.7: Planned Maintenance Intervals for Conveyor routes

DAILY BAR CHAR

RESCHEDULED	Vessels that have defaulted
SCHEDULED	Vessels that are scheduled
OPPORTUNITY	Schedule vessels nominated < 1
OCCUPATIONS	Berth Occupation -Planned Maint

Date	Time	Day	703	LOA	ETA	704 / 705	LOA	ETA	801	LOA	ETA
8	6:00	Wed	PLANNED MAINTENANCE - P02			IVS NORTH BERWICK = 24 000	200	8-May	STAR TRADER = 50 000	229	2-May
	14:00		PLANNED MAINTENANCE - P02			TRONOX SLOT 07 - 09 MAY			CHROMTECH SLOT 26 APR - 01 MAY		
	22:00		PLANNED MAINTENANCE - P02			TRONOX CHLORIDE = 20 000	DBT 1st		CHROME CHROMTECH = 30 000		
9	6:00	Thur	PLANNED MAINTENANCE - P02			TRONOX RUTILE = 4 000			CHROME ANGLO = 20 000		
	14:00		PLANNED MAINTENANCE - P02			TRONOX CHLORIDE			CHROME ANGLO		
	22:00		PLANNED MAINTENANCE - P02			TRONOX RUTILE			CHROME CHROMTECH		
10	6:00	Frid	PLANNED MAINTENANCE - P02			TRONOX CHLORIDE			CHROME ANGLO		
	14:00					TRONOX RUTILE			CHROME CHROMTECH		
	22:00					ROUTE CLEANING			CHROME ANGLO		
11	6:00	Sat							CHROME CHROMTECH		
	18:00								PENDULUM = +-80 000	229	10-May

Figure 5.8: Operational schedule showing actual maintenance interval

Failures can be seen as having an impact on achieving planned tonnages. Conveyor routes to berth 703 experienced an anticipated drop in actual tonnages for the periods in which maintenance occurred which were December of 2018 and January, May and July of 2019, as shown in Figure 5.9. This was also experienced during the months in which the national lockdown was implemented which were March, April and May of 2020.

The maintenance intervals differed in date and frequency from the planned schedule shown in Figure 5.6. The number of failures after maintenance in December 2018 and January 2019 reduced implying the maintenance had performed its role in ensuring uptime of operations with the route achieving 87% of its planned target in the month of January 2019 (7). Interestingly, the opposite occurred after the maintenance interval in May 2019 with an increase in failures occurring post the maintenance shut, leading the researcher to assume that the failures were maintenance induced (26).

It is important to note that there were no planned or achieved tonnages for July 2019 due to the route undergoing a maintenance interval. During this time, it had experienced the highest number of failures which the researcher believes may have occurred during the testing of the route. The lockdown period significantly reduced the actual achieved tonnages as the route achieved an average of 31% of its planned targets for the periods of lockdown. The failures for these periods were also at a minimum which would be expected due to its limited operation.

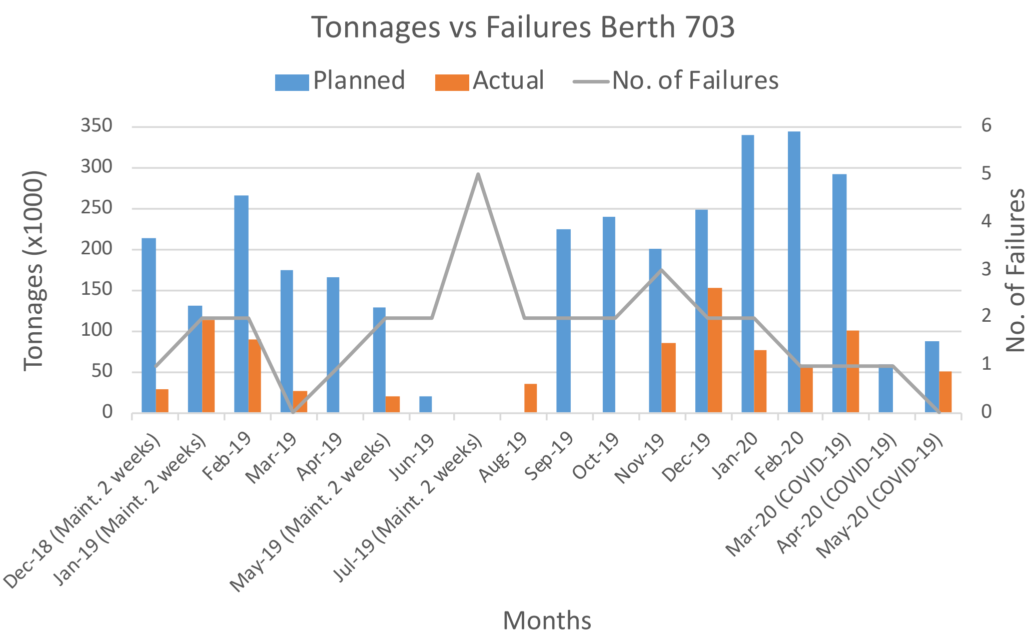

Figure 5.9: Bar chart showing failure correlation of planned vs actual tonnages for 703

Conveyor routes to berth 704 underwent maintenance intervals during December 2018, May 2019 and November 2019, as shown in Figure 5.10, which slightly differed from the planned intervals shown in Figure 5.7. Maintenance downtime has accounted for the decreased actual tonnages achieved during those periods. The route experienced the highest number of failures in April 2019, when reviewing the planned maintenance intervals in Figure 5.7 against the actual maintenance shuts from the operational schedules, which indicates the change of the maintenance shut was prompted by the increased number of failures experienced. The bar chart further shows an increase in the number of failures following the planned maintenance intervals indicating an issue with the components used or with the maintenance actions (26).

The national lockdown appears to have had a minor impact on this route with the operations team getting close to their planned targets, with the route exceeding its target for March 2019. As suggested by the data displayed in Figure 5.11, this was due to an opportunity to load a vessel that was not on the planned loading schedule (shown in yellow highlight). The routes to berth 704 had achieved on average 88% of its planned targets during the lockdown period. The failures were also at a minimal for these periods, due to operations not running at full capacity. The highest planned target was for September 2019, which noted a spike in failures, and the operations team only achieving 28% of the target.

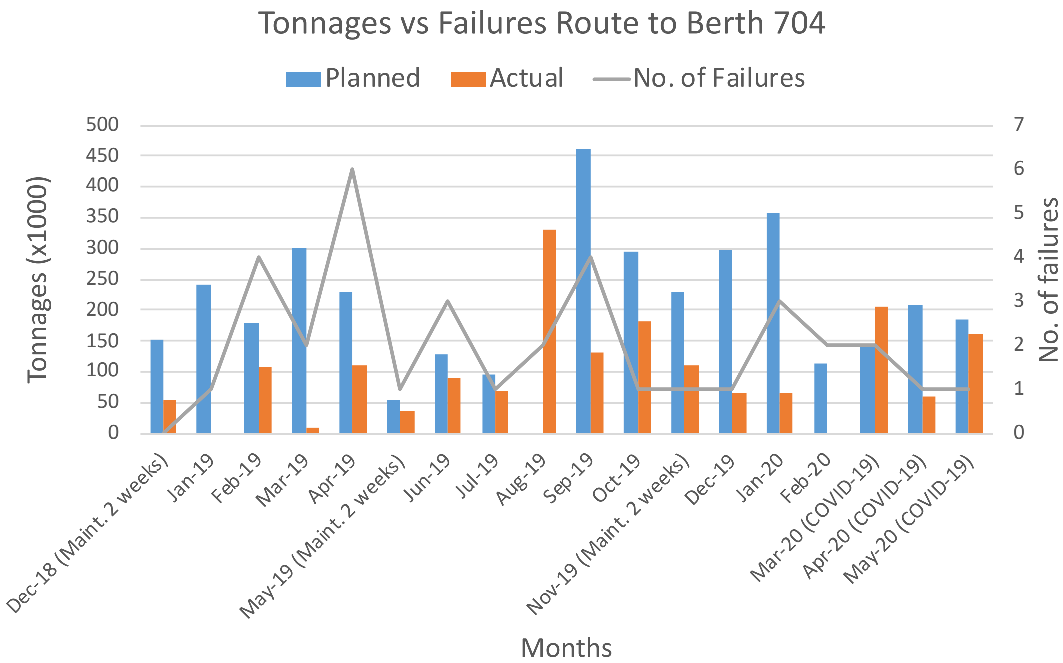

Figure 5.10: Bar chart showing failure correlation of planned vs actual tonnages for 704

DAILY BAR CHA						
RESCHEDULED	Vessels that have defaulted					
SCHEDULED	Vessels that are scheduled					
OPPORTUNITY	Schedule vessels nominated< 14					
OCCUPATIONS	Berth Occupation -Planned Maint					
Date	**Time**	**Day**	**704 / 705**	**LOA**	**ETA**	**801**
	22:00		CLEANING			CLEANING
10	6:00	Tue	KNOSOSS WAVE = 80 000	229	9-Mar	CLEANING
	14:00		ARXO SLOT 10 - 15 MAR		11-Mar	
	22:00		ARXO CHROME = 60 000			
11	6:00	Wed	ASM CHROME = 20 000			
	14:00		ARXO & ASM CHROME			
	22:00		ARXO & ASM CHROME			
12	6:00	Thur	ARXO & ASM CHROME			
	14:00		ARXO & ASM CHROME			
	22:00		ARXO & ASM CHROME			
13	6:00	Frid	ARXO & ASM CHROME			
	14:00		ARXO & ASM CHROME			

Figure 5.11: Snapshot of operational schedule data

Maintenance intervals on conveyor routes to berth 801 were during May, November and December 2019, as shown in Figure 5.12, roughly in line with the planned intervals, and February and April 2020 which were not on the planned schedule shown in Figure 5.7. These maintenance disruptions have accounted for the decreased actual tonnages achieved during those periods. The maintenance intervals on routes to berth 801 are more frequent when compared to the other routes. Berth 801 was originally designed for woodchips whilst other berths were designed to handle coal, which appears to possibly play a factor in causing failures (5). The route experienced the highest number of failures in September 2019, which leads the researcher to believe the maintenance interval was prompted by these failures.

The bar chart further shows an increase in the number of failures following two consecutive maintenance intervals in November (unplanned) and December 2019 (planned) indicating an issue with the components used or with the maintenance actions (26). It can also be noted that the unplanned maintenance in February 2020 was prompted by the increase in failures experienced in January 2020, a period in which no tonnages were conveyed. The national lockdown due to the coronavirus pandemic has impacted the tonnages loaded through this route with no cargo conveyed for the months of April and May 2020. This route had achieved, on average, 15% of its planned targets during the lockdown period. The failures were also at its lowest during these periods due to no operations taking place for two months, April and May 2020.

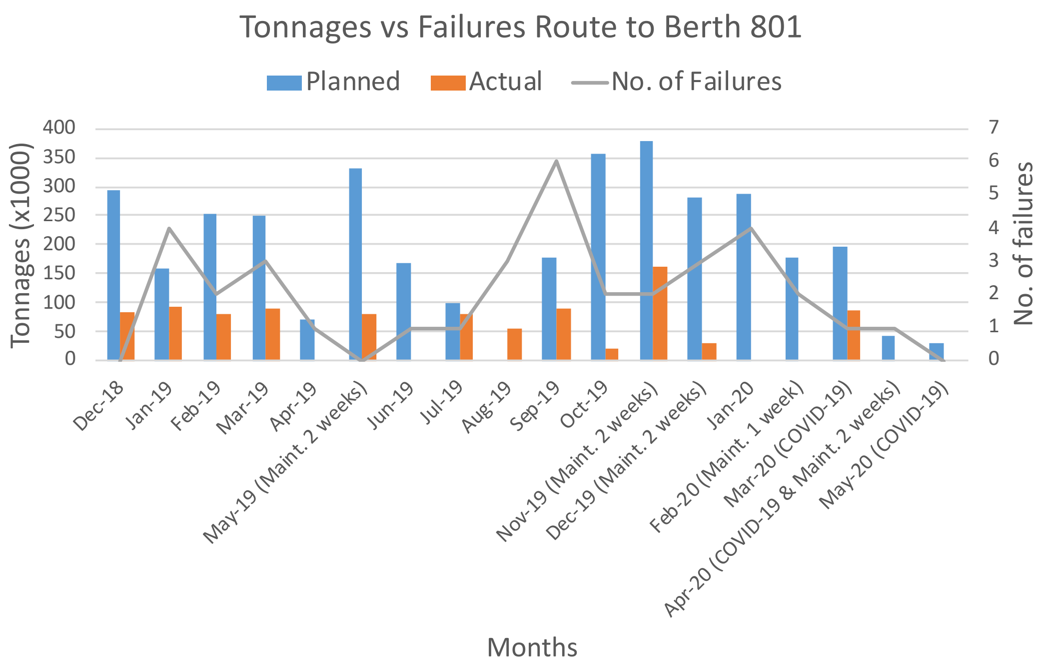

Figure 5.12: Bar chart showing failure correlation of planned vs actual tonnages for 801

The combined failure correlation on the selected berths is found on the bar chart in Figure 5.13. The maximum failures were experienced during September 2019, tying in to the individual berths' correlation pattern. The failures appear to reduce during the lockdown periods, which is an expected result due to conveyor routes not being utilised to full capacity or standing idle.

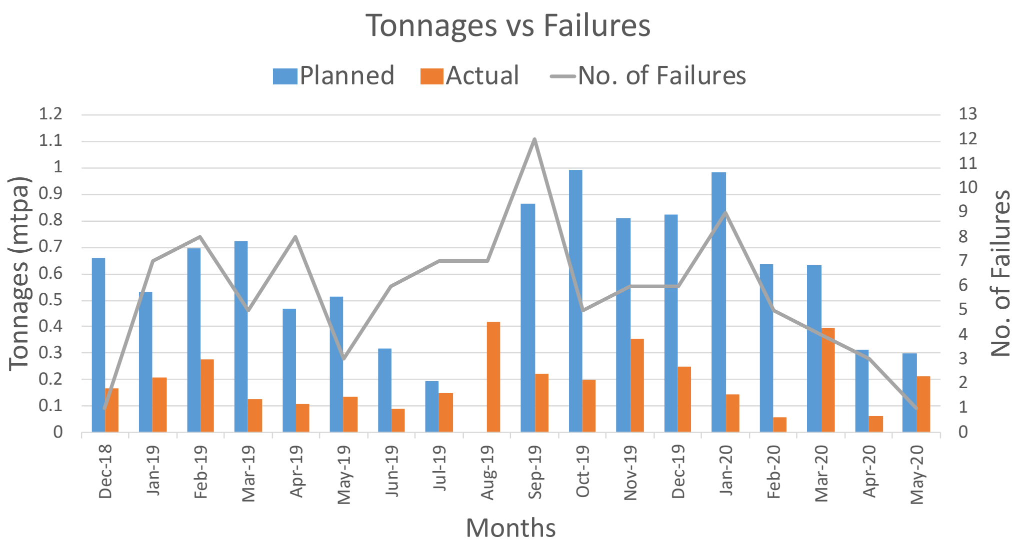

Figure 5.13: Failure correlation of planned vs actual tonnages for all routes

5.3 First Survey Questionnaire Results: General

The first survey questionnaire was developed to gain a status quo view of existing strategies in the port. This questionnaire acts as an introductory phase to the research in gathering all information and data on the ports existing maintenance approach and challenges. The questionnaire contained 9 questions focused on gaining an understanding of what type of maintenance strategy staff believe they are conducting.

The researcher distributed the first survey related to general maintenance practices and strategies in the Port to 15 respondents and attempted to achieve a 50% response rate. A minimum of 7 - 8 responses on the first questionnaire was required to allow for meaningful analysis with the researcher receiving 9 responses achieving a 60% response rate. A maximum of three weeks was allowed for each of the questionnaires to be completed. This survey questionnaire can be found in APPENDIX E. A total of 9 questions were asked to maintenance and engineering staff working with conveyor belts in the PORB.

All respondents believe a maintenance strategy is important in business and that the PORB currently operates with a maintenance strategy in place. The questionnaire has highlighted that staff within the PORB have differing opinions on what strategy they believe they are adopting as 1 out of 9 answered that they are undertaking corrective maintenance, 3 out 9 answered that they are conducting condition-based preventive maintenance and 5 out of 9 answered that they are conducting a combination of maintenance strategies (corrective, preventive, predictive). Upon review of maintenance plans and strategies, conducting site investigations and liaising with the maintenance manager for the conveyors in the port, it can be established that condition-based preventive maintenance is conducted within the port with built-in condition-monitoring only found on drives (21). This is further supported with the responses received from Question 4, with 55.56% of respondents declaring maintenance on a component is done after periodic visual assessment based on the condition of the component. The collated responses further show that 33.33% respondents believe that maintenance is done using condition monitoring devices with 11.11% believing maintenance is done after failure occurs.

It is also interesting to note that the respondents believe different maintenance strategies are adopted for different components and for the same component in different areas as shown in Figure 5.14. This can be seen with pulleys and idlers, where in some areas they are being run to failure whilst condition-based inspections take place in other areas. The results indicate that 44% of the team believed drives had undergone predictive maintenance, which is in line with the ports sole predictive maintenance approach discussed earlier, as the drives have in-built temperature monitoring (21). The belting is recorded as undergoing condition-based maintenance in some instances and corrective in others. There are varying views on the maintenance carried out on the components which leads the researcher to believe that the maintenance staff have misconceptions on what strategy they believe they are conducting and what are the foundation of each particular strategy in the questionnaire.

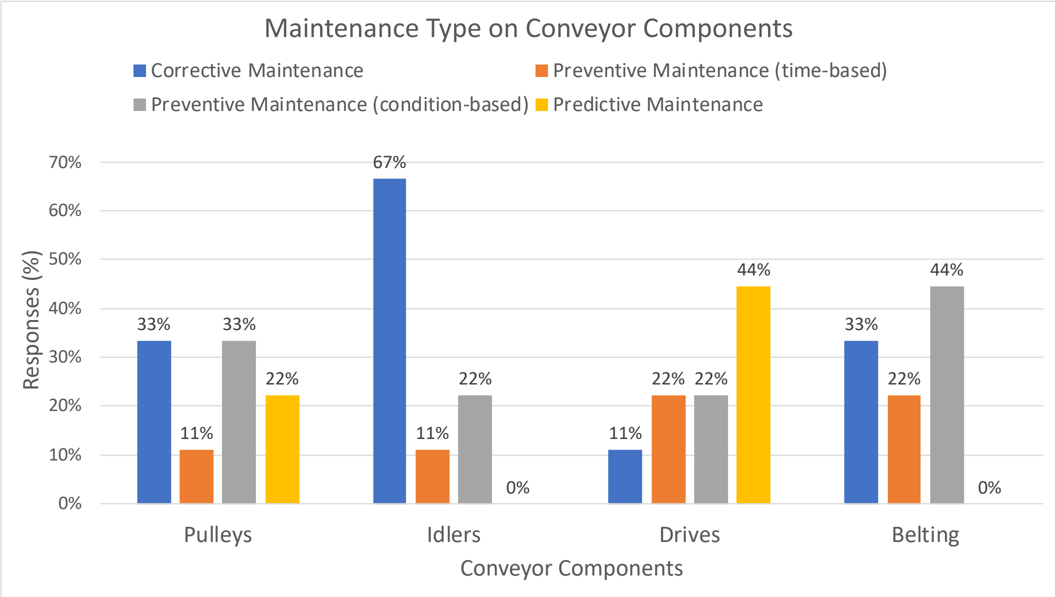

Figure 5.14: Survey Questionnaire responses – component maintenance

The survey results also noted that maintenance is done according to a schedule with 44% believing it is done after inspections identify an issue. Majority of the respondents believe that the existing approach is somewhat reliable with room for improvement with 67% responding that a maintenance strategy that uses a combination of reactive, preventive and predictive maintenance based on the part/component and the consequences of its failure is best suited to conveyor belts in the port, which points toward an RCM approach.

5.4 Failure Modes, Effects and Criticality Analysis (FMECA) Results

The FMECA was used to categorise and evaluate any probable failure modes based on the critical item selection on the conveyor system's components. It further highlighted the consequences or effects these failures may have on the system and actions to circumvent these failures, and/or alleviate the failure consequences or effects (56). The objective of FMECA was to determine possible remedial actions that need to be implemented for the conveyor failure modes in order to reduce failure effects and consequences.

The simplified FMECA shown in Table 5.2 with respective remedial actions shown in Table 5.3, are both derived from the detailed tables found in APPENDIX C. The FMECA was developed utilising data and literature on critical equipment and components of the conveyor belt system (34,74). The equipment, as mentioned previously in Section 3.3.3 are; drive, belting, idlers, pulleys and take-up. The simplified FMECA table captured the highest RPN's experienced for each critical component and proposed remedial actions for those RPN's. The detailed FMECA table found in APPENDIX C captures RPN rankings for all failure modes. Remedial actions were also ranked with a new RPN to determine if the actions will have reduced the failure modes and their effects.

From the simplified FMECA in Table 5.2 under the drive category; conveyor tripping, gearbox failure and coupling failure were failure modes recorded to require remedial actions based on their RPN's of 175, 160 and 160 respectively (108). Belt flap, edge buckling, belt snap and splice failures were recorded as failure modes under belting with respective RPN's of 180, 480 and 480 (21,104). The RPN's are high for belt snap and splice failure as these failures pose a risk of injury or fatality to personnel in the vicinity. Bearing seizure and shaft/end disk failure were captured as failure modes that required remedial actions under idlers with both having an RPN of 280 (74). Bearing (seized, mounting or worn), shaft or shell and end disk failures were recorded as failure modes in the pulleys grouping with RPN's of 256, 224 and 224 respectively (21,74,111). Take-up (trolley, winch and sheave) failures and rope fatigue or break were captured as failure modes under the Take-up with RPN's of 270 and 200 respectively (111).

Table 5.2: Simplified failure modes, effects and criticality analysis table

Component	Process Function/Equipment	Functional Failure	Failure Mode	Effects of Failure	Severity	Possible Causes	Probability of Occurrence	Detection Probability	RPN
Drive System									
Electric Motor	Create power in the form a rotating movement	Unable to spin or inadequate momentum to create energy	Conveyor tripped	Motor won't run, sparking at brushes, spillages	5	Excessively high temperature, conveyor overloaded, belt drift, tripwire activated,	5	7	175
Gearbox	Gearing the rotating movement to another angular speed and torque and transferring the power	Unable to transfer Power from Electric motor to Pulley/Moving head	Pitting, Root fillet cracking, Tooth shear	Tooth surface damage, Surface contact fatigue and tooth failure, vibration and noise	4	Cyclic contact stress, Tooth bending fatigue, fracture, Lubrication breakdown, Contaminants	5	8	160
Coupling	Transmits movement, absorbs vibational alignment deviation, joins to ratational shafts	Not being able to transfer the power	Coupling failure	Material spillage, chute blockage, drive failure, conveyor trip	4	Improper selection; improper, inadequate, or insufficient lubrication; excessive speeds or loads	5	8	160
Belting									
Top Cover	To protect carcass	Unable to protect carcass and plys within belting	Belt flap, edge buckling, belt flip	Belt tracking incorrectly, material spillage,	6	Overloaded belt, idler not changed/monitored, Bad belt training causing belt to miss track and run into steelwork, Belt radius incorrect causing over stressing of belt edge, Belt misaligned, load not centralised, dislodged idler, belt drift switch failure	6	5	180
Carcass	Absorb forces and tension in system	Unable to transmit and absorb loads	Belt snap	Material spillage, take-up trolley and counterweight damage, personnel injury/fatality,	10	Foreign objects on belt, hardened commodity on belt, inferior splice, overloaded, incorrect belt specification	6	8	480
Splice	To join and complete belt	Belt unable to complete loop	Splice failure	Material spillage, take-up trolley and counterweight damage, personnel injury/fatality,	10	Erratic loading, inferior splice quality and workmanship, Environmental conditions during splicing procedure	6	8	480
Idlers									
Bearings	Allows shaft rotational movement with an allowable friction limit	Unable to allow rotational movement friction limits exceeded resulting in won or broken bearing	Idler seizure	Cargo spillage, Heat build-up, noisy	7	Material lodged between frame and roll, load on idler in excess of design load, impact of material on roll.	5	8	280
Idler End Cap	To join the idler roll to the shaft and bearings To provide resistance to loads	Unable to absorb loads	End cap/disk failure	Roll failure, belt damage, material spillage	7	Weld between roll and end cap being worn away by belt, End cap plate thickness incorrect.	5	8	280

Pulleys									
Bearings	Allows for changes in direction at transfer points, Transfers power to drive belt, absorbs loads and tensions in system, allows the shafts rotate with a maximum amount of friction	Unable to allow rotational movement friction limits exceeded resulting in won or broken bearing	Bearing collapsed, Bearing seized, Worn bearing, Bearing mount failure	Cargo spillage, take-up failure, Noisy, Heat build-up	8	Excessively high loads, incorrect bearing size, incorrect mounting for bearing, Poor lubrication, Contamination, Overloading, improper handling and storage, improper installation,	4	8	256
Shaft or Shell failure	Absorb forces and tensions experienced on the pulley shell and allows rotational movement	Unable to absorb loads or unable to rotate freely	Shaft break, shell rupture	Cargo spillage, belt flip, take-up damage	7	Overloaded, pulley misaligned creating uneven moment and torsion, incorrect pulley size and specification,	4	8	224
End Disk Failure	To join the pulley shell to the shaft and provide resistance to loads	Unable to absorb loads	End disk break	Cargo spillage, belt flip, take-up damage	7	Overloaded, pulley misaligned creating uneven moment and torsion, incorrect pulley size and specification, Inferior weld between end disc and shaft	4	8	224
Take-up									
Take up mechanism	Allows for minimum system tension to run empty belt, applies load to pulleys, Apply tension on the pulley	Unable to maintain sufficient system tension	Take-up trolley, counterweight or winch failure	Personnel injury/fatality, belt elongation or snap, structural damage, cargo spillage	10	Mounting platforms for winch incorrect, trolley sheave arrangement incorrect, Misalignment between trolley and winch, insufficient travel on trolley,	3	9	270
Take up Wire rope	To connect the counterweight and winch to the trolley via sheaves	Unable to provide tension to the conveyor belt	Breakage, Fatigue failure	Cargo spillage, Personnel injury, structural damage	10	Sporadic loading, blockages resulting in excessive loads, installation error, lack of lubrication, incorrect equipment specifications (i.e. sheave or rope size), fatigue of components	2	10	200

5.4.1 FMECA Remedial Actions

The remedial actions further form part of the FMECA process in providing and determining solutions to the failure modes noted in the FMECA table. These remedial actions were then re-measured against the RPN scoring criteria to determine if they had reduced the ranking. Some of the remedial actions are shown in Table 5.3 and these include the introduction of condition monitoring equipment to monitor temperature, noise, vibrations and to control the loading of cargo onto the belt which introduces additional maintenance activities that need to be accounted for by the maintenance department. For example, the introduction of condition monitoring equipment introduces extra activities such as ensuring the control equipment are calibrated regularly and maintained, but in the overall view of the maintenance strategy ensure reduced downtime (31,103). Figure 5.15 shows an example of the various condition monitoring devices that can be applied to conveyor belts which fall under the predictive maintenance strategy (116).

A return on investment analysis must be done before implementing any condition monitoring devices to ensure the initial capital outlay will provide long term value (31,103). Design verifications for components such as the idler and pulley specifications and sizes were also captured as a remedial action for the design team to action (26).

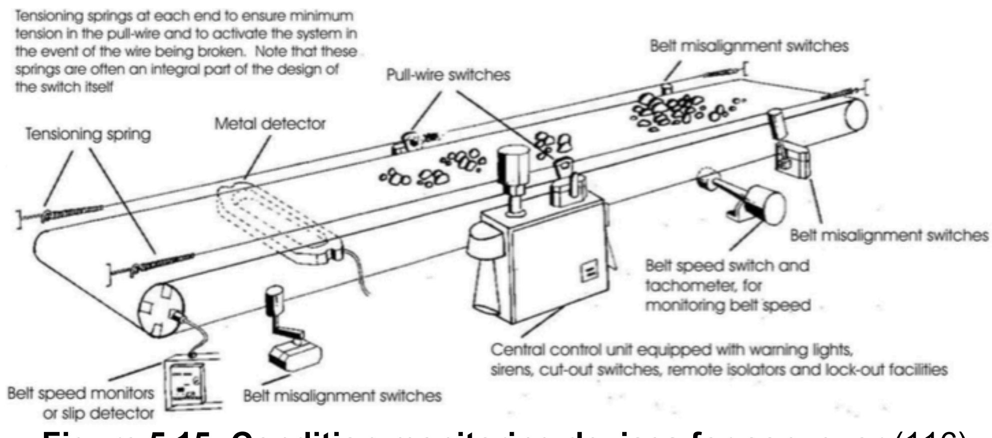

Figure 5.15: Condition monitoring devices for conveyor (116)

Table 5.3: Remedial actions on simplified FMECA table

Design Action	Responsible person	Severity	Probability of Occurrence	Detection Probability	RPN
Drive System					
Install thermocouples or resistance temperature detectors (RTDs) to monitor temperature, Design team to ensure motor adequately sized for load, belt shape monitoring, install belt weighmeters or scales to monitor and control loading	Maintenance staff, Design team	5	5	3	75
Introduce continuous vibration and oil monitoring devices, ensure proper lubrication procedure and levels, introduce training to inexperienced staff, Install level monitors and switches for lubrication levels, ensure proper training and lubrication procedure is followed, introduce finite measures and tools for lubrication quanitities	Maintenance Staff, Management	4	5	5	100
Temperature sensors, vibration monitoring, oil analysis, install belt weighmeters or scales to monitor and control loading	Maintenance Staff, Management	4	5	5	100
Belting					
Belt shape monitoring devices, Check loading is centralised. Realign belt empty and loaded, Install additional idlers in vertical convex curves, Belt shape monitoring devices, Belt drift switches to be calibrated, install belt weighmeters or scales to monitor and control loading	Maintenance staff, Design team	6	4	3	72
Foreign object detection and magnet, Belt rip monitoring with “inverted” figure “8” antennae, Design verification for every change in cargo handled, install belt weighmeters or scales to monitor and control loading	Maintenance Staff, Design team and Management	10	5	3	150
Belt elongation monitoring device embedded in belt, Belt rip monitoring with “inverted” figure “8” antennae, Management to introduce controls on appointment of splice contractors	Maintenance Staff, Management	10	6	3	180
Idlers					
Introduce intermittent positional switches to ensure vertical tolerance are not too high, use infrared non-contact scanners, ultrasonic inspections, install temperature and vibration monitoring for bearings, install belt weighmeters or scales to monitor and control loading, Design check to verify idler sizes, install belt weighmeters or scales to monitor and control loading	Design Check to be done and applied by maintenance staff	7	4	3	84
Check idler alignment. Check load and idler pitch, temperature sensors, Design team to verify idler specification and size, install shaft vibration and speed monitoring	Maintenance staff, Design team	7	5	5	175
Pulleys					
Temperature monitoring, Vibration or frequency analysis, ensure SOP is followed, conduct regular refresher training, install belt weighmeters or scales to monitor and control loading	Maintenance Staff	8	4	3	96
Install shaft vibration and speed monitoring, design verification on pulley shell and shaft sizes	Maintenance Staff, Design team	7	4	3	84
Ensure pulleys are supplied with relevant certificates for welds and heat treatment, Manual inspection by certified Welding Inspector	Maintenance Staff	7	4	8	224
Take-up					
Position encoder to monitor take-up movement within allowed limits, limit switches on take-up travel limit/end, Belt rip detection interlocked with e-stop	Maintenance staff, Design team	10	3	3	90
Use of inductive sensors to monitor ropes condition, Design verification and appropriate rope specification to withstand loads, robustness factored into rope design and selection. Take-up error to be guarded appropriately and work to be carried out only when conveyor belt is locked out for maintenance.	Design Team	10	2	5	100

With reference to drive system in Table 5.3, remedial actions to monitor temperature through installation of temperature monitoring, and introducing vibration and oil analysis were proposed in order to prevent failures and prompt action by maintenance staff (31,103). The use of belt scales to monitor and prevent overloading of the belt was identified as a possible solution to conveyor overloading (21,103). It must be noted that under the belting category, belt snap and splice failures detection and probability of occurrence had theoretically reduced with the proposed use of condition monitoring equipment, but the severity of a failure, should one occur, had remained due to possibility of injury to personnel. It was also noted that modifications are needed to improve the robustness of existing belt drift switches as these switches are at times switched off by staff (21,31,103).

In the idlers and pulleys category, the RPN of the end disk failure could not be substantially reduced as failure of the end disks can be categorized as random with the only controls being that of ensuring the component is adequately designed for the load and application and ensuring regular inspections are conducted on safety critical welds (34). Use of infrared scanners to monitor idler temperatures was identified as a solution to overheating of idlers and bearings as they are a bulk item and localised permanent monitoring would not be cost effective (21) .

Under the take-up category, the take-up rope failure due to breakage has not reduced its RPN rating as there are currently no measurement tools to monitor the steel wire rope (117). The take-up remedial actions proposed the use of positional switches in order to monitor take-up travel which would point to impending failures (31). Design activities stated as remedial actions are to ensure the equipment and/or components are adequately specified and sized for their application and these were proposed for the belting, pulleys and idlers due to the conveyor overloading failure cause (26).

The remedial actions are conducted in conjunction with the Weibull analysis to ensure the proposed actions are aligned to the type of failure and whether the failure can be addressed.

5.5 Weibull Analysis

The Weibull Analysis is applied to the conveyor failure data to identify the failure pattern, that is, whether the failures are infant mortality, random or wear-out failures. This will assist in determining appropriate remedial actions. The Weibull analysis can only be used for one failure mode at a time (26). The conveyor failure data was accordingly split per component in order to conduct the Weibull analysis and determine failure patterns. This split data enabled the researcher to link results between each analysis conducted, i.e. the failure modes from the FMECA were inputted to the Weibull analysis and results were used to correlate to the remedial actions developed in the FMECA.

The individual Weibull density and distribution functions can be found in APPENDIX D. The results were summarised in Table 5.4 and will be used in the discussion. The results from the Weibull analysis indicate random failures for the speed switch, conveyor misalignment, bearing or coupling, tripped conveyor and idler. Infant mortality failures were noted on the belting, drive and for unplanned maintenance actions.

Table 5.4: Weibull results summary

Conveyor Failure type	Failure Classification	Beta (mins)	Eta (mins)	MTTF (mins)	Correlation %
Speed switch	**Random**	**1**	**149**	**145**	**96.17**
Maintenance actions	**Infant Mortality**	**<1**	**263**	**268**	**89.05**
Misalignment of conveyor belt	**Random**	**1**	**118**	**105**	**94.17**
Bearing or coupling	**Random**	**1**	**711**	**504**	**99.30**
Tripped conveyor	**Random**	**1**	**94**	**87**	**94.12**
Belting	**Infant Mortality**	**<1**	**664**	**768**	**97.72**
Drive (not starting)	**Infant Mortality**	**<1**	**211**	**216**	**87.86**
Idler	**Random**	**1**	**79**	**71**	**96.67**

Random failures are a reality in many systems and are difficult to apply preventive maintenance to (26). These items will have to be monitored using condition monitoring devices which supports the remedial actions from the FMECA analysis. Further investigations and data collection are needed to understand the root cause of these failures as belting, idlers and bearings are components that generally experience wear for its specified life (34). Bearing and coupling failures also consisted of a negative failure offset (gamma) which indicates that the bearings/couplings could have already been failing before data collection was conducted (26). Infant mortality failures were noted on the belting, drive and for maintenance actions.

An example of the results outputted from the Weibull analysis for speed switch failures can be seen in the paragraphs below. The sorted speed switch data used in the Weibull software is shown in Table 5.5. The full tables for each component can be found in APPENDIX D. The data consists of failures experienced and suspensions which are standard operating periods without any failures.

Table 5.5: Speed switch failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
1/3/19	Pre-ship	120	S
1/4/19	Takraft boom conveyor run skew	30	F
5/29/19	Cleaning	120	S
5/30/19	S05 Conveyor Running Skew	25	F
6/19/19	Cleaning	60	S
6/20/19	Boom Conveyor Running Skew	30	F
8/4/19	Pre-Ship and Cleaning	120	S
8/5/19	Boom Conveyor Running Skew	75	F
8/5/19	Cleaning	60	S
8/6/19	Boom Conveyor Running Skew	175	F
10/22/19	Pre-Ship and Cleaning	120	S
10/23/19	Boom Conveyor Running Skew	55	F
2/23/20	Cleaning	60	S
2/24/20	Loader Conveyor Run Skew	105	F
4/23/20	pre-ship	60	S
4/24/20	O02 conveyor running skew	40	F

An example of the Weibull distribution function and Weibull distribution for the speed switch failures can be seen in Figure 5.16 and Figure 5.17 respectively.

The beta, gamma, and MTTF values are obtained from the graph and are described below. The beta value informs us about the failure pattern, that is (26):

- Beta <1, Infant mortality.
- 1 < Beta < 2, Random failure.
- Beta >2, Wear-out Failure.

An example of the results from the Weibull analysis for speed switches indicate a beta of 1 that could imply that the failure pattern of the speed switches on the selected routes are random (26) as shown in Figure 5.16. The correlation of the regression is reasonable at 96.71% and based on that, there is confidence exhibited in the results.

The gamma value highlights the offset of the failure distribution. A positive gamma implies there will be a failure free operating period (FFOP), whilst a negative gamma indicates that the component had already begun failing prior to monitoring and collection of data (26). From the report output in Figure 5.16, the gamma value is zero, indicating that the probability of failure immediately upon start-up is unlikely.

The mean time to failure (MTTF) is also obtained from the Weibull results which indicates the average operating time of the component before a tripped switch occurs. It is the reciprocal of the failure rate (57). From the Weibull analysis, the MTTF was found to be 145 minutes, which implies that a trip of the speed switch should be expected every 2.5 hours during operations on the selected berths unless the root cause of the failure is resolved. This MTTF is low compared to the expected lifespan of component critical for the operation of the conveyor.

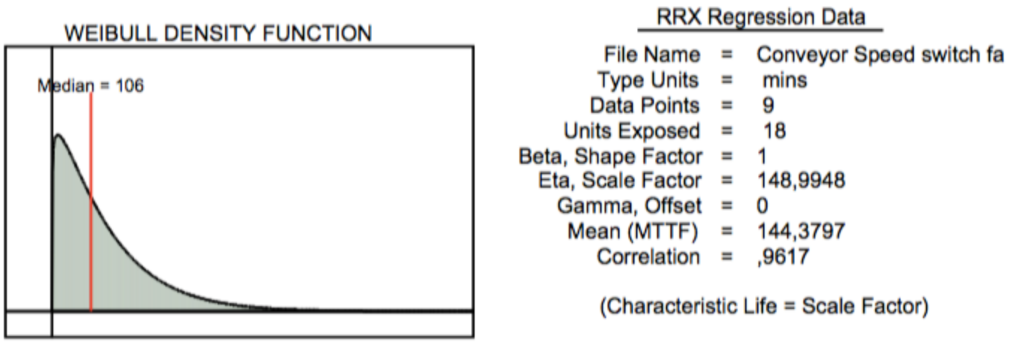

Figure 5.16: Weibull Density Function and Regression Data for speed switch failure

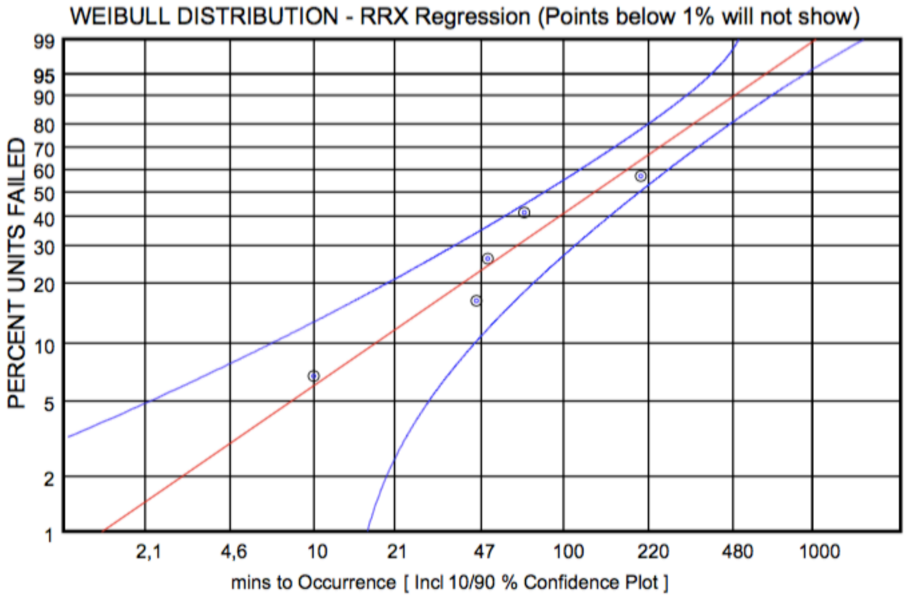

Figure 5.17: Weibull distribution for failure and suspension of the conveyor speed switch

5.6 Second Survey Questionnaire Results: MCA

The second survey questionnaire was developed to feed into an MCA model in order to select a most suited maintenance strategy for conveyor systems in the PORB. Utilising the results from the first survey the researcher issued the second questionnaire, detailing the MCA criteria and selection of a strategy, to 5 senior maintenance and engineering staff that can be considered experts in the field and attempted to receive an 80% response rate. A minimum of 4 responses on the second questionnaire would allow for meaningful analysis (102). A maximum of three weeks was allowed for the questionnaire to be completed. The survey data from the web-survey platform was entered into an MCA model developed in excel to calculate the ranking of the maintenance strategies.

This survey questionnaire and responses can be found in APPENDIX F. A total of 10 questions were asked to experienced maintenance and engineering staff working with conveyor belts in the PORB. A total of 4 out of 5 responses were received achieving an 80% response rate. The second questionnaire was developed in line with the criteria and weightings used in the MCA analysis. The weightings were ranked in the order of cost considering the cost of implementation and spares holding; safety encompassing personnel and environment, value added in terms of reputation, improving reliability, reducing maintenance costs, operational impact and downtime; and schedule considering timeline for implementation and impact to operations. The scores for each item were taken as the average of the scores received from the respondents on the questionnaire as shown in Table 5.6 with the summarised scoring found in Table 5.7.

Table 5.6: MCA results received on questionnaire two

No.	Criteria	Rank	Weighting	Reactive Maintenance	Preventive Maintenance (time-based)	Preventive Maintenance (condition-based)	Predictive Maintenance	Reliability Centred Maintenance
			100%	24%	43%	47%	59%	57%
1	**Cost**	1	30%	10%	14%	15%	16%	15%
1.1	How would you score the costs of implementation (Training, hardware, software) for each maintenance strategy?		20%	4	5.75	5.5	5	4.75
1.2	How are score the costs for spares holding for each maintenance strategy?		10%	2.25	2.75	4	5.75	5.75
2	**Safety**	2	30%	7%	12%	14%	19%	19%
2.1	How would you score the maintenance strategy in relation to the safety and protection of personnel?		20%	2.25	3.75	4.5	6.5	6
2.2	How would you score the maintenance strategy in relation to the safety and protection of the environment, both internal and external?		10%	2.5	4	4.75	6.25	6.5
3	**Value added**	3	25%	4%	11%	11%	15%	14%
3.1	How would you score the strategy for improving reliability?		10%	2	3.25	3.75	6	5.75
3.2	How would you score the strategy for reducing maintenance costs?		5%	2	3.5	4	6	6.25
3.3	How would you score the strategy with regards to minimising downtime and operational impacts?		5%	1.25	5.25	5.5	6.5	5
3.4	How would you score the strategy with regards to improving reputation of the company?		5%	1.25	6.25	5	5.25	5.25
4	**Schedule**	4	15%	3%	6%	7%	9%	9%
4.1	How would you score each strategy in relation to the timeline for implementation?		7.5%	2.25	3.75	5	5.75	6
4.2	How would you score each strategy with relation to required occupations to implement strategy?		7.5%	1.25	4.5	4.75	6.5	5.75

Table 5.7: Summarised MCA results

No.	Criteria	Rank	Weighting	Reactive Maintenance	Preventive Maintenance (time-based)	Preventive Maintenance (condition-based)	Predictive Maintenance	Reliability Centred Maintenance
			100%	**24%**	**43%**	**47%**	**59%**	**57%**
1	Cost	1	30%	10%	14%	15%	16%	15%
2	Safety	2	30%	7%	12%	14%	19%	19%
3	Value added	3	25%	4%	11%	11%	15%	14%
4	Schedule	4	15%	3%	6%	7%	9%	9%

The MCA results were analysed and summarised in the bar chart presented in Figure 5.18. The reactive approach to maintenance had received the lowest score of 24% across all the criteria. Time-based PM ranks fourth with a score of 43% and condition-based PM ranks third with 47% across the criteria indicating that these approaches are not considered the most effective on conveyor systems. The first and second ranked strategies outputted from the MCA scoring had a 2% difference. The RCM approach placed second with a score of 57% and the predictive maintenance strategy ranked first with a score of 59%.

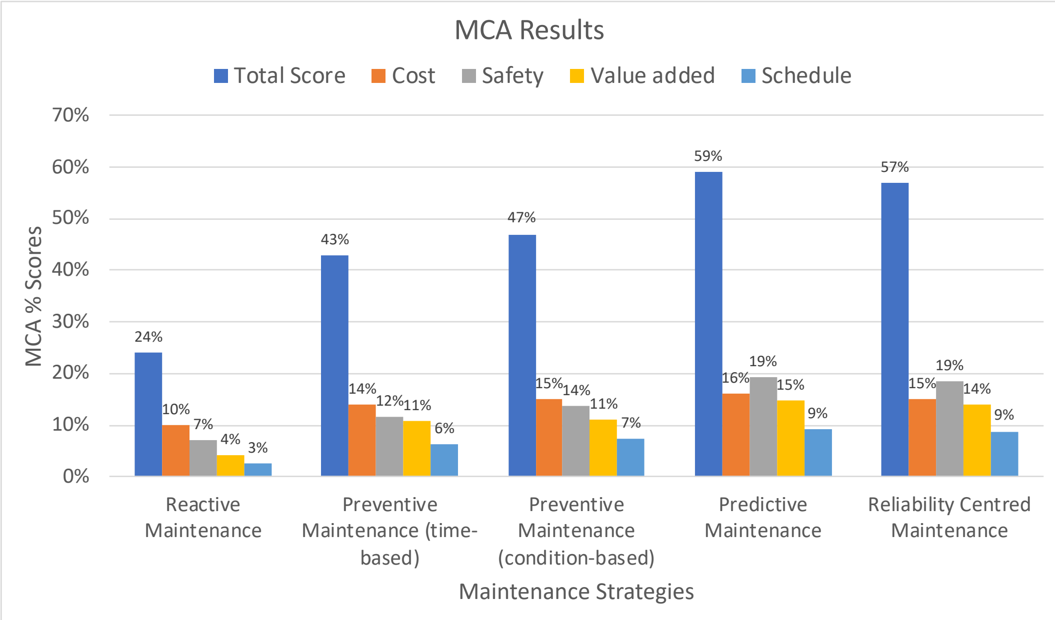

Figure 5.18: Bar Chart showing MCA questionnaire results

Whenever an MCA is performed, it is a prudent exercise to discover how sensitive the MCA is to various criteria omissions to ascertain whether a single criterion had in effect propelled a maintenance strategy to the number one option. For example, a low-cost impact could affect the selection of a single strategy to the disadvantage of the other criteria being assessed. Each criteria is omitted in turn to see if the scoring or weighting for a single criteria is affecting the robustness of the model (99). The results from the sensitivity analysis are shown in Table 5.8 and graphically represented on the radar graph in Figure 5.19. It can be seen that the option of the predictive maintenance (PdM) strategy consistently ranks first with RCM ranking a very close second throughout the sensitivity analysis. The proximity of the scores between the top two ranked strategies leads the researcher to believe that a combination of the strategies should be considered.

Table 5.8: Sensitivity Analysis of MCA scoring

Options	Reactive Maintenance	Preventive Maintenance (time-based)	Preventive Maintenance (condition-based)	Predictive Maintenance	Reliability Centred Maintenance
All domains	24%	43%	47%	59%	57%
	5	4	3	1	2
Less Costing	14%	28%	32%	43%	41%
	5	4	3	1	2
Less Safety	17%	31%	33%	40%	38%
	5	4	3	1	2
Less Value added	20%	32%	36%	44%	43%
	5	4	3	1	2
Less Schedule	22%	37%	40%	50%	48%
	5	4	3	1	2

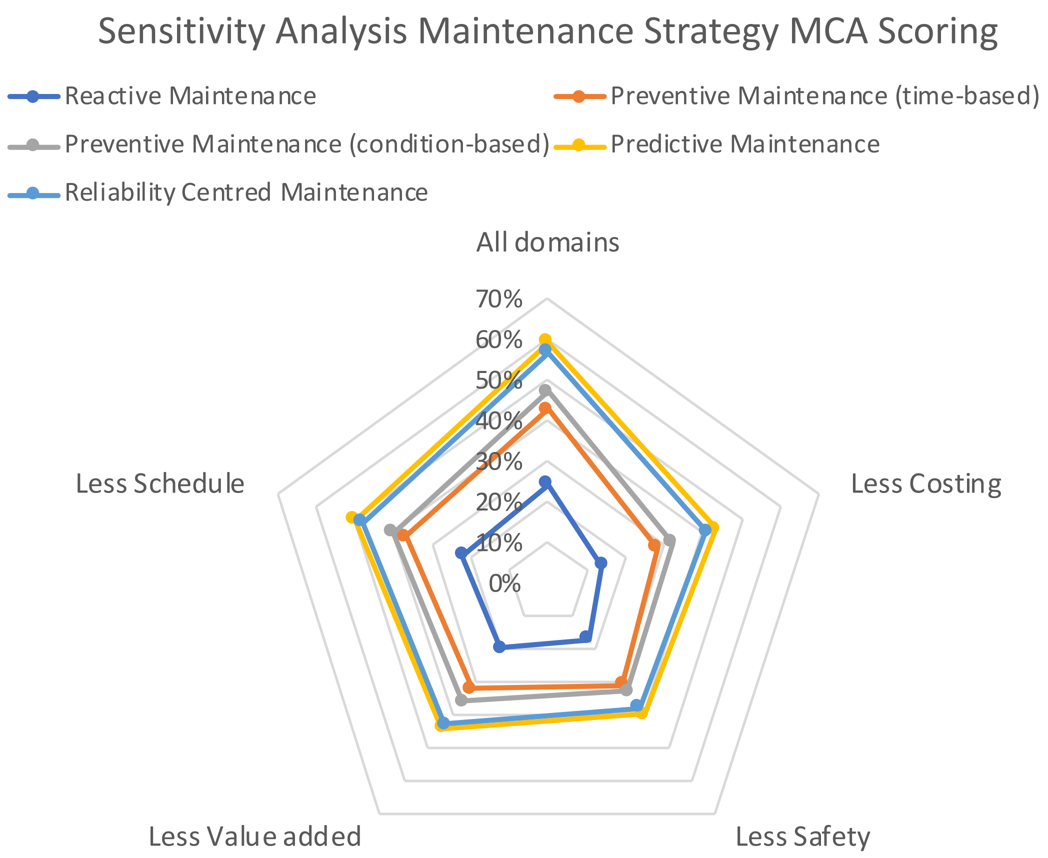

Figure 5.19: Sensitivity radar graph

5.7 Discussion

In this discussion the objectives of the research will be revisited and linked to the results from the research analysis methods. In investigating the existing strategies through the review of maintenance plans, operational schedules, failure data and survey results, it was found that there is a differing view amongst staff at the port with regards to what type of maintenance is being carried out, which will be elaborated on and assessed in this section. For this research project, the data was available in the form of conveyor failures experienced which was analysed and filtered in order to provide the required inputs to perform the failure analyses. The results from the various analysis tools will be highlighted, related and discussed with a view on a recommended maintenance approach. There exists an ideal opportunity to test the theory and application of improving the maintenance approach, strategies and mind-set of staff within the PORB. This research project will deduce the most suitable maintenance strategy or combination of strategies to be followed with the least amount of consequential effects that can be applied to conveyor belts in the port.

5.7.1 Existing Failure Effects

Upon review and analysis of the failure data, the existing strategies were theorised to be ineffective in ensuring operations of the conveyor equipment as the selected routes showed poor uptime performances. The data shows that the failures experienced on the export routes alone contribute to a substantial revenue loss, as movement of cargo directly correlates to revenue with a rate per ton of cargo charged to clients whom utilise the PORB's infrastructure. The charge out rates are confidential and as such could not be obtained for this research project. The failures could also lead to reputational damage and a loss of confidence in the port, from which the client could utilise other means of transportation to convey their cargo, resulting in loss of future revenue. The conveyor failures and subsequent downtime further burden the company with possible penalties incurred for loss of the client's income and standing time of the vessel docked at the berth. The researcher is aware of incurred penalties with the take-up winch failure experienced on a conveyor route to berth 703 as previously shown in Figure 4.11. Through a deeper analysis of the failure data utilising the Pareto principle, it was found that majority of failures experienced on the export route were related to three berths, i.e. berths 703, 704 and 801.

The conveyor routes to berth 801 and 804 had originally been designed for woodchips and are the sole remaining routes for exporting woodchips in the PORB. The remaining routes (including berths 703 and 704) had originally been designed for coal. The change of cargoes was as a result of volatility in the market as well as market demand for different products. As a result of this, woodchip volumes decreased forcing other cargoes to be handled on these routes in order to sustain the business. The new cargoes that were introduced, namely magnetite and chrome, possess different material properties and behavioural characteristics when compared to woodchips and coal. Consequently, the existing infrastructure and equipment should have been modified or replaced in order to successfully transport these products, however the higher density cargoes were routed to the selected berths without a complete re-design or verification of the equipment.

Further review of the failure data indicates that the change in cargo is directly contributing to the failures and downtime on these routes. Through further analysis of the data, it was shown that the majority of failures had occurred on the routes to both 704 and 801 as shown in Figure 4.3. As such, the change in the type of cargoes handled is believed to have increased the number of failures experienced on the handling infrastructure.

The failures reviewed from the data directly correlated with a significant decline in the achieved tonnages with berths 703, 704 and 801 achieving

26%, 45% and 28% of their planned tonnage targets respectively as shown in Figure 4.4. The failure to achieve the tonnages results in a backlog of cargo to be moved which creates difficulty in planning routes. This could also force the client to move their cargo through other channels resulting in a loss of immediate and future revenue. The impact of the COVID-19 pandemic has also played a role in the reduced volumes achieved, but at the same time also reduced the number of failures during this period due to the limited operation of the equipment under the national lockdown.

The review of tonnages and failure data under the lockdown period had also indicated an expected decrease in the planned targets. This, when further interrogated, shows that with the reduced planned tonnages, berth 704 had achieved 88% of its target. This could suggest the routes to berth 704 are being run beyond their capabilities and the operational "sweet spot" is as per the reduced targets. Berths 703 and 801 had achieved 31% and 15% respectively of their planned targets which indicates that the assets, even at a reduced rate, are being utilised beyond their present capabilities which prompts further investigations in order to identify any underlying issues within these routes.

The Pareto principle and analysis of the existing data has shown variance between planned and actual achieved tonnages which addresses the objective of identifying the impact the existing approach has to the business. The variance was attributed to the lack of maintenance with the tonnages correlated against the downtime and failures experienced. This supported the objective of investigating alternative maintenance strategies to improve performance.

5.7.2 First Survey Questionnaire

The first survey questionnaire aids in achieving the objective of identifying the existing maintenance strategies and understanding status quo conditions from personnel within the port. It acts as an introductory method to this research to develop a base to measure the results against.

The results from the questionnaire showed that all respondents believe a maintenance strategy is important in the business, and that the PORB currently operates with a maintenance strategy in place. This shows that the staff are aware of the importance of maintenance and their current regimes. The questionnaire results pointed to the common misconceptions staff have with regard to the strategies they believe they are adopting, as respondents showed different maintenance approaches for the same conveyor component. This led the researcher to believe that the staff possibly require refresher training on the merits of the various maintenance strategies.

It was established, through review of maintenance plans, conducting site investigations and through face-to-face and virtual engagements with the maintenance manager, that condition-based maintenance is conducted at the port. It was also found that built-in condition-monitoring is only found on drives and belting to monitor temperature and belt alignment respectively.

5.7.3 FMECA

The FMECA process and tool aims to address the objective of identifying whether a new approach is needed by categorising failure modes and their risk rating and determining whether it can be reduced by adopting remedial actions linked to a different maintenance strategy. It also supports the need for a new or modified maintenance approach in understanding the outputs from the existing failure effects. The Five Why's and Ishikawa Fishbone diagram were developed in order to determine primary and secondary root causes of failures, which will support the remedial actions developed in the FMECA analysis. These cause-and-effect analysis tools support the objective of investigating the need for a new maintenance strategy. The FMECA, Five Whys and Fishbone diagram additionally addresses the objective of allowing the researcher to analyse and understand the effects and impact on the port.

The failures experienced on the conveyor components appear to have failed more frequently under the operation of chrome and/or by running a combination of chrome and magnetite. The combination of commodities could not accurately be defined which means that the most failure causing commodity could not accurately be determined at this stage of the research. Therefore, further investigations will be required to pinpoint the cargo causing the most failures. It is known that both these commodities are heavier density cargoes than the conveyor routes original design premise with chrome being a free-flowing cargo and magnetite having a viscous-like nature. This, in theory, should mean that magnetite is the problematic cargo to handle, but based on analysis of the failure data as shown in Figure 5.5, the running of chrome had accounted for 74% of failures whilst magnetite experienced 24% when comparing chrome and magnetite only operations.

Belting, idler, speed switch failures and unplanned maintenance occurred the most when running chrome or a combination of both chrome and magnetite which, in the view of the researcher, speaks to the high impact and flow of chrome. Drive and bearing failure occur more frequently on magnetite which could be the result of its viscous nature and the resultant increased load experienced on the drive and pulleys which is required to break the adhesiveness. Material flow testing had been conducted by the company on chrome and magnetite with results indicating a higher coefficient of adhesion for magnetite than chrome which reaffirms the researchers view. The cargoes effects on the failures would need to be confirmed with further investigations, particularly the effects of combined cargoes.

The Five Why's and Ishikawa Fishbone diagram were developed in order to determine primary and secondary root causes of failures, which will support the remedial actions developed in the FMECA analysis. A common cause amongst both these methods were that of conveyor overloading with increased abrasiveness on the belt due to the cargo. This is due to the change in cargo from the low to high density as well as the mandate from management to achieve higher loading rates. The change in cargo not only induces increased loads but the material properties of woodchips compared to both chrome and magnetite differ drastically and must be considered when modifying, designing or selecting conveyors and their associated equipment. The material properties influence component selection and chute angles, which reduce impact and abrasive wear on the conveyor belts by ensuring a smooth changeover between transfer points.

It was also noted that maintenance staff not performing basic tasks such as lubrication or housekeeping (cleaning up spillages) has added to the breakdown of the equipment. Installing condition monitoring devices would be in line with the proposed actions of the FMECA as these monitoring devices are capable of predicting looming failures. As an example, condition monitoring of bearings can predict failures such as overloading, overheating or lack of lubrication.

The research analysis also considered the planned and unplanned maintenance activities in order to gain an objective view into the failures and their effects on revenue. In the review of the data, it was noted that the maintenance intervals were not in accordance to the schedule as shown in Figure 5.7 and Figure 5.13. This is a common occurrence in the port with operations taking precedence over all other activities. It was found that routes to berth 801 had experienced the most unplanned maintenance actions when compared to the other berths, which could be attributed to the change in cargo without a verification in design. Another possibility could be due to the conveyor route having passed its operating life of between 10 to 15 years, with frequent maintenance conducted to prolong its usage. This will need to be further investigated to determine if the current maintenance costs and revenue lost due to added downtime, outweigh a complete replacement/refurbishment of the asset.

Using the FMECA, the components identified in the critical item selection were; the drive, belting, pulleys, idlers and the take-up system. The failure types gathered from the failure data and literature were used within the table to rank the risk posed from these failures by determining a risk priority number (RPN). In evaluating the RPN's, it was noted that the highest risk failure was under the belting category as the failures endangered the lives of employees in the vicinity. The conveyor belt is under extreme tension and contains an ample amount of kinetic energy that will be released should the belt snap. Detection and occurrence of the failure could be addressed, but the severity remained the same as the risk posed to the operator during a failure does not change.

The suggested remedial actions were to verify the equipment sizing and specification through design calculations, in addition to implementing condition monitoring equipment to either notify staff of imminent failures or to trip the system to prevent failures. The installation of condition monitoring equipment would also prompt staff to conduct maintenance activities. For example, a bearing squeal monitored by vibration and temperature monitoring equipment would require maintenance action. The remedial actions under the belting category mainly dealt with causes such as incorrect design or specification, inferior workmanship on splices that join belts and lack of general maintenance and housekeeping which reduces the usable life of the belt. Predictive maintenance on belt alignment cannot resolve the cause of the misalignment but merely prevents secondary damages and prompts the maintenance team to perform fault finding.

5.7.4 Weibull

The Weibull analysis has shown that random failures occurred for the speed switch, conveyor misalignment, bearing or coupling, tripped conveyor and idler failure modes with infant mortality failures being noted on the belting, drive and for planned and unplanned maintenance actions. This implies that maintenance is having an adverse effect on the equipment and components and could suggest that staff are excessively maintaining their equipment, resulting in breakdowns or maintenance tasks being carried out incorrectly. The results from the Weibull analysis on the drives links to the drive failure modes in the FMECA table. The data from the Weibull analysis, shown in Table 5.4, indicate infant mortality failures. This is an unusual finding as drives are specified for predetermined loading conditions with a design life in-built from the supplier (34). These premature failures suggests that there is an issue with the component and/or system designs as well as sizing for the application, which could be linked to the change in cargo from low to high density without a detailed design verification (5).

The Weibull outputs have supported the failure modes developed in the FMECA by acknowledging the standard of workmanship and lack of lubrication, which supports infant mortality failure. The findings from the Weibull review were concerning as no components were determined to undergo wear-out failure. This means that the components are failing before reaching their theoretical design life of 10 to 15 years. Components such as the belting and drives, when correctly specified and designed, are meant to last in excess of 40000 hours and are intended to experience gradual wear during their operational life. The analysis, however, shows that they are failing prematurely. This suggests that these items have a quality problem either with the supplier or with the installation and/or repair staff (26). This supports the belt splice failure mode under belting in the FMECA table as inferior workmanship on splices were noted as a failure cause (21). This is an extremely unusual finding for belting which is considered to be a wearing component that fails due to the wear of the belt surface under a specified period of operation as mentioned earlier (34).

In a similar fashion, the idlers were determined to be failing randomly. In a correctly designed system, idlers are intended to experience gradual wear. This random failure could be the as a result of an inherent issue with the component designs and sizing for the application which could possibly be linked to the change in cargo from low to high density without a detailed design verification. Another possibility could be incorrect installation, with installation methods to be revisited to ensure compliance to the manufacturers or suppliers' guidelines.

The Weibull outputs have supported the failure modes developed in the FMECA and addressed the objective of the need for a new maintenance strategy by determining failure patterns and correlations based on the failure data analysed.

5.7.5 Second Survey Questionnaire and MCA

The multi criteria analysis (MCA) tool was then used, in conjunction with an online questionnaire sent to key maintenance and engineering staff, in order to rank the existing maintenance strategies against an optimised approach. The results from the MCA questionnaire were ranked and had shown that respondents had scored the corrective maintenance strategy the lowest score of 24% across all the criteria. This score essentially eliminates this approach as a single strategy that can be implemented or used on conveyor belts. This is supported by the outputs from the Weibull results summarised in Table 5.4 and Fishbone diagram shown in Figure 4.12, which had shown that some components are failing prematurely. This is contrary to its specification and intended use, which indicates the reactive approach is not reducing failures. This was an expected outcome given the type of operation as some components in a conveyor system are long lead items which cannot be run-to-failure, whilst some components, if run to failure, can cause serious injury or fatality of staff.

There are also a large number of conveyors, approximately 40, in operation at the port which, if operating under the premise of running to failure, poses a massive risk to the operations and revenue. Time-based preventive maintenance placed fourth with a score of 43% and condition-based PM ranked third with 47% across the criteria indicating that these approaches are not considered as the most effective on conveyor systems. This result proved interesting as it is the existing approach within the port but the results from the questionnaire have shown it to be the third most effective maintenance strategy for conveyor belts. This supports the outputs from the FMECA where it had shown the existing actions to have resulted in high RPN's requiring immediate attention.

The outputs from the Weibull analysis summarised in Table 5.4 have indicated that no components were experiencing wear-out failure. Wear-out failure correlates with the time-based and condition-based preventive maintenance approach, which is the existing strategy being implemented. This suggests that this approach is ineffective in reducing failures and downtime at the port which further supports the need to consider other maintenance approaches in order to improve maintenance practices, maintenance initiatives and to reduce failures, downtime and costs.

The top two maintenance strategies outputted from the MCA scoring according to the respondents were the RCM approach in second, with a score of 57%, and the predictive maintenance strategy ranking first, with a score of 59%. The results from the MCA connected to the remedial actions in the FMECA process in that condition monitoring recommendations are associated with both RCM and the PdM approach.

A sensitivity analysis, as shown in Table 5.8 and Figure 5.19, was conducted as part of the MCA process to ensure no single criteria had influenced the position of the results, with the strategies ranking in the same order. Predictive maintenance will introduce monitoring equipment which forms the basis of this strategy, whilst RCM considers the best suited combination of maintenance strategies dependent on the component and consequential effects of its failure. The use of predictive maintenance is common for conveyor systems, but is not common within the port and will introduce additional maintenance and calibration activities.

The suggestion of utilising condition monitoring equipment as remedial actions may indicate that a predictive maintenance strategy is required in order to reduce failure effects, secondary consequential damages and to possibly improve reliability and availability of the conveyor routes. But this could be incorrect and must be carefully explored before implementation. The use of monitoring devices must not create a false belief that all maintenance issues will be resolved once condition monitoring devices are installed. As such, the failure consequences and the receptiveness of maintenance staff to a strategy and its processes are critical in ensuring its success.

The second survey questionnaire and the MCA process addresses the objective of recommending a suitable maintenance strategy/strategies for the conveyors in the PORB by collating the responses received together with outputs from the failure analysis tools, previous studies as well as status quo conditions in the port to recommend the way forward.

5.7.6 Maintenance Strategy Selection

The outputs from the FMECA supported by the results from the Fishbone diagram and Five Whys method, correlate to the results from the MCA in that a significant number of remedial actions consider the use of condition monitoring equipment, in line with the predictive approach. The FMECA further covers scenarios where the RPN’s could not be sufficiently reduced with monitoring equipment and as such, different remedial actions and maintenance approaches were considered. The combination of maintenance strategies in an operational environment aligns to the notions of an RCM approach.

This FMECA process aligns to the research conducted by Alsyouf, El-dogdog, Kumar and Ojha (27,69,77,79) in determining failure modes and remedial actions (27,69,77,79). The Weibull review had shown that the components in the port are undergoing failures at differing rates and this, in the researchers view, could also point to the components requiring different maintenance approaches to meet and extend their operational life. This further ties into the principles of an RCM strategy. The respondents of the MCA questionnaire had ranked the top two strategies, PdM and RCM, with a difference of only 2%. This suggests that a possible combination of these two strategies could reap greater benefits. RCM applies a combination of RM, PM and PdM strategies in its approach. All of the respondents in the first questionnaire believe that a maintenance strategy that uses a combination of reactive, preventive and predictive maintenance based on the part/component and the consequences of its failure is best suited to conveyor belts, which points toward an RCM approach.

Based on the research analysis results from the FMECA, Weibull, Fishbone Diagram, and The Five Whys, supported by the MCA survey results, serious consideration must be given to a combination of the strategies with predictive maintenance taking a dominant position in the approach. Areas in the conveyor routes that are not prone to secondary damages and operational impact may consider the other maintenance approaches, i.e. RM and/or PM. A combination of strategies appears to be the effective approach as different components on the conveyor belts possess different operational characteristics, maintenance procedures and design lives which are highly likely to prompt different strategies. This is supported by the results from the Weibull analysis in showing varying failure rates for different components. The use of a combination of strategies is not widely covered in the port but has been implemented in various other industries. This is further supported by the previous research conducted by Alsyouf, Deshpande, Vishnu and Yuan (11,14,30,69) who have concluded that varying system components require independent actions in order to improve overall performance (11,14,30,69).

The costs associated with the maintenance optimisation strategies are excessive and thus, where possible, adaptations should be made in order to ensure a tailored fit to conveyors in the PORB. This is similar to the research conducted by Alsyouf, Deshpande, Vishnu and Yuan (11,14,30,69). The researcher believes a modified form of RCM would provide the most benefit to conveyor routes in the PORB and not result in wasteful expenditure. The modified form must be adapted to the equipment and maintenance requirements of conveyors and ensure predictive principles are dominant within the maintenance strategy through the use of robust condition monitoring devices. The implementation of monitoring equipment on all conveyor routes and components in the port would require a cost and breakeven analysis, prior to any implementation, to ensure a return on investment. The predictive only maintenance approach would require monitoring equipment to be installed on approximately all 40 conveyor belts. But through the use and implementation of RCM, the number of condition monitoring equipment could be reduced, as areas of high concern are prioritised and areas where risk cannot be reduced, even with monitoring, are filtered through on the RCM FMECA table. This will theoretically reduce expenditure as these areas will require a different maintenance approach to PdM. This further supports the principles of RCM by utilising a combination of maintenance strategies.

The principles of RCM recognise the variations in equipment and components within a plant and that each equipment or component possesses a varying level of importance guided by their application, failure effects and potential consequential damages. This provides a superior advantage to maintenance management in prioritising maintenance efforts and actions to critical components and areas within the plant. This approach aims to address the fundamental causes of system (equipment and components) failure whilst also ensuring adequate controls and monitoring are in place to envisage, circumvent or alleviate any possible failures which in turn will reduce business, reputational and financial impacts.

RCM is a relatively new development within the maintenance strategy area that considers the pros from traditional maintenance techniques in its approach. Particularly, RCM adopts the strategy or strategies that are highly suited to the equipment or component based on the equipment's' criticality score together with the industry or plant it is operating in. Previous studies indicate that the implementation of RCM entails historical data collection and analysis to establish requires the collection and analysis of historical failure and maintenance data to establish status quo conditions of the plant and equipment (14,77). The researcher has followed a similar approach with the data in the form of the actual conveyor failure data, maintenance schedules and survey questionnaires developed and presented in this study. The survey questionnaires should be conducted by attempting to gain responses and answers from key experts within the maintenance and operations departments (20) which this study had done through the use of survey questionnaires and communication with maintenance personnel.

Carretero (20) stated in his study on maintenance strategy selection and applying RCM to large scale industries, that RCM is considered as one of the most prominent strategies utilised to maintain high levels of operational efficiency in crucial industries such as power generation plants, weapons industries, aircrafts, rail systems, oil and gas plants and ship building and repair industries (20). Considering the outputs from the research methods and failure tools conducted in this project, together with the literature, the researcher believes the RCM approach is most suited to conveyor belt systems and will provide the most benefit to conveyor systems. It will have lasting benefits such as a possible increase in the lifespan of equipment, decrease in unplanned maintenance costs and delivery of effective and modern monitoring reports with better knowledge on the behaviour of the conveyor routes and its associated equipment.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The overall objective of this study is to analyse and determine the most suitable maintenance strategy, principles and procedures that can be applied to conveyor systems in the PORB.

One of the first objectives of the study was to identify, examine and analyse the existing maintenance strategies within the port and its impact on the business. This was first achieved through obtaining the relevant site data regarding the failures as well as the first survey questionnaire sent to maintenance personnel. The review of the failure data through the Pareto principle and analysing the data had shown the impact the failures had on achieving planned tonnage targets.

The researcher has determined that there are misconceptions by staff regarding maintenance activities on conveyor equipment in the port which could be due to lack of refresher training. It was also established that the existing maintenance strategies are ineffective in ensuring uptime of equipment and as a result there are increased failures which result in lost revenue as through the analysis methods and tools, it was shown that planned targets are rarely achieved due to downtime from conveyor failures. The research has shown that the export routes (particularly berths 703, 704, 801) account for majority of all failures experienced on conveyor routes in the port which can be attributed to increased loading rates required to meet higher targets as well as the change in cargoes without any detailed calculations to verify the capabilities of the existing infrastructure.

The analysis of the failure data and maintenance schedules has highlighted the impact that the national lockdown due to the COVID-19 pandemic has had on the conveyor routes to berth 703, 704 and 801. The data had shown that the routes to berth 704 had been over-utilised during its normal operations due to the increased failures and downtime of the conveyors, with the optimal use being highlighted during the lockdown periods with increased uptime with minimal breakdowns. The analysis of the data had also highlighted the impact to berths 703 and 801 with both berths showing an over-utilisation in both normal and lockdown operations which require further investigations to determine the underlying issues.

The second objective of this study was to identify whether a new maintenance strategy/strategies or a change in maintenance approach is needed at the PORB. This was achieved through the analysis of the failure data in showing the relation of downtime and tonnages to the failures that occurred. It was further accomplished through the use of failure analysis tools such as the FMECA, Weibull, Fishbone diagram and The Five Whys.

It has been found that the conveyor components are failing randomly and prematurely which is unusual for the type of component and application and points to the infrastructure not being able to cope with the variance in cargoes. It could also indicate that the equipment and routes need a refurbishment or replacement as it may have surpassed its operating life. This will require further investigations to identify root causes and to establish whether frequent maintenance tasks to extend the life of the equipment outweigh the cost of a refurbishment or replacement of the equipment over the period of its life, i.e. a positive return on investment.

The Five Whys and Fishbone diagram have indicated that overloading is a common cause of the failures. This overloading is attributed to two factors, actual belt being overloaded beyond the allowable belt fill to meet targets and overloading as a result of the change in cargoes which the infrastructure is unable to support. The FMECA has shown that condition monitoring can theoretically increase detection probability which in turn reduces failure occurrences. The condition monitoring equipment also carry additional capital and maintenance costs which must be factored in when introducing any new strategy or approach.

The third objective of this research study was to identify possible alternative maintenance strategies. This was achieved through the literature review on existing maintenance strategies and previous research that had conducted similar studies in selecting maintenance strategies. The failure analysis methods (Five Whys, Ishikawa, and Pareto) support the outputs from the FMECA in using condition monitoring equipment to reduce failure occurrences which in turn will reduce secondary damages. The use of an optimised strategy will reduce failure effects in the port, particularly the use of RCM with an inclination toward predictive maintenance.

The final objective of this research project was to provide recommendations on the most suitable maintenance strategy/strategies for the conveyors in the PORB. The recommended strategy concluded from the research study is an RCM approach with a heavy bias toward predictive maintenance as this has proved the single best option from the MCA in support of the results from the other analysis methods. The RCM considers combination of the strategies based on the component type and failure effects and consequences which is similar to the results found in a study conducted by Yuan (30) on a blast furnace conveyor where the paper presents a reliability simulation to evaluate and compare different maintenance strategies, with the study concluding that maintenance conducted on individual components based on its own characteristics improves reliability and performance, which points to a tailored approach to maintenance, i.e. RCM (30). This was also similar to the study conducted by Vishnu (14) on a titanium oxide plant where the plant had shown signs of following a combination of planned and reactive maintenance strategies with the implementation of RCM being justified through simulation results which indicated poor availability and performance of equipment with the existing maintenance approach (14).

6.2 Recommendations for Future Work

Based on the findings of this research, the following future work is recommended.

Investigate belting failures: The belts on routes to berths 703, 704 and 801 are failing frequently and prematurely which is contradictory to its design premise and operating life. As such, a thorough review or investigation needs to be conducted in order to uncover the core reasons for these failures.

Review conveyor design: An investigation into the conveyor design must be conducted to verify its capabilities of transferring the heavier density cargoes successfully as the routes that experienced the majority of failures are those that convey the heavier density cargoes. A design review is required to establish the conveyor throughput capacity in order to understand the conveyors maximum rated utilisation capabilities. This will prove pivotal in minimising failures by ensuring the capacity is not exceeded and therefore may improve the uptime of conveyors in the port.

Failure tracking and monitoring: The tracking and monitoring of failures, tools and resources used during repairs requires improvement in order to correctly assess the impacts the asset has to the business. A tracking management tool should be implemented to improve the traceability of the failure type attended to, the location of the failure and the resources or tools that are used to rectify the failure. Accurate tracking provides a transparent view of the resources and associated costs needed to maintain the plant and could improve the overall uptime of the conveyor system.

Implement booking system: The process for booking out of tools to conduct repairs is to be reviewed and adjusted to ensure stricter compliance to the protocols and rules. This should correlate to the above recommendation of implementing a tracking management tool.

Training of staff: The training of staff regarding maintenance procedures, tools and processes must be conducted annually. Refresher training needs to be conducted should the management and supervisory team notice a decline in the standards of work.

Management involvement: Monthly meetings with management must be implemented in order to report progress of maintenance tasks, maintenance issues and challenges. This will ensure that maintenance is given sufficient attention whilst also creating a clear and transparent line of accountability. This will also incite involvement of senior management to expedite solutions to challenges or difficulties that may be encountered in maintaining the plant.

Material testing: An investigation into the materials conveyed at the port is required as the conveyors that experienced majority of the failures were those that conveyed the heavier density cargoes. Material testing is to be done on any new or changed cargoes prior to it being conveyed on any routes in order to ensure that the conveyor belt is capable of transporting the new product. Material testing will also provide an insight into the changes required on conveyor belts to successfully convey the new cargo.

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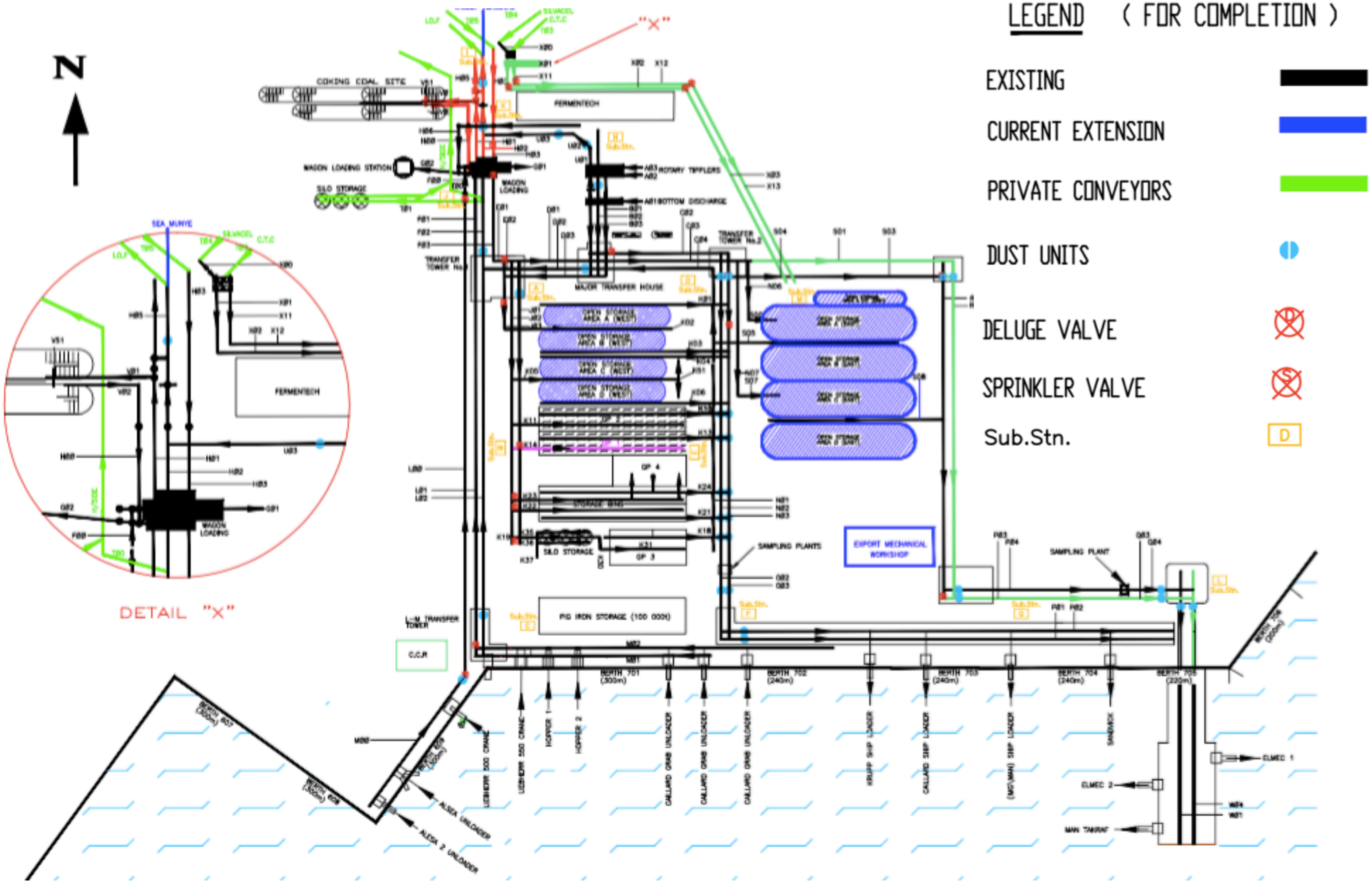
APPENDICES

A. APPENDIX A: CONVEYOR LAYOUT PORB



B. APPENDIX B: CONVEYOR FAILURE DATA

B1 Conveyor failure data received from PORB

DATE	DESCRIPTION	Actual Time (Minutes)	BERTH	SECTION	Product 1	Product 2
2/25/19	MECHANIC WORKING ON CHAIN CONVEYOR	10	609	Import	Magnetite	Chrome
12/9/19	INSPECTING CHAIN CONVEYOR	10	609	Import	Magnetite	Chrome
2/14/19	CHECKING CHAIN CONVEYOR	10	609	Import	Alumina	Petcoke
2/14/19	CHAIN CONVEYOR STUCK	10	609	Import	Alumina	Petcoke
11/13/19	CHAIN CONVEYOR NOT STARTING	10	609	Import	Alumina	Petcoke
12/24/19	CLEANING CHAIN CONVEYOR / REPAIR CHAIN LINK	210	609	Import	Alumina	Petcoke
12/26/19	CHAIN CONVEYOR THERMAL OVERLOAD	55	609	Import	Alumina	Petcoke
12/30/19	MECH BUSY WITH CONVEYOR CHAIN	10	609	Import	Alumina	Petcoke
1/6/20	REPAIRING CHAIN CONVEYOR	10	609	Import	Alumina	Petcoke
2/15/20	INSPECTING A2 CHAIN CONVEYOR	130	609	Import	Alumina	Petcoke
2/16/20	INSPECTING A2 CHAIN CONVEYOR	40	609	Import	Alumina	Petcoke
2/16/20	CLEANING A2 CHAIN CONVEYOR	35	609	Import	Alumina	Petcoke
2/22/20	Mechanical busy on the chain conveyor	15	609	Import	Alumina	Petcoke
3/4/20	CHAIN CONVEYOR THERMAL TRIP	65	609	Import	Alumina	Petcoke
3/2/20	CHAIN CONVEYOR TRIPPED	40	609	Import	Alumina	Petcoke
4/26/20	chain conveyor tripped	15	609	Import	Alumina	Petcoke
8/29/19	FIRE NEARMISS AT M01 CONVEYOR	35	701	Import	Magnetite	Coal
1/8/19	M02 conveyor running skew	20	702	Import	Coal	Sulphur
1/9/19	M02 conveyor running skew	20	702	Import	Coal	Sulphur
2/6/19	L02 CONVEYOR SNAPPED	405	702	Import	Coal	Sulphur
3/20/19	F01 CONVEYOR SNAPPED	1440	702	Import	Coal	Sulphur
3/19/19	F01 CONVEYOR SNAPPED	255	702	Import	Coal	Sulphur
3/21/19	F01 CONVEYOR SNAPPED	105	702	Import	Coal	Sulphur
11/21/19	M02 CONVEYOR CUT	35	702	Import	Coal	Sulphur
5/7/20	TESTING F01 CONVEYOR SPEED SWITCH	20	702	Import	Coal	Sulphur
12/19/18	K10 SPEEDSWITCH DUE TO CARGO ON RETURN CONVEYOR	45	703	Export	Magnetite	Chrome
1/4/19	H03 conveyor booked out by mech	50	703	Export	Magnetite	Chrome
1/7/19	repair splice on E01 conveyor	220	703	Export	Magnetite	Chrome
2/24/19	SPLICE ON CAILLARD BOOM CONVEYOR	120	703	Export	Magnetite	Chrome
2/27/19	CHANGED ROLLER ON BOOM CONVEYOR	20	703	Export	Magnetite	Chrome
4/17/19	CUTTING FLAP ON K10 CONVEYOR	10	703	Export	Magnetite	Chrome
5/14/19	HT WORK OVER P01 CONVEYOR (CAILARD CABLE)	35	703	Export	Magnetite	Chrome
5/30/19	S05 CONVEYOR RUNNING SKEW	25	703	Export	Magnetite	Chrome
6/4/19	ERRECTING SCAFFOLDING OVER P01 CONVEYOR	65	703	Export	Magnetite	Chrome
6/20/19	BOOM CONVEYOR RUNNING SKEW	30	703	Export	Magnetite	Chrome
7/18/19	REPAIR S05 HOPPER CONVEYOR	210	703	Export	Magnetite	Chrome
7/18/19	MANUAL TRIP ON N01 CONVEYOR	130	703	Export	Magnetite	Chrome
7/18/19	INSPECTING S05 HOPPER CONVEYOR FOR DAMAGE	30	703	Export	Magnetite	Chrome
7/20/19	CUT FLAP ON O03 CONVEYOR	15	703	Export	Magnetite	Chrome
7/18/19	CUT FLAP ON O03 CONVEYOR	10	703	Export	Magnetite	Chrome
8/6/19	BOOM CONVEYOR RUNNING SKEW	175	703	Export	Magnetite	Chrome
8/5/19	BOOM CONVEYOR RUNNING SKEW	75	703	Export	Magnetite	Chrome
9/6/19	N03 CONVEYOR OVERLOADED	265	703	Export	Magnetite	Chrome
9/16/19	F03 CONVEYOR SNAPPED	425	703	Export	Magnetite	Chrome
10/6/19	CHANGED ROLLER ON BOOM CONVEYOR	45	703	Export	Magnetite	Chrome
10/23/19	BOOM CONVEYOR RUNNING SKEW	55	703	Export	Magnetite	Chrome
11/10/19	NO LONG TRAVEL - LOUVRE DOOR FELL ONTO CONVEYOR	70	703	Export	Magnetite	Chrome
11/11/19	CHANGED ROLLER ON BOOM CONVEYOR	35	703	Export	Magnetite	Chrome
11/17/19	CHANGED ROLLER ON BOOM CONVEYOR	15	703	Export	Magnetite	Chrome
12/14/19	K24 CONVEYOR NOT STARTING	205	703	Export	Magnetite	Chrome
12/14/19	CHANGED ROLLER ON BOOM CONVEYOR	45	703	Export	Magnetite	Chrome
1/14/20	REMOVED BRACKET BY P01 CONVEYOR	45	703	Export	Magnetite	Chrome
1/24/20	BOOM CONVEYOR DRIVE FAULT	330	703	Export	Magnetite	Chrome
2/24/20	LOADER CONVEYOR RUN SKEW	105	703	Export	Magnetite	Chrome
3/20/20	MECHANICAL CHECKING SPLICE ON O2 CONVEYOR	10	703	Export	Magnetite	Chrome
4/24/20	O02 conveyor running skew	40	703	Export	Magnetite	Chrome
1/17/19	K21 PLOUGH AND CONVEYOR NOT STARTING	70	704	Export	Magnetite	Chrome
2/5/19	SPLICE REPAIR ON BOOM CONVEYOR	160	704	Export	Magnetite	Chrome
2/6/19	CLEANING BY K01 CONVEYOR	125	704	Export	Magnetite	Chrome
2/5/19	CHECKING SPLICE ON BOOM CONVEYOR	20	704	Export	Magnetite	Chrome
2/9/19	CHANGED SKIRTING RUBBER BY IMG BOOM CONVEYOR	15	704	Export	Magnetite	Chrome
3/4/19	SPLICE ON IMG MANN BOOM CONVEYOR	530	704	Export	Magnetite	Chrome
3/5/19	SPLICE ON IMG MANN BOOM CONVEYOR	360	704	Export	Magnetite	Chrome
4/11/19	STANDBY - AWAITING PLUMBER WORKING UNDER P02 CONVEYOR	100	704	Export	Magnetite	Chrome
4/12/19	STANDBY - AWAITING PLUMBER WORKING UNDER P02 CONVEYOR	100	704	Export	Magnetite	Chrome
4/9/19	CHANGED ROLLERS BY BOOM CONVEYOR	90	704	Export	Magnetite	Chrome
4/9/19	CONVEYOR TRIPPED - SUBSTATION FAULT	45	704	Export	Magnetite	Chrome
4/9/19	CUT FLAP ON BOOM CONVEYOR	5	704	Export	Magnetite	Chrome
4/21/19	CHANGED ROLLER BY BOOM CONVEYOR	70	704	Export	Magnetite	Chrome
5/6/19	BOOM CONVEYOR NOT STARTING	20	704	Export	Magnetite	Chrome
6/12/19	S05 CONVEYOR FLIPPED	480	704	Export	Magnetite	Chrome
6/13/19	S05 CONVEYOR FLIPPED	75	704	Export	Magnetite	Chrome
6/14/19	INSPECTING CUT ON S05 CONVEYOR	10	704	Export	Magnetite	Chrome
7/7/19	CHANGED ROLLER BY BOOM CONVEYOR	10	704	Export	Magnetite	Chrome
8/4/19	BOOM CONVEYOR FAULT	25	704	Export	Magnetite	Chrome
8/20/19	WATER LEAK ON C03 CONVEYOR	40	704	Export	Magnetite	Chrome
9/21/19	F03 CONVEYOR FLIPPED	130	704	Export	Magnetite	Chrome
9/15/19	SPLICE ON BOOM CONVEYOR	85	704	Export	Magnetite	Chrome
9/25/19	F03 CONVEYOR FLIPPED	370	704	Export	Magnetite	Chrome
9/26/19	F03 CONVEYOR FLIPPED	340	704	Export	Magnetite	Chrome
10/13/19	CUT FLAP ON P02 CONVEYOR	20	704	Export	Magnetite	Chrome
11/10/19	BOOM CONVEYOR SPEEDSWITCH FAULT	50	704	Export	Magnetite	Chrome
12/10/19	CHANGED ROLLERS ON BOOM CONVEYOR	50	704	Export	Magnetite	Chrome
1/9/20	CHANGED ROLLER BY BOOM CONVEYOR	40	704	Export	Magnetite	Chrome
1/16/20	S05 CONVEYOR FLIPPED	35	704	Export	Magnetite	Chrome
1/30/20	F03 CONVEYOR SPEED SWITCH	70	704	Export	Magnetite	Chrome

2/25/20	S05 CONVEYOR SNAPPED	785	704	Export	Magnetite	Chrome
2/26/20	CHANGE ROLLER ON S05 CONVEYOR	15	704	Export	Magnetite	Chrome
3/2/20	LOADER CONVEYOR TRIPPED	15	704	Export	Magnetite	Chrome
3/12/20	REPAIR SPLICE ON LOADER BOOM CONVEYOR	200	704	Export	Magnetite	Chrome
4/1/20	P02 CONVEYOR TRIPPED	15	704	Export	Magnetite	Chrome
5/8/20	CHANGE ROLLER ON O3 CONVEYOR	40	704	Export	Magnetite	Chrome
1/4/19	Takraft boom conveyor run skew	30	801	Export	Magnetite	Chrome
1/14/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	205	801	Export	Magnetite	Chrome
1/15/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	170	801	Import	Magnetite	Chrome
1/29/19	P04 conveyor snapped	30	801	Export	Magnetite	Chrome
2/19/19	CHANGED ROLLER ON BOOM CONVEYOR	20	801	Export	Magnetite	Chrome
2/24/19	CHECKING SPLICE ON N01 CONVEYOR	25	801	Export	Magnetite	Chrome
3/5/19	K03 SPEEDSWITCH DUE TO SLACK ON CONVEYOR	205	801	Export	Magnetite	Chrome
3/10/19	CHANGED ROLLERS ON THE BOOM CONVEYOR	45	801	Import	Magnetite	Chrome
3/15/19	CHANGED ROLLERS ON BOOM CONVEYOR	45	801	Import	Magnetite	Chrome
4/19/19	CUT FLAP ON W01 CONVEYOR	40	801	Export	Magnetite	Chrome
6/15/19	REMOVED RUBBER FROM R01 CONVEYOR	15	801	Export	Magnetite	Chrome
7/16/19	CHANGED ROLLERS BY BOOM CONVEYOR	25	801	Export	Magnetite	Chrome
8/3/19	CUT FLAP ON W01 CONVEYOR	20	801	Export	Magnetite	Chrome
8/29/19	S08 CONVEYOR CUT	565	801	Export	Magnetite	Chrome
8/30/19	S08 CONVEYOR CUT	565	801	Export	Magnetite	Chrome
9/9/19	LOADER BOOM CONVEYOR BEARING COLLAPSED	640	801	Export	Magnetite	Chrome
9/8/19	LOADER BOOM CONVEYOR BEARING COLLAPSED	255	801	Export	Magnetite	Chrome
9/21/19	S03 CONVEYOR FLIPPED	1440	801	Export	Magnetite	Chrome
9/19/19	S03 CONVEYOR FLIPPED	740	801	Export	Magnetite	Chrome
9/20/19	S03 CONVEYOR FLIPPED	205	801	Export	Magnetite	Chrome
9/22/19	Q04 CONVEYOR SNAPPED	810	801	Export	Magnetite	Chrome
10/10/19	BOOM CONVEYOR SLIPPING	40	801	Export	Magnetite	Chrome
10/9/19	SPEEDSWITCH ON BOOM CONVEYOR	10	801	Export	Magnetite	Chrome
11/10/19	CHANGED ROLLER ON BOOM CONVEYOR	50	801	Export	Magnetite	Chrome
11/13/19	SPLICE ON BOOM CONVEYOR	260	801	Export	Magnetite	Chrome
12/17/19	BOOM CONVEYOR FAULTY	30	801	Export	Magnetite	Chrome
1/2/20	CUT ON K04 CONVEYOR	960	801	Export	Magnetite	Chrome
1/3/20	CUT ON K04 CONVEYOR	960	801	Export	Magnetite	Chrome
12/31/19	CUT ON K04 CONVEYOR	480	801	Export	Magnetite	Chrome
12/30/19	CUT ON K04 CONVEYOR	240	801	Export	Magnetite	Chrome
1/10/20	BOOM CONVEYOR TRIPPED	15	801	Export	Magnetite	Chrome
1/28/20	MECH INSPECTING METAL ON CONVEYOR	80	801	Export	Magnetite	Chrome
2/20/20	S03 CONVEYOR MELTED RUBBER COUPLING	355	801	Export	Magnetite	Chrome
2/24/20	CUT FLAP ON Q4 CONVEYOR	40	801	Export	Magnetite	Chrome
3/23/20	BOOM CONVEYOR VSD FAULT	35	801	Export	Magnetite	Chrome
4/7/20	K04 conveyor failed to stop	225	801	Export	Magnetite	Chrome
1/4/19	FUSABLE PLUG POPPED/Invisible thing stuck in cross conveyor	32	804	Export	Woodchips	
1/6/19	cross conveyor tripped	40	804	Export	Woodchips	
7/15/19	CROSS CONVEYOR BELY MISALIGNMENT	15	804	Export	Woodchips	
8/2/19	REPLACED CROSS CONVEYOR SKIRTING RUBBER	120	804	Export	Woodchips	
8/7/19	CROSS CONVEYOR SKIRTING RUBBER FAULTY	29	804	Export	Woodchips	
9/20/19	ADJUSTING SKIRTING RUBBER ON CROSS CONVEYOR	50	804	Export	Woodchips	
9/27/19	CROSS CONVEYOR TRIPPED	13	804	Export	Woodchips	
10/3/19	CROSS CONVEYOR TRIPPED	54	804	Export	Woodchips	
9/29/19	CROSS CONVEYOR TRIPPED	12	804	Export	Woodchips	
1/11/20	A01 STOPPED (GEARBOX COALLAPSED CONVEYOR NOT STARTING UP)	360	Bottom Discharge	Storage	Magnetite	Chloride
1/12/20	A01 CONVEYOR BREAKDOWN (GEARBOX COLLAPSED)	720	Bottom Discharge	Storage	Magnetite	Chloride
1/12/20	GEARBOX COLLAPSED - A01 CONVEYOR BOOKED OUT	720	Bottom Discharge	Storage	Magnetite	Chloride
3/23/20	J01 STOPPED, MOTOR TURNING CONVEYOR NOT RUNNING	510	Bottom Discharge	Storage	Magnetite	Chloride
3/25/20	J01 CONVEYOR TRIPPING ON SPEED SWITCH	155	Bottom Discharge	Storage	Magnetite	Chloride
5/19/20	D02 CONVEYOR OUT OF POSITION	55	Bottom Discharge	Storage	Magnetite	Chloride
4/17/19	B03 LOCAL POSITION ON C CONVEYOR	15	Botton Discharge	Storage	Magnetite	Chloride
11/18/19	A02 CONVEYOR TRIPPED	20	T1	Storage	Magnetite	Chrome
3/3/19	BOOM CONVEYOR SPEED SWITCH	30	Tippler 1	Storage	Magnetite	Chrome
5/6/19	B01 CONVEYOR STOPPED - PROBE FAULTY	75	Tippler 1	Storage	Magnetite	Chrome
5/28/19	START ROUTE -NO INDICATION OF BOOM CONVEYOR RUNNING	25	Tippler 1	Storage	Magnetite	Chrome
6/8/19	C03 CONVEYOR MISSED ALIGNMENT RUNNING SKEW	20	Tippler 1	Storage	Magnetite	Chrome
6/15/19	BOOM CONVEYOR NOT SLOWING AND LUFFING UP	40	Tippler 1	Storage	Magnetite	Chrome
8/31/19	A02 CONVEYOR ILLOGICAL POSITION	35	Tippler 1	Storage	Magnetite	Chrome
9/23/19	BOOM CONVEYOR IS SHOWING ELECTRICAL FAULT	15	Tippler 1	Storage	Magnetite	Chrome
9/23/19	BOOM CONVEYOR STOPPED WITH NO FAULT	10	Tippler 1	Storage	Magnetite	Chrome
12/14/19	K05 CONVEYOR NOT STARTING UP	185	Tippler 1	Storage	Magnetite	Chrome
12/14/19	J01 CONVEYOR NOT STARING	120	Tippler 1	Storage	Magnetite	Chrome
12/22/19	BOOM CONVEYOR SPEEDSWITCH ELEC BUSY	20	Tippler 1	Storage	Magnetite	Chrome
2/25/20	BOOM CONVEYOR NOT STARTING	195	Tippler 1	Storage	Magnetite	Chrome
3/26/20	BOON CONVEYOR NOT LUFFING UP	20	Tippler 1	Storage	Magnetite	Chrome
4/2/20	BOOM CONVEYOR TRIPPED	90	Tippler 1	Storage	Magnetite	Chrome
5/18/20	STARTIGN CONVEYOR - D02 ILLOGICAL	90	Tippler 1	Storage	Magnetite	Chrome
1/21/19	MECH CUT FLAP ON N06 CONVEYOR	30	Tippler 2	Storage	Magnetite	Chrome
1/24/19	CUTTING FLAP AT C02 CONVEYOR	5	Tippler 2	Storage	Magnetite	Chrome
1/27/19	CHANGING C02 CONVEYOR CENTRE ROLLER	5	Tippler 2	Storage	Magnetite	Chrome
2/24/19	C02 CONVEYOR SNAPPED	180	Tippler 2	Storage	Magnetite	Chrome
4/23/19	C02 CONVEYOR SHOWING MULTIBLE INDICATION	50	Tippler 2	Storage	Magnetite	Chrome
6/23/19	MECH CHANGING ROLLER ON C02 CONVEYOR	15	Tippler 2	Storage	Magnetite	Chrome
8/19/19	MECH TENSIONING A03 CONVEYOR	30	Tippler 2	Storage	Magnetite	Chrome
1/8/20	C02 CONVEYOR SNAPPED	180	Tippler 2	Storage	Magnetite	Chrome
1/8/20	C03 CONVEYOR NOT TRAVELLING	45	Tippler 2	Storage	Magnetite	Chrome
2/16/20	CONTRACT PASSING LINE EMPTY SIDE TO A02 CONVEYOR	30	Tippler 2	Storage	Magnetite	Chrome
3/23/20	C02 CONVEYOR SPLICE	240	Tippler 2	Storage	Magnetite	Chrome
4/11/20	CHANGING ROLLER ON B02 CONVEYOR	10	Tippler 2	Storage	Magnetite	Chrome
5/6/20	BOOM CONVEYOR BEARING FAIL	385	Tippler 2	Storage	Magnetite	Chrome
5/5/20	STACKER BOOMBELT CONVEYOR BEARING COLLAPSED	240	Tippler 2	Storage	Magnetite	Chrome

B2 Conveyor failure data per component

Table B.1: Filtered Conveyor failure Data

Failure type	No. of Failures
Belt Failure	53
Drive Failure	26
Idler Roller Failure	20
Maintenance	19
Chain Conveyor Failure	16
Conveyor Misalignment	15
Conveyor Tripped	9
Speed Switch Failure	9
Bearing/Coupling Failure	7

B3 Planned versus Achieved Tonnages

Table B.2: Summarised Planned vs Actual tonnages for selected berths

Month	**703 Actual**	**703 Planned**	**704 Actual**	**704 Planned**	**801 Actual**	**801 Planned**
Dec-18	28000	215000	53200	151530	85000	294816
Jan-19	114550	131000		241667	91500	158899
Feb-19	90000	266550	107300	178400	80000	251500
Mar-19	26680	174600	10000	300100	90000	250000
Apr-19	0	166170	109100	228500	0	71485
May-19	20000	130000	35000	52400	80000	330000
Jun-19	0	20000	90000	127300	0	170000
Jul-19	0	0	70000	95000	80000	100000
Aug-19	35000	0	329842	0	55000	0
Sep-19	0	223670	131000	462747	90680	176500
Oct-19	0	240775	180300	395875	19300	355300

Nov-19	85000	200400	110000	230850	160630	379000
Dec-19	154000	247510	64097	298832	30000	279165
Jan-20	75300	339672	67000	357054	0	286480
Feb-20	58000	344800	0	112600	0	179000
Mar-20	100000	293000	206000	140000	88000	197882
Apr-20	0	60800	60000	210000	0	43500
May-20	50500	86170	160000	183145	0	30000
Total	**837030**	**3140117**	**1782839**	**3766000**	**950110**	**3553527**

C. APPENDIX C: DETAILED FMECA TABLE

Component	Process Function/Equipm	Functional Failure	Failure Mode	Effects of Failure	Severity	Possible Causes	Probability of Occurrence	Detection Probability	RPN	Design Action	Responsible person	Seve	Probability of Occurrence3	Detection Probability	RPN4
Drive System															
Electric Motor	Create power in the form a rotating movement	Unable to rotate or insufficient rotating speed	Conveyor not starting	Cargo spillage, Belt flip, Belt snap, Idler roll damage	6	Power outage, Control failure, Belt overloaded	5	3	90	Maintenance staff to introduce back-up power supplies, Design check on drive size to start under full load, Regular inspection and maintenance on control infrastructure	Maintenance staff, Design team	6	5	3	90
			Conveyor tripped	Motor won't run, sparking at brushes, spillages	5	Excessively high temperature, conveyor overloaded, belt drift, tripwire activated,	5	7	175	Install thermocouples or resistance temperature detectors (RTDs) to monitor temperature, Design team to ensure motor adequately sized for load, belt shape monitoring, install belt weighmeters or scales to monitor and control loading	Maintenance staff, Design team	5	5	3	75
Gearbox	Gearing the rotating movement to another angular speed and torque and transferring the power	Unable to transfer Power from Electric motor to Pulley/Moving head	Pitting, Root fillet cracking, Tooth shear	Tooth surface damage, Surface contact fatigue and tooth failure	4	Cyclic contact stress, local areas of high stress due to uneven surfaces on the gear tooth, Tooth bending fatigue, fracture	5	8	160	Introduce continuous vibration and oil monitoring devices, ensure proper lubrication procedure and levels, introduce training to inexperienced staff	Maintenance Staff, Management	4	5	5	100
			Scuffing	Wear and eventual tooth failure	3	Lubrication breakdown	6	7	126	Install level monitors and switches for lubrication levels, ensure proper training and lubrication procedure is followed, introduce finite measures and tools for lubrication quanitities	Maintenance Staff, Management	3	5	5	75
			Plastic deformation	Surface damage resulting in vibration, noise and eventual failure	4	Loading and surface yielding	4	8	128	Introduce continuous vibration monitoring devices	Maintenance Staff, Management	4	3	5	60
			Spalling , Tooth bending fatigue, contact fatigue, thermal fatigue	Mating surface deterioration, welding, galling, eventual tooth failure	4	Fatigue , Incorrect heat treatment	4	8	128	Introduce continuous vibration and oil monitoring devices, ensure proper lubrication procedure and levels, introduce training to inexperienced staff	Maintenance Staff, Management	3	3	5	45
			Abrasive wear	Tooth scoring, eventual gear vibration, noise	3	Contaminants in the gear mesh area or lubrication system due to spillages, overlubrication	6	7	126	Introduce continuous vibration monitoring devices, maintenance staff to ensure cleanliness in areas of concern, Install level monitors and switches for lubrication levels, introduce finite measures and tools for lubrication quantities	Maintenance Staff, Management	3	6	5	90
Coupling	To transmit power, accommodate misalignment and compensate for axial movement (end movement of shafts)	Not being able to transfer the power	Coupling failure	Material spillage, chute blockage, drive failure, conveyor trip	4	Improper selection; improper, inadequate, or insufficient lubrication; excessive speeds or loads	5	8	160	Temperature sensors, vibration monitoring, oil analysis, install belt weighmeters or scales to monitor and control loading	Maintenance Staff, Management	4	5	5	100

Belting															
Top Cover	To protect carcass	Worn so that protecting the inner structure isn't sufficient anymore	Belt flap, edge buckling	Belt tracking incorrectly, material spillage,	6	Overoaded belt, idler not changed/monitored, belt misaligned, Bad belt training causing belt to miss track and run into steelwork, Belt radius incorrect causing over stressing of belt edge.	4	5	120	Belt shape monitoring devices, Check loading is centralised. Realign belt empty and loaded, Install additional idlers in vertical convex curves, Belt shape monitoring devices, Belt drift switches to be calibrated, install belt weighmeters or scales to monitor and control loading	Maintenance staff, Design team	6	4	3	72
Top Cover	To protect carcass	Worn so that protecting the inner structure isn't sufficient anymore	Belt flip	Belt tracking incorrectly, material spillage,	6	Belt misaligned, load not centralised, dislodged idler, belt drift switch failure	6	5	180	Belt shape monitoring devices, Belt drift switches ar critical points and redundancy, install belt weighmeters or scales to monitor and control loading	Maintenance Staf	6	6	3	108
Top Cover	To protect carcass	Worn so that protecting the inner structure isn't sufficient anymore	Excessive belt sag between idlers	Increased belt wear, belt snap, material spillage,	6	Take up tensions too low, Idler spacing too high, Erratic loading of belt causing high load points.	3	6	108	Recheck conveyor design (Idler spacing, take-up mass, system tension), Monitor feed and deflector plate adjustments, install belt weighmeters or scales to monitor and control loading, Install Vibratory devices to prevent high load "bubbles"	Maintenance Staff, Design team and Management	6	3	5	90
Top Cover	To protect carcass	Worn so that protecting the inner structure isn't sufficient anymore	Belt miss tracking	Excess belt edge wear, Belt snap	6	Idler frames misaligned and not level, Load not central, overloaded, Idler rolls seized, splice not central, excessive number of splices	7	3	126	Adjust frames, replace seized rolls, calibrate belt drift switches and introduce redundancy, Ensure number of splices in line with Industry norm, monitor belt feed, install belt weighmeters or scales to monitor and control loading	Maintenance Staff	6	7	2	84
Top Cover	To protect carcass	Worn so that protecting the inner structure isn't sufficient anymore	Belt overload	Material Spillage, Belt mistracking, Increased idler loads, increased belt wear	4	Chute Failure, Operator error, Speedswitch failure, Design capacity of idler set exceeded.	8	4	128	Reduce feed rate or increase belt speed, Blocked chute detection, install belt weighmeters or scales to monitor and control loading	Maintenance and Operations Staff	4	8	2	64
Carcass	Absorb forces and tension in system	Unable to hold tension since ripped	Belt snap	Material spillage, take-up trolley and counterweight damage, personnel injury/fatality,	10	Foreign objects on belt, hardened commodity on belt, inferior splice, overloaded, incorrect belt specification	6	8	480	Foreign object detection and magnet, Belt rip monitoring with "inverted" figure "8" antennae, Design verification for every change in cargo handled, install belt weighmeters or scales to monitor and control loading	Maintenance Staff, Design team and Management	10	5	3	150
Carcass	Absorb forces and tension in system	Unable to hold tension since ripped	Belt damage in centre	Material spillage, belt snap, centre roll failure	5	Belt pulled into nip point between rolls, Transitions incorrect.	7	7	245	Increase gauge length, introduce additional idlers and/or increase length of transition zones	Maintenance staff, Design team	5	7	7	245
Carcass	Absorb forces and tension in system	Unable to hold tension since ripped	Belt elongation	Material spillage, belt slip, belt tracking incorrectly,	2	Belt grade and class underspecified, Overstressed and overloaded belt, Too many splices on belt	4	10	80	Redesign and simulation of chute loading and belt class, Belt elongation monitoring device embedded in belt, Slip calculation in PLC controller, Ensure number of splices in line with Industry norm, install belt weighmeters or scales to monitor and control loading	Maintenance staff, Design team	2	4	2	16
Splice	To join and complete belt	Belt unable to complete loop	Splice failure	Material spillage, take-up trolley and counterweight damage, personnel injury/fatality,	10	Erratic loading, inferior splice quality and workmanship, Environmental conditions during splicing procedure	6	8	480	Belt elongation monitoring device embedded in belt, Belt rip monitoring with "inverted" figure "8" antennae, Management to introduce controls on appointment of splice contractors	Maintenance Staff, Management	10	6	3	180

Idlers															
Roll	Align, support and let the belt run with limited friction	Not being able to align, sup- port or let the belt run with limited friction	Roll Wear	Roll puncture, Excessive belt wear, belt rip,	2	Idler misaligned, contamination between belt and roll, idler set not sitting at right angles to belt. i.e. tilted.	6	8	96	Ensure roll is at right angles to direction of belt travel through regular inspections, Ensure belt is clean on contact surface.	Maintenance Staff	2	6	8	96
			Roll buckle and vibrating	Material spillage, belt mistracking, belt flap, belt wear, belt edge damage	2	Incorrect roll shell thickness, Excessive load on idler, Incorrect alignment between shaft, bearings and end cap.	5	8	80	Design check to verify idler sizes, reduce conveyor throughput. Increase belt speed, install belt weighmeters or scales to monitor and control loading	Maintenance Staff	2	5	5	50
Bearings	Let the shafts rotate with a maximum amount of friction	Worn so that friction is to high or completely broken	Idler seizure	Cargo spillage, Heat build-up, noisy	7	Material lodged between frame and roll, load on idler in excess of design load, impact of material on roll.	5	8	280	Introduce intermittent positional switches to ensure vertical tolerance are not too high, use infrared non-contact scanners, ultrasonic inspections, install temperature and vibration monitoring for bearings, install belt weighmeters or scales to monitor and control loading, Design check to verify idler sizes	Design Check to be done and applied by maintenance staff	7	4	3	84
			Reduced idler bearing life	Increased change in rolls, material spillage	6	Idler loads in excess of design loads, Idlers misaligned to belt, Belt tensions too low, Belt vibrating (flap)	5	8	240	Design verification, align idlers, verify and adjust belt tensions through take-up, install condition monitoring for bearings,install belt weighmeters or scales to monitor and control	Design Check to be done and applied by maintenance	6	4	3	72
General	To create smooth transfer from troughed shape to flat at head and tail ends	Ineffective transition from troughed to flat	Transition idler failure	Belt edge buckling, belt flap, material spillage	5	Excessive distance between idlers, Incorrect idler trough angle.	5	8	200	Install additional idlers to distribute load, Design verification of idler frames and angle	Design Team	5	2	8	80
	To join the idler roll to the shaft and bearings To provide resistance to loads	Unable to absorb loads	End cap/disk failure	Roll failure, belt damage, material spillage	7	Weld between roll and end cap being worn away by belt, End cap plate thickness incorrect.	5	8	280	Check idler alignment. Check load and idler pitch, temperature sensors, Design team to verify idler specification and size, install shaft vibration and speed monitoring	Maintenance staff, Design team	7	5	5	175
Pulleys															
Bearings	To change the direction of the belt in a conveyor system, to drive the belt, and to tension the belt, Let the shafts rotate with a maximum amount of friction	Worn so that friction is to high or completely broken	Bearing collapsed,	Cargo spillage, take-up failur	8	Excessively high loads, incorrect bearing size, incorrect mounting for bearing	4	8	256	Temperature monitoring, Vibration or frequency analysis, ensure SOP is followed, conduct regular refresher training, install belt weighmeters or scales to monitor and control loading	Maintenance Staf	8	4	3	96
			Bearing seized, Worn bearing, Bearing mount failure	Noisy Heat build-up	7	Poor lubrication, Contamination, Overloading, improper handling and storage, improper installation, misalignment, start/stop processes.	4	8	224	Temperature monitoring, Vibration or frequency analysis	Maintenance Staf	7	4	3	84
Shaft or Shell failure	Absorb forces and tensions experienced on the pulley shell and allows rotational movement	Unable to absorb loads or unable to rotate freely	Shaft break, shell rupture	Cargo spillage, belt flip, take-up damage	7	Overloaded, pulley misaligned creating uneven moment and torsion, incorrect pulley size and specification,	4	8	224	Install shaft vibration and speed monitoring, design verification on pulley shell and shaft sizes	Maintenance Staff, Design team	7	4	5	140
End Disk Failure	To join the pulley shell to the shaft and provide resistance to loads	Unable to absorb loads	End disk break	Cargo spillage, belt flip, take-up damage	7	Overloaded, pulley misaligned creating uneven moment and torsion, incorrect pulley size and specification, Inferior weld between end disc and shaft	4	8	224	Ensure pulleys are supplied with relevant certificates for welds and heat treatment, Manual inspection by certified Welding Inspector	Maintenance Staff	7	4	8	224

Take-up															
Take up mechanism	Apply tension on the pulley, Take up enough of the belt to keep sufficient tension in the belt for operation.	Not applying sufficient tension on the pulley, Not being able to keep sufficient tension in the belt	Take-up trolley, counterweight or winch failure	Personnel injury/fatality, belt elongation or snap, structural damage, cargo spillage	10	Mounting platforms for winch incorrect, trolley sheave arrangement incorrect, Misalignment between trolley and winch, insufficient travel on trolley,	3	9	270	Position encoder to monitor take-up movement within allowed limits, limit switches on take-up travel limit/end, Belt rip detection interlocked with e-stop	Maintenance staff, Design team	10	3	3	90
Take up Wire rope	To connect the counterweight and winch to the trolley via sheaves	Unable to provide tension to the conveyor belt	Breakage, Fatigue failure	Cargo spillage, Personnel injury, structural damage	10	Abrupt starts, sudden stops exceeding dead weight load, Sharp bending around sheave, vibrational fatigue, installation error, loss of lubricant	2	10	200	Design verification and appropriate rope specification to withstand loads, robustness factored into rope design and selection. Take-up error to be guarded appropriately and work to be carried out only when conveyor belt is locked out for maintenance.	Design Team	10	2	10	200

D. APPENDIX D: WEIBULL RESULTS

D1 Speed switch failure

Table D.1: Speed switch failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
12/18/18	Chrome loading	3360	S
12/19/18	K10 SPEEDSWITCH DUE TO CARGO ON RETURN CONVEYOR	45	F
3/4/19	Route cleaning	60	S
3/5/19	K03 SPEEDSWITCH DUE TO SLACK ON CONVEYOR	205	F
10/8/19	Pre-ship	60	S
10/9/19	SPEEDSWITCH ON BOOM CONVEYOR	10	F
11/9/19	Chrome loading	3600	S
11/10/19	BOOM CONVEYOR SPEEDSWITCH FAULT	50	F
1/29/20	Pre-ship	60	S
1/30/20	F03 CONVEYOR SPEED SWITCH	70	F

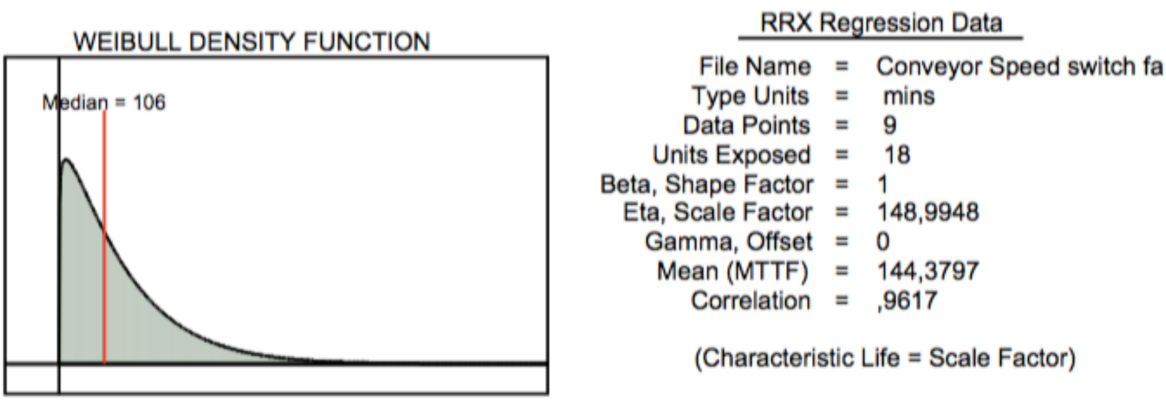


Figure D.1: Weibull Density Function and Regression Data for speed switch failure

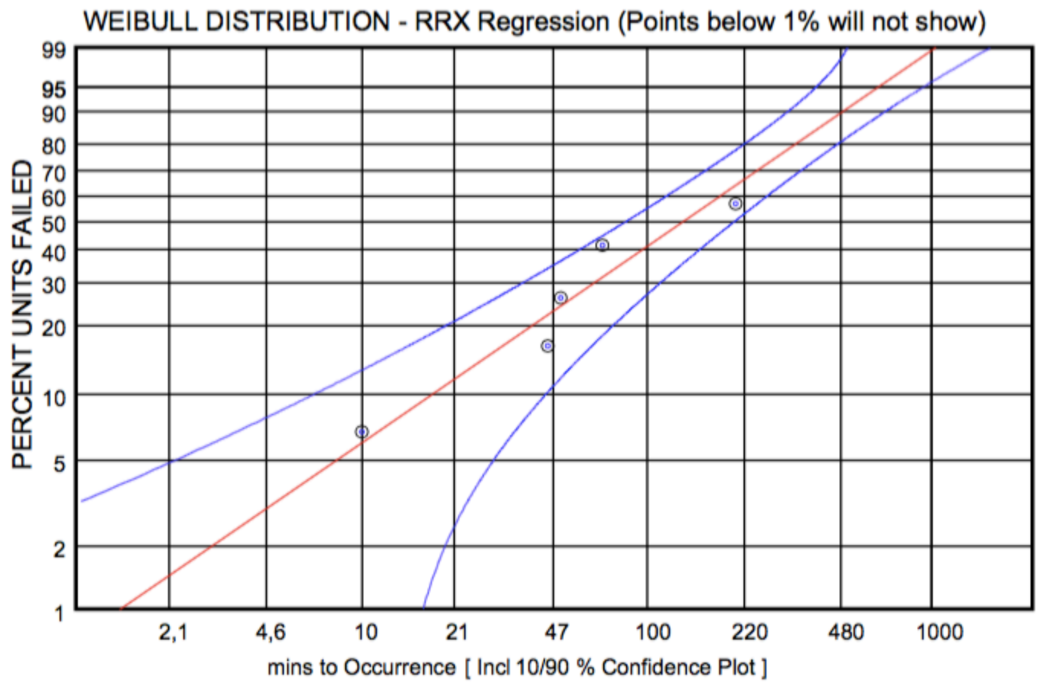


Figure D.2: Weibull distribution for failure and suspension of the conveyor speed switch

Based on the results presented in Figure D.1 and Figure D.2, the following can be deduced:

Beta Value

The results of the Weibull analysis for speed switches indicate a beta of 1 that could imply that the failure pattern the speed switches on the selected routes are random, implying a constant failure rate. The correlation of the regression is reasonable at 96.71% and based on that, the beta value could be less to 1 which would imply infant mortality.

Gamma Value

From the report output in Figure D.1, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 145 minutes, which implies that a failure/replacement of the speed switch should be expected every 2.5 hours during operations on the selected berths unless the root cause of the failure is resolved. This MTTF is low compared to the expected lifespan of component critical for the operation of the conveyor.

Eta Value - Characteristic Life

The characteristic life of the speed switch can be determined from the value deduced from the value of Eta, which indicates the time it would take for the speed switch failure to be triggered. Eta was found to be 149 minutes.

D2 Conveyor unplanned maintenance actions

Table D.2: Unplanned maintenance data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
1/3/19	Pre-ship	60	S
1/4/19	H03 conveyor booked out by mech	50	F
1/13/19	Magnetite loading	2400	F
1/14/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	205	F
1/14/19	Magnetite loading	960	S
1/15/19	FIXING E-STOP AND MANUAL TRIPS ON Q04 CONVEYOR	170	F
2/4/19	Chrome loading	2400	S
2/5/19	CHECKING SPLICE ON BOOM CONVEYOR	20	F
2/5/19	Cleaning	60	S
2/6/19	CLEANING BY K01 CONVEYOR	125	S
2/23/19	Clean running	60	S
2/24/19	CHECKING SPLICE ON N01 CONVEYOR	25	F
4/10/19	Magnetite offloading	240	S

4/11/19	STANDBY - AWAITING PLUMBER WORKING UNDER P02 CONVEYOR	100	F
4/11/19	Magnetite offloading	240	S
4/12/19	STANDBY - AWAITING PLUMBER WORKING UNDER P02 CONVEYOR	100	F
5/13/19	Pre-ship	60	S
5/14/19	HT WORK OVER P01 CONVEYOR (CAILARD CABLE)	35	F
6/3/19	Chrome loading	720	S
6/4/19	ERRECTING SCAFFOLDING OVER P01 CONVEYOR	65	F
6/14/19	Cleaning	30	S
6/15/19	REMOVED RUBBER FROM R01 CONVEYOR	15	F
7/17/19	Cleaning	30	S
7/18/19	REPAIR S05 HOPPER CONVEYOR	210	F
7/18/19	Cleaning	60	S
7/18/19	INSPECTING S05 HOPPER CONVEYOR FOR DAMAGE	30	F
8/19/19	Cleaning	30	S
8/20/19	WATER LEAK ON C03 CONVEYOR	40	F
1/13/20	Chrome loading	480	S
1/14/20	REMOVED BRACKET BY P01 CONVEYOR	45	F
1/27/20	Pre-ship	60	S
1/28/20	MECH INSPECTING METAL ON CONVEYOR	80	F
3/19/20	Coal loading	960	S
3/20/20	MECHANICAL CHECKING SPLICE ON O2 CONVEYOR	10	F

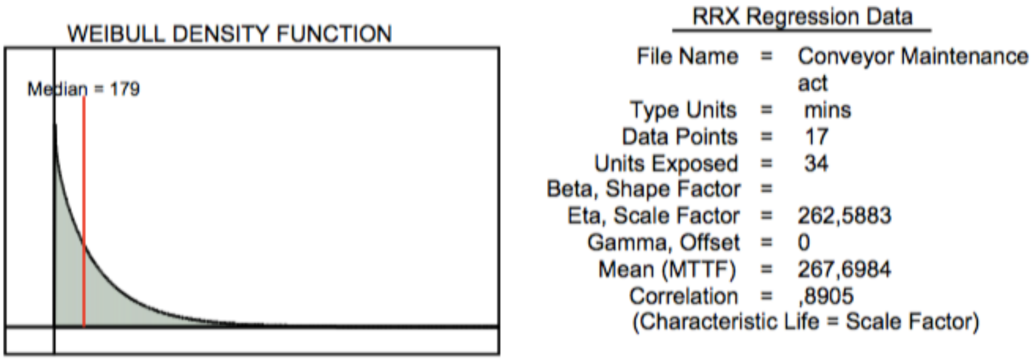


Figure D.3: Weibull Density Function and Regression Data for Maintenance actions

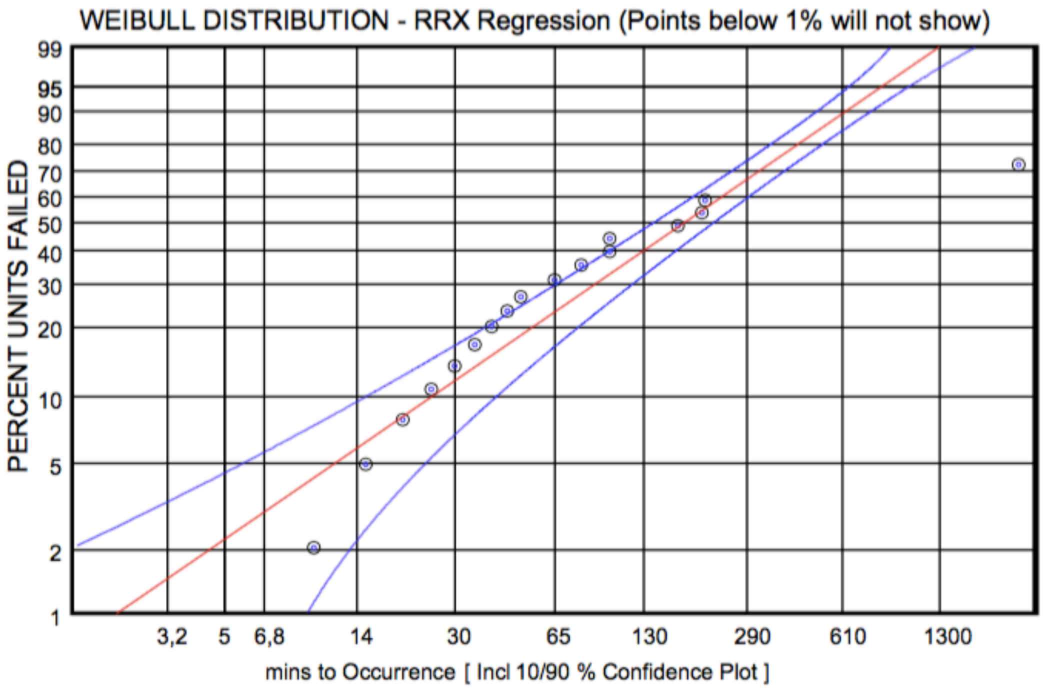


Figure D.4: Weibull distribution for failure and suspension of conveyor maintenance

Based on the results presented in Figure D.3 and Figure D.4, the following can be deduced:

Beta Value

The results of the Weibull analysis for maintenance actions indicate a beta of less than 1 that could imply that the failure pattern maintenance actions have on the selected routes are infant mortality, implying early failure rate.

The correlation of the regression is low at 89.05% which supports the results to deduce an infant mortality rate introduced by over maintenance or inferior maintenance actions.

Gamma Value

From the report output in Figure D.3, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 268 minutes, which implies that maintenance actions are expected to occur every 5 hours on the selected conveyor routes. This MTTF is low considering maintenance actions are meant to increase the lifespan of critical components. This could possibly point to other issues with components that are failing prematurely.

Eta Value - Characteristic Life

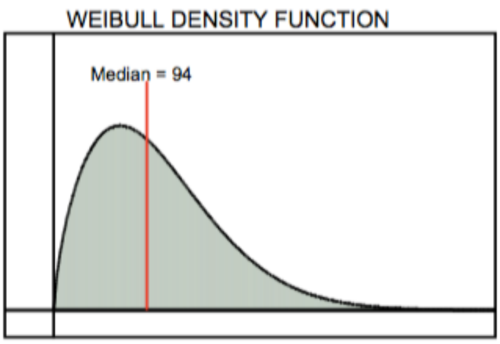
The characteristic life that maintenance actions have can be determined from the value deduced from the value of Eta, which indicates the time it would take before the next maintenance activity is needed. Eta was found to be 263 minutes.

D3 Conveyor misalignment

Table D.3: Misalignment failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
1/3/19	Pre-ship	120	S
1/4/19	Takraft boom conveyor run skew	30	F
5/29/19	Cleaning	120	S
5/30/19	S05 CONVEYOR RUNNING SKEW	25	F
6/19/19	cleaning	60	S

6/20/19	BOOM CONVEYOR RUNNING SKEW	30	F
8/4/19	Pre-ship and cleaning	120	S
8/5/19	BOOM CONVEYOR RUNNING SKEW	75	F
8/5/19	Cleaning	60	S
8/6/19	BOOM CONVEYOR RUNNING SKEW	175	F
10/22/19	Pre-ship and cleaning	120	S
10/23/19	BOOM CONVEYOR RUNNING SKEW	55	F
2/23/20	Cleaning	60	S
2/24/20	LOADER CONVEYOR RUN SKEW	105	F
4/23/20	pre-ship	60	S
4/24/20	O02 conveyor running skew	40	F



RRX Regression Data

File Name = Conveyor misalignment
Type Units = mins
Data Points = 8
Units Exposed = 16
Beta, Shape Factor = 1
Eta, Scale Factor = 117,6552
Gamma, Offset = 0
Mean (MTTF) = 105,1809
Correlation = ,9417

(Characteristic Life = Scale Factor)

Figure D.5: Weibull Density Function and Regression Data for misaligned conveyor

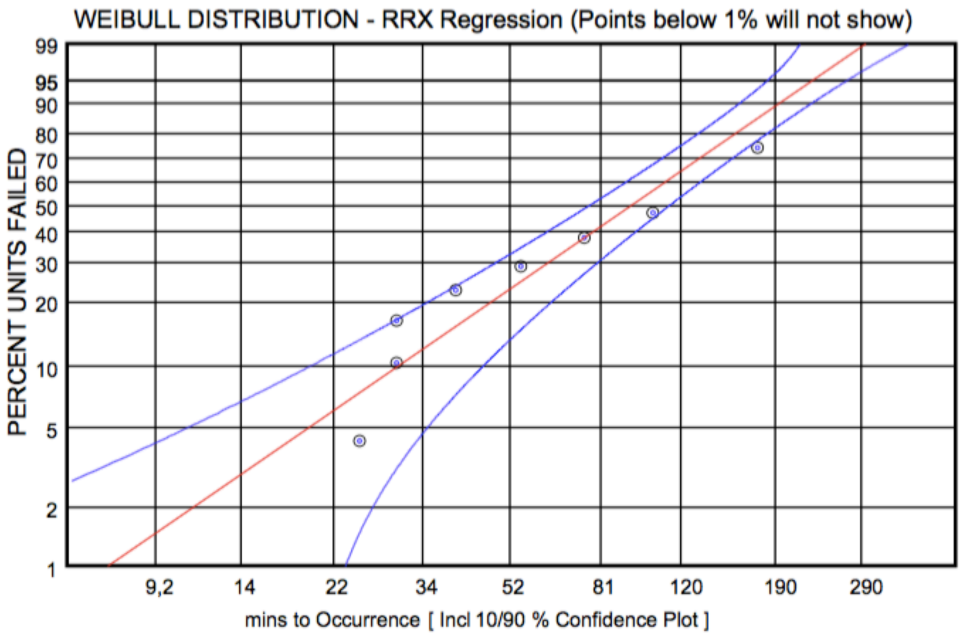


Figure D.6: Weibull distribution for failure and suspension of the misaligned conveyor

Based on the results presented in Figure D.5 and Figure D.6, the following can be deduced:

Beta Value

The results of the Weibull analysis for misalignment of the conveyor indicate a beta of 1 that could imply that the failure pattern on the selected routes are random, implying a constant failure rate. The correlation of the regression is reasonable at 94.71% indicating a relatively high confidence in the results.

Gamma Value

From the report output in Figure D.1, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 105 minutes, which implies that the misalignment of the belt is occur every 1.5 hours should the issue not be resolved. This MTTF is extremely low and maintenance intensive when running a conveyor belt and points to deep issues with other components and maintenance activities that occur on the belt resulting in the belt running skew.

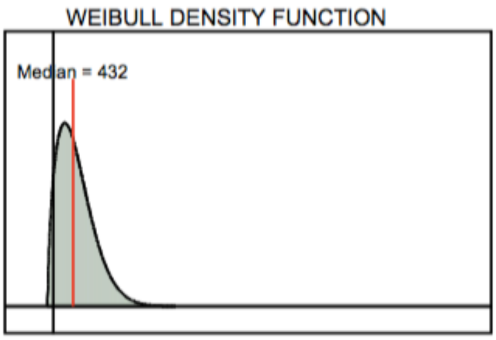
Eta Value - Characteristic Life

The characteristic life of the conveyor alignment can be determined from the value deduced from the value of Eta, which indicates the time it would take for the conveyor to run skew on the selected routes. Eta was found to be 118 minutes.

D4 Conveyor bearing or coupling failure

Table D.4: Bearing/Coupling failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
8/28/19	Coal offloading	20	S
8/29/19	FIRE NEARMISS AT M01 CONVEYOR	35	F
9/7/19	Pre-ship	60	S
9/8/19	LOADER BOOM CONVEYOR BEARING COLLAPSED	255	F
9/8/19	Magnetite loading	720	S
9/9/19	LOADER BOOM CONVEYOR BEARING COLLAPSED	640	F
2/19/20	Pre-ship and Cleaning	120	S
2/20/20	S03 CONVEYOR MELTED RUBBER COUPLING	355	F



RRX Regression Data

File Name = Conveyor bearing or coup
Type Units = mins
Data Points = 4
Units Exposed = 8
Beta, Shape Factor = 1
Eta, Scale Factor = 710,5157
Gamma, Offset = -133,54
Mean (MTTF) = 504,2303
Correlation = ,9930

(Characteristic Life = Scale Factor)

Figure D.7: Weibull Density Function and Regression Data for bearing/coupling failure

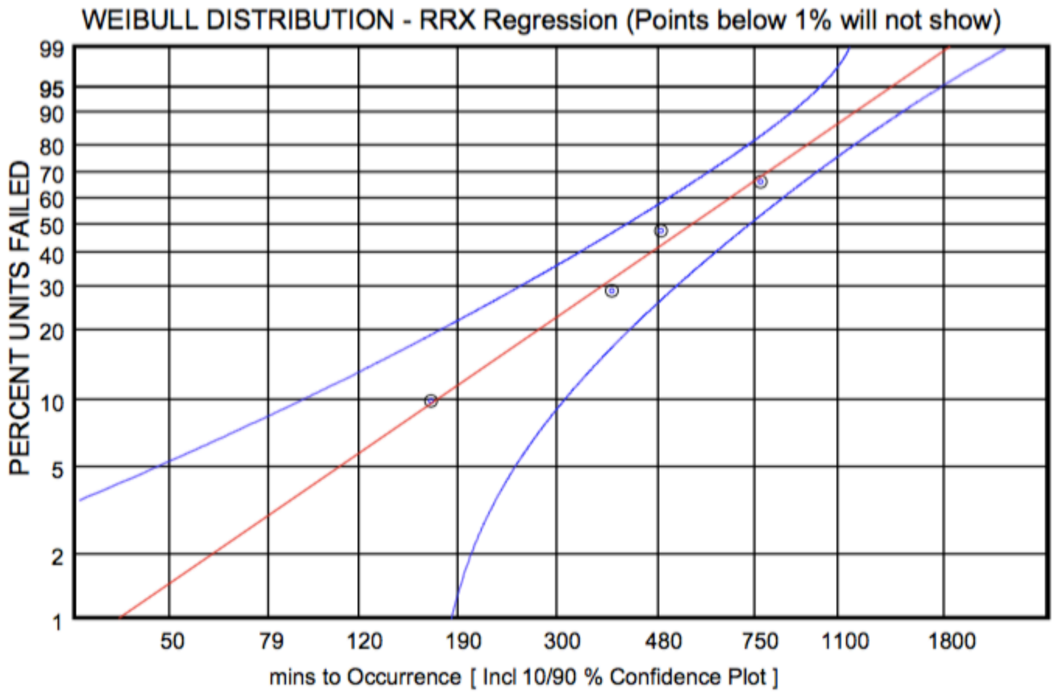


Figure D.8: Weibull distribution for failure and suspension of the conveyor bearing/coupling

Based on the results presented in Figure D.7 and Figure D.8, the following can be deduced:

Beta Value

The results of the Weibull analysis for bearings/couplings indicate a beta of 1 that could imply that the failure pattern on the selected routes are random, implying a constant failure rate. The correlation of the regression is high at 99.30% indicating an extremely high confidence in the results.

Gamma Value

From the report output in Figure D.7, the gamma value is -133.54 minutes which indicates that the failures could have been occurring before the data was captured. This indicates the bearings/couplings on the selected routes had already undergone excessive strain and wear before the maintenance staff had begun monitoring them and capturing maintenance related data.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 504 minutes, which implies that a maintenance of the bearings/couplings should be expected every 8.5 hours which is higher than other maintainable components. This implies the bearings and couplings must be looked at after every loading operation that occurs. From an overall maintenance perspective, this MTTF is low compared to the expected lifespan of component but can be adopted in the maintenance plan to conduct maintenance inspections after every loading operation.

Eta Value - Characteristic Life

The characteristic life of the bearings/couplings can be determined from the value deduced from the value of Eta, which indicates the time it would take for the bearing/coupling to need maintenance. Eta was found to be 711 minutes or approximately 12 hours.

D5 Conveyor tripped

Table D.5: Conveyor tripped data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
4/8/19	Magnetite offloading	2400	S
4/9/19	CONVEYOR TRIPPED - SUBSTATION FAULT	45	F
7/17/19	cleaning	30	S
7/18/19	MANUAL TRIP ON N01 CONVEYOR	130	F
1/9/20	Magnetite loading	3840	S
1/10/20	BOOM CONVEYOR TRIPPED	15	F

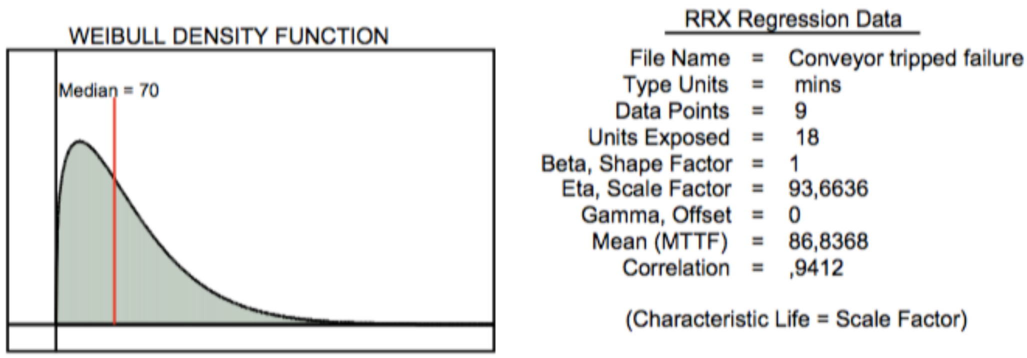


Figure D.9: Weibull Density Function and Regression Data for tripped conveyor

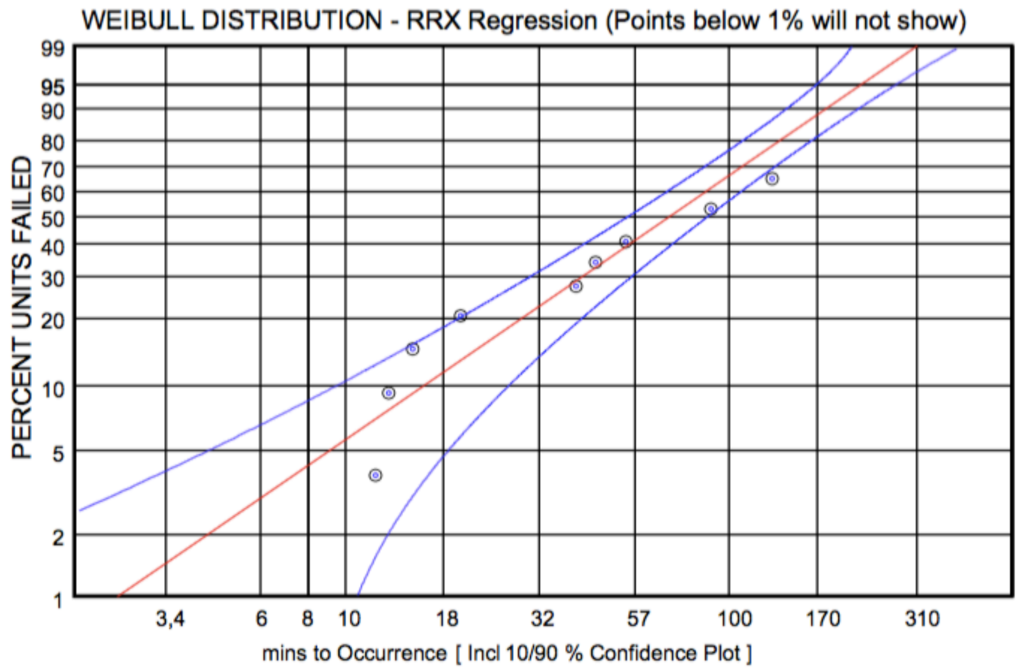


Figure D.10: Weibull distribution for failure and suspension of a tripped conveyor

Based on the results presented in Figure D.9 and Figure D.10, the following can be deduced:

Beta Value

The results of the Weibull analysis for the conveyor tripping indicate a beta of 1 that could imply that the failure pattern on the selected routes are random, implying a constant failure rate. The correlation of the regression is reasonable at 94.12% and based on that, the beta value could be less to 1 which would imply infant mortality.

Gamma Value

From the report output in Figure D.9, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 87 minutes, which implies that a conveyor should be expected to trip every 1.5 hours on the selected routes unless the root cause is resolved. This MTTF is extremely concerning and points to underlying issues with the conveyor operations.

Eta Value - Characteristic Life

The characteristic life of the conveyor tripping can be determined from the value deduced from the value of Eta, which indicates the time it would take for the conveyor to trip. Eta was found to be 94 minutes.

D6 Conveyor belting failure

Table D.6: Belting failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
1/6/19	Cleaning	60	S
1/7/19	repair splice on E01 conveyor	220	F
1/28/19	Cleaning	60	S
1/29/19	P04 conveyor snapped	30	F
2/4/19	Chrome loading	1680	S
2/5/19	SPLICE REPAIR ON BOOM CONVEYOR	160	F
2/8/19	Chrome loading	2880	S
2/9/19	CHANGED SKIRTING RUBBER BY IMG BOOM CONVEYOR	15	F

2/23/19	coal loading	1200	S
2/24/19	SPLICE ON CAILLARD BOOM CONVEYOR	120	F
3/3/19	Magnetite loading	240	S
3/4/19	SPLICE ON IMG MANN BOOM CONVEYOR	530	F
3/4/19	Magnetite loading	120	S
3/5/19	SPLICE ON IMG MANN BOOM CONVEYOR	360	F
4/8/19	Magnetite offloading	2400	S
4/9/19	CUT FLAP ON BOOM CONVEYOR	5	F
4/16/19	Cleaning	60	S
4/17/19	CUTTING FLAP ON K10 CONVEYOR	10	F
4/18/19	Maintenance shut	60	F
4/19/19	CUT FLAP ON W01 CONVEYOR	40	F
6/11/19	Magnetite loading	960	S
6/12/19	S05 CONVEYOR FLIPPED	480	F
6/12/19	Cleaning	60	S
6/13/19	S05 CONVEYOR FLIPPED	75	F
6/13/19	Cleaning	60	S
6/14/19	INSPECTING CUT ON S05 CONVEYOR	10	F
7/17/19	Cleaning	60	S
7/18/19	CUT FLAP ON O03 CONVEYOR	10	F
7/19/19	Cleaning	30	S
7/20/19	CUT FLAP ON O03 CONVEYOR	15	F
8/2/19	Magnetite offloading	240	S
8/3/19	CUT FLAP ON W01 CONVEYOR	20	F
8/28/19	Pre-ship and cleaning	120	S
8/29/19	S08 CONVEYOR CUT	565	F
8/29/19	Magnetite offloading	60	S
8/30/19	S08 CONVEYOR CUT	565	F
9/5/19	Coal offloading	960	S
9/6/19	N03 CONVEYOR OVERLOADED	265	F
9/14/19	Cleaning	60	S
9/15/19	SPLICE ON BOOM CONVEYOR	85	F
9/15/19	Pre-ship and cleaning	120	S
9/16/19	F03 CONVEYOR SNAPPED	425	F
9/18/19	Pre-ship and cleaning	120	S
9/19/19	S03 CONVEYOR FLIPPED	740	F
9/19/19	Cleaning	60	S
9/20/19	S03 CONVEYOR FLIPPED	205	F

9/20/19	Pre-ship and loading	120	S
9/21/19	F03 CONVEYOR FLIPPED	130	F
9/21/19	Cleaning	60	S
9/21/19	S03 CONVEYOR FLIPPED	1440	F
9/21/19	Pre-ship and cleaning	120	S
9/22/19	Q04 CONVEYOR SNAPPED	810	F
9/24/19	Cleaning	60	S
9/25/19	F03 CONVEYOR FLIPPED	370	F
9/25/19	Cleaning	60	S
9/26/19	F03 CONVEYOR FLIPPED	340	F
10/9/19	Magnetite offloading	960	S
10/10/19	BOOM CONVEYOR SLIPPING	40	F
10/12/19	Chrome offloading	2640	S
10/13/19	CUT FLAP ON P02 CONVEYOR	20	F
11/9/19	Chrome Loading	3600	S
11/10/19	NO LONG TRAVEL - LOUVRE DOOR FELL ONTO CONVEYOR	70	F
11/12/19	Chrome loading	960	S
11/13/19	SPLICE ON BOOM CONVEYOR	260	F
12/29/19	Cleaning	60	S
12/30/19	CUT ON K04 CONVEYOR	240	F
12/30/19	Magnetite loading	60	S
12/31/19	CUT ON K04 CONVEYOR	480	F
1/1/20	Chrome loading	480	S
1/2/20	CUT ON K04 CONVEYOR	960	F
1/2/20	Chrome loading	480	S
1/3/20	CUT ON K04 CONVEYOR	960	F
1/15/20	magnetite offloading	3600	S
1/16/20	S05 CONVEYOR FLIPPED	35	F
2/23/20	cleaning	60	S
2/24/20	CUT FLAP ON Q4 CONVEYOR	40	F
2/24/20	Cleaning	60	S
2/25/20	S05 CONVEYOR SNAPPED	785	F

3/11/20	Chrome offloading	1920	S
3/12/20	REPAIR SPLICE ON LOADER BOOM CONVEYOR	200	F

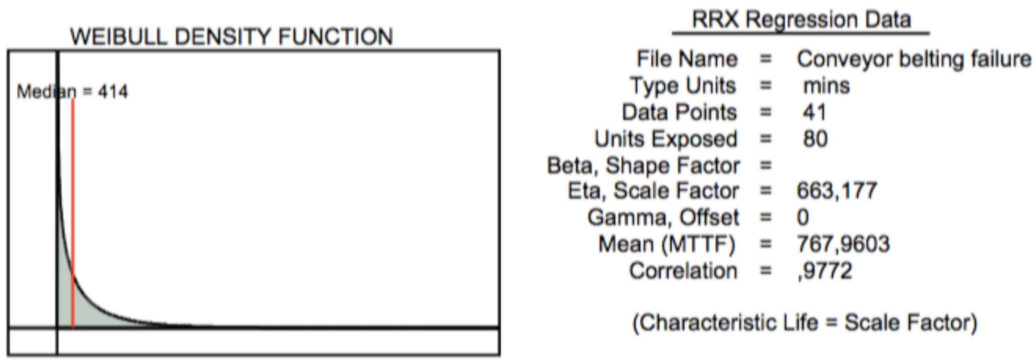


Figure D.11: Weibull Density Function and Regression Data for belting failure

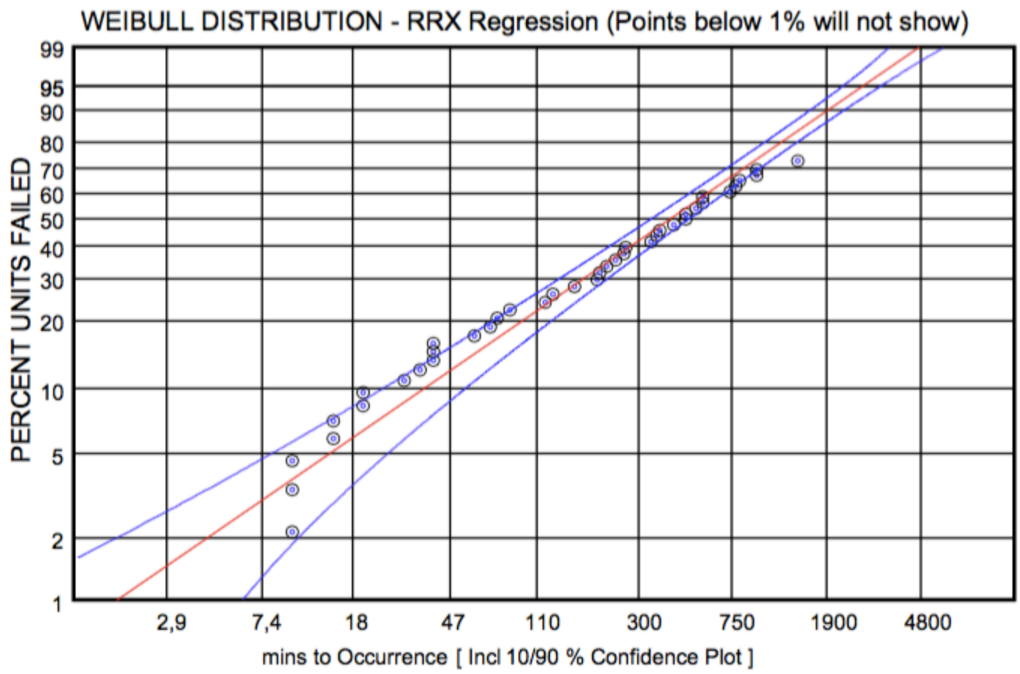


Figure D.12: Weibull distribution for failure and suspension of the conveyor belting

Based on the results presented in Figure D.11 and Figure D.12, the following can be deduced:

Beta Value

The results of the Weibull analysis for belting failures indicate a beta of less than 1 that could imply that the failure pattern on the selected routes are infant mortality, implying early failure rate. The correlation of the regression is reasonably high at 97.72% which provides confidence in the results to deduce conveyor belting is failing prematurely.

Gamma Value

From the report output in Figure D.11, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

1.1.1.1. Mean Time to Failure

The mean time to failure (MTTF) was found to be 768 minutes, which implies that a belt failure or maintenance on the belt should be expected every 13 hours unless the root cause is resolved. This MTTF for a conveyor belt is low compared to the expected lifespan of the belt based on design and supplier's specifications.

Eta Value - Characteristic Life

The characteristic life of the conveyor belting failures can be determined from the value deduced from the value of Eta, which indicates the time it would take for the belt to require maintenance action. Eta was found to be 664 minutes or approximately 11 hours.

D7 Conveyor drive failure

Table D.7: Drive failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
1/16/19	Chrome loading	960	S

1/17/19	K21 PLOUGH AND CONVEYOR NOT STARTING	70	F
5/5/19	Cleaning	60	S
5/6/19	BOOM CONVEYOR NOT STARTING	20	F
8/3/19	pre-ship and cleaning	120	S
8/4/19	BOOM CONVEYOR FAULT	25	F
12/13/19	Chrome loading	960	S
12/14/19	K24 CONVEYOR NOT STARTING	205	F
12/16/19	Magnetite loading	960	S
12/17/19	BOOM CONVEYOR FAULTY	30	F
1/23/20	pre-ship	60	S
1/24/20	BOOM CONVEYOR DRIVE FAULT	330	F
3/1/20	pre-ship	60	S
3/2/20	LOADER CONVEYOR TRIPPED	15	F
3/22/20	Magnetite loading	3360	S
3/23/20	BOOM CONVEYOR VSD FAULT	35	F
3/31/20	Magnetite Offloading	3360	S
4/1/20	P02 CONVEYOR TRIPPED	15	F
4/7/20	K04 conveyor failed to stop	225	F

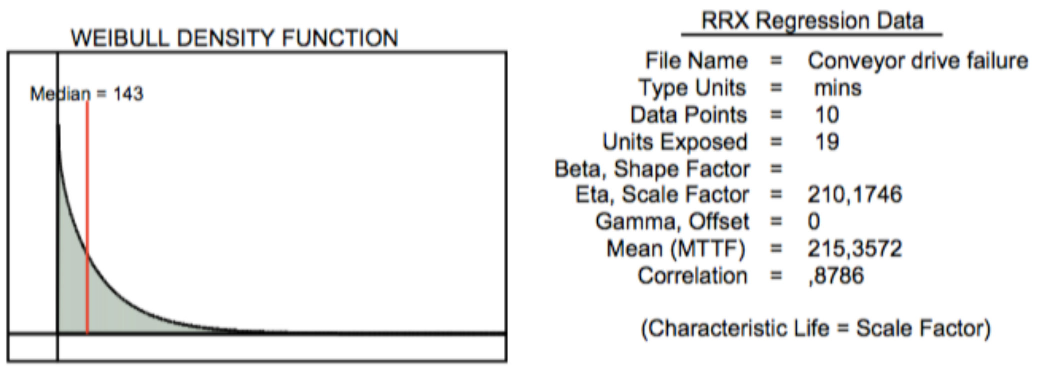


Figure D.13: Weibull Density Function and Regression Data for drive failure

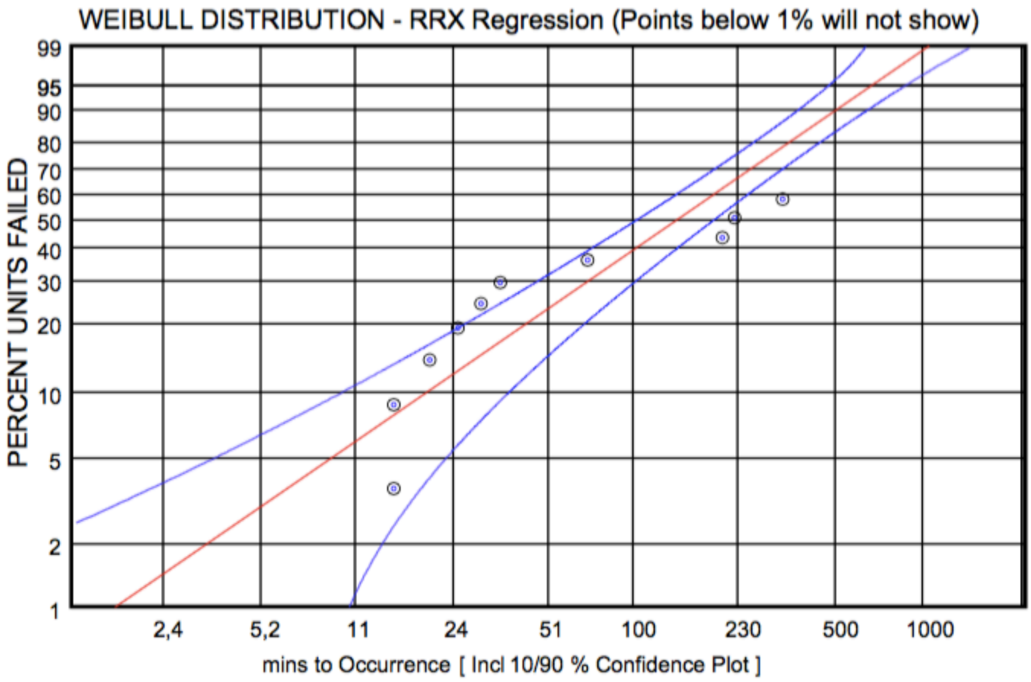


Figure D.14: Weibull distribution for failure and suspension of the conveyor drive

Based on the results presented in Figure D.13 and Figure D.14, the following can be deduced:

Beta Value

The results of the Weibull analysis for drive failure or breakdowns indicate a beta of less than 1 that could imply that the failure pattern on the selected routes are infant mortality, implying early failure rate. The correlation of the regression is low at 87.86% which supports the results to deduce drive breakdown requiring maintenance actions prematurely.

Gamma Value

From the report output in Figure D.13, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 216 minutes, which implies that a drive failure or maintenance should be expected every 4 hours unless the root cause is resolved. This MTTF for a conveyor drive is low compared to the expected lifespan of the drive based on manufacturers specifications.

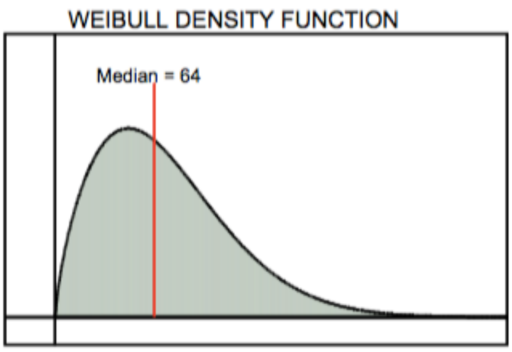
Eta Value - Characteristic Life

The characteristic life of the conveyor drive and breakdowns can be determined from the value deduced from the value of Eta, which indicates the time it would take for the drive to require maintenance action. Eta was found to be 211 minutes or approximately 4 hours.D8 Conveyor idler failure

Table D.8: Idler failure data in Weibull Analysis

DATE	DESCRIPTION	Actual Time (Minutes)	Failure/ Suspension
2/18/19	Pre-ship	2400	S
2/19/19	CHANGED ROLLER ON BOOM CONVEYOR	20	F
2/26/19	Coal loading	4320	S
2/27/19	CHANGED ROLLER ON BOOM CONVEYOR	20	F
3/9/19	Pre-ship	60	S
3/10/19	CHANGED ROLLERS ON THE BOOM CONVEYOR	45	F
3/14/19	Cleaning	60	S
3/15/19	CHANGED ROLLERS ON BOOM CONVEYOR	45	F
4/8/19	Magnetite offloading	2400	S
4/9/19	CHANGED ROLLERS BY BOOM CONVEYOR	90	F
4/20/19	cleaning	60	S
4/21/19	CHANGED ROLLER BY BOOM CONVEYOR	70	F
7/6/19	Coal offloading	2160	S

7/7/19	CHANGED ROLLER BY BOOM CONVEYOR	10	F
7/15/19	Cleaning	30	S
7/16/19	CHANGED ROLLERS BY BOOM CONVEYOR	25	F
10/5/19	Chrome loading	960	S
10/6/19	CHANGED ROLLER ON BOOM CONVEYOR	45	F
11/9/19	Chrome loading	3600	S
11/10/19	CHANGED ROLLER ON BOOM CONVEYOR	50	F
11/10/19	Cleaning	60	S
11/11/19	CHANGED ROLLER ON BOOM CONVEYOR	35	F
11/16/19	Coal Loading	1680	S
11/17/19	CHANGED ROLLER ON BOOM CONVEYOR	15	F
12/9/19	Chrome loading	960	S
12/10/19	CHANGED ROLLERS ON BOOM CONVEYOR	50	F
12/13/19	Chrome loading	960	S
12/14/19	CHANGED ROLLER ON BOOM CONVEYOR	45	F
1/8/20	Magnetite offloading	3600	S
1/9/20	CHANGED ROLLER BY BOOM CONVEYOR	40	F
2/25/20	pre-ship	60	S
2/26/20	CHANGE ROLLER ON S05 CONVEYOR	15	F
5/7/20	Chrome loading	1680	S
5/8/20	CHANGE ROLLER ON O3 CONVEYOR	40	F



RRX Regression Data

File Name = Conveyor idler failure
Type Units = mins
Data Points = 17
Units Exposed = 34
Beta, Shape Factor = 1
Eta, Scale Factor = 78,9908
Gamma, Offset = 0
Mean (MTTF) = 70,4672
Correlation = ,9667

(Characteristic Life = Scale Factor)

Figure D.15: Weibull Density Function and Regression Data for idler failure

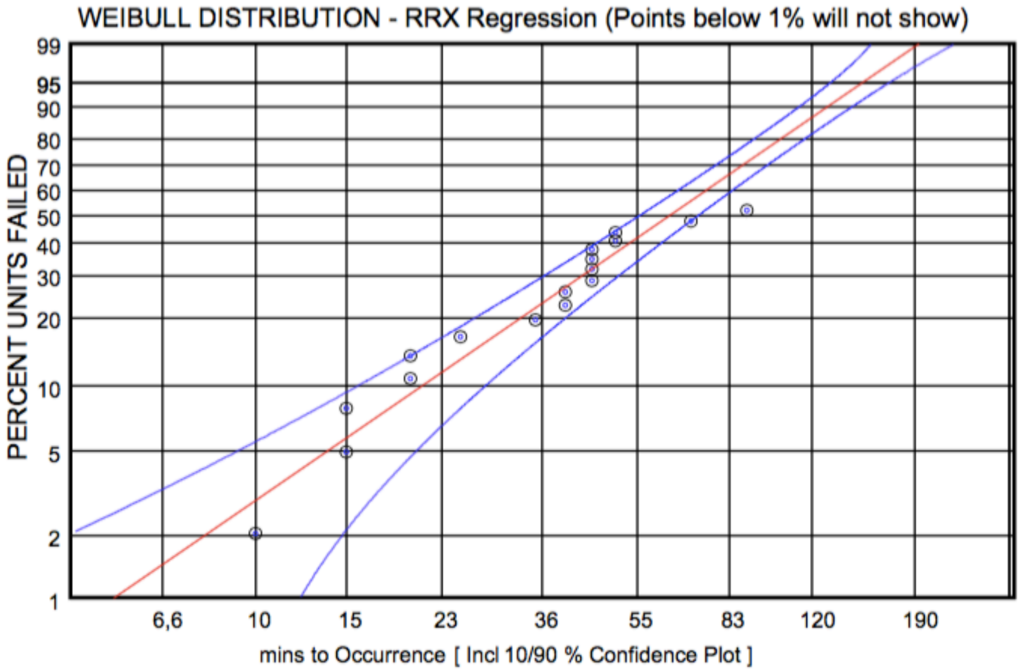


Figure D.16: Weibull distribution for failure and suspension of the conveyor idlers

Based on the results presented in Figure D.15 and Figure D.16, the following can be deduced:

Beta Value

The results of the Weibull analysis for idler failure indicate a beta of 1 that could imply that the failure pattern on the selected routes are random, implying a constant failure rate. The correlation of the regression is reasonably high at 96.67% indicating a relatively high confidence in the results.

Gamma Value

From the report output in Figure D.15, the gamma value $(\gamma = 0)$, this indicates that there is a small probability of failure immediately on start – up.

Mean Time to Failure

The mean time to failure (MTTF) was found to be 71 minutes, which implies that a failure or maintenance task should be expected every hour unless the root cause is resolved. This MTTF is concerningly low compared to the expected lifespan of component critical for the operation of the conveyor.

Eta Value - Characteristic Life

The characteristic life of the idler before requiring any maintenance action can be determined from the value deduced from the value of Eta, which indicates the time it would take for the idler to require action. Eta was found to be 79 minutes or approximately 1.5 hours.

E. APPENDIX E: FIRST QUESTIONNAIRE

No.	Questions	Multiple Choice Answers				
1	How important is a maintenance strategy for conveyor systems?	Very important **9 (100%)**	somewhat important **0 (0.00%)**	not at all important **0 (0.00%)**		
2	Is there a Maintenance strategy currently being followed?	Yes **9 (100%)**	No **0 (0.00%)**			
	What type of maintenance strategy do you believe is currently used on conveyor systems/components at the Port?	Corrective (Run component to failure, then replace or repair) **1 (11.11%)**	Preventive (Run component for a specified time period, then replace or repair) **0 (0.00%)**	Preventive (Run component for a specified time period, conduct inspections and only replace/repair based on condition of component) **3 (33.33%)**	Predictive (Through use of condition monitoring equipment, run component to a specified condition limit, then replace or repair) **0 (0.00%)**	Combination of All of the Above **5 (55.56%)**
4	What best describes the maintenance actions taken within the Port?	Maintenance of a component is done after it fails **1 (11.11%)**	Maintenance of a component is done based on hours of use regardless of condition **0 (0.00%)**	Maintenance of a component is done based on periodic visual assessment on the condition of the component **5 (55.56%)**	Maintenance of a component is done based on the condition of the component using condition monitoring devices **3 (33.33%)**	
5	How often is maintenance carried out on conveyor equipment?	After breakdown **0 (0.00%)**	After inspection determines problem **4 (44.44%)**	After regular periods according to a schedule **5 (55.56%)**		
6	Do you believe you are adequately trained to conduct maintenance activities on the conveyor belts?	Yes **6 (66.67%)**	No **3 (33.33%)**			
7	What kind of Maintenance is conducted on the following components?	Corrective (Run component to failure, then replace or repair)	Preventive (Run component for a specified time period, then replace or repair)	Preventive (Conduct periodic inspections and replace/repair based on condition of component)	Predictive (Condition monitoring equipment and then replacement/repair based on condition)	
	Pulleys	**3 (33.33%)**	**1 (11.11%)**	**3 (33.33%)**	**2 (22.22%)**	
	Idlers	**6 (66.67%)**	**1 (11.11%)**	**2 (22.22%)**	**0 (0.00%)**	
	Drives	**1 (11.11%)**	**2 (22.22%)**	**2 (22.22%)**	**4 (44.44%)**	
	Belting	**3 (33.33%)**	**2 (22.22%)**	**4 (44.44%)**	**0 (0.00%)**	
8	How would you describe the existing strategy?	Unreliable **1 (11.11%)**	Somewhat reliable **5 (55.56%)**	Reliable **3 (33.33%)**		
9	What type of maintenance strategy do you believe is needed to improve the reliability of conveyor belts in the Port?	Corrective (Run component to failure, then replace or repair) **0 (0.00%)**	Preventive (Run component for a specified time period, then replace or repair) **1 (11.11%)**	Preventive (Conduct periodic inspections and replace/repair based on condition of component) **1 (11.11%)**	Predictive (Through use of condition monitoring equipment, run component to a specified condition limit, then replace or repair) **1 (11.11%)**	Strategy that uses a combination of all the above dependent on the part/component and the consequences of its failure **6 (66.67%)**

F. APPENDIX F: SECOND QUESTIONNAIRE

No.	Criteria	Rank	Weighting	Strategy that replaces parts/components after failure	Strategy that replaces parts/components based on hours in service/use	Strategy that replaces parts/components based on condition of component through periodic visual assessment	Strategy that replaces parts/components based on actual condition of component through use of condition monitoring equipment	Strategy that uses a combination of the above dependent on the part/component and its failure consequences
			100%	24%	43%	47%	59%	57%
1	Cost	1	30%	10%	14%	15%	16%	15%
1.1	How would you score the costs of implementation (Training, hardware, software) for each maintenance strategy?		20%	4	5.75	5.5	5	4.75
1.2	How are score the costs for spares holding for each maintenance strategy?		10%	2.25	2.75	4	5.75	5.75
2	Safety	2	30%	7%	12%	14%	19%	19%
2.1	How would you score the maintenance strategy in relation to the safety and protection of personnel?		20%	2.25	3.75	4.5	6.5	6
2.2	How would you score the maintenance strategy in relation to the safety and protection of the environment, both internal and external?		10%	2.5	4	4.75	6.25	6.5

No.	Criteria	Rank	Weighting	Strategy that replaces parts/components after failure	Strategy that replaces parts/components based on hours in service/use	Strategy that replaces parts/components based on condition of component through periodic visual assessment	Strategy that replaces parts/components based on actual condition of component through use of condition monitoring equipment	Strategy that uses a combination of the above dependent on the part/component and its failure consequences
3	Value added	3	25%	4%	11%	11%	15%	14%
3.1	How would you score the strategy for improving reliability?		10%	2	3.25	3.75	6	5.75
3.2	How would you score the strategy for reducing maintenance costs?		5.0%	2	3.5	4	6	6.25
3.3	How would you score the strategy with regards to minimising downtime and operational impacts?		5.0%	1.25	5.25	5.5	6.5	5
3.4	How would you score the strategy with regards to improving reputation of the company?		5%	1.25	6.25	5	5.25	5.25
4	Schedule	4	15%	3%	6%	7%	9%	9%
4.1	How would you score each strategy in relation to the timeline for implementation?		7.5%	2.25	3.75	5	5.75	6
4.2	How would you score each strategy with relation to required occupations to implement strategy?		7.5%	1.25	4.5	4.75	6.5	5.75