

Critical Review of Sri Lankan Tyre Companies on How Their Plant Maintenance Strategy Works

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ABSTRACT:

The tyre manufacturing industry plays a critical role in the industrial sector of Sri Lanka, contributing significantly to export earnings, employment, and technological advancement. As a capital-intensive, process-driven industry, effective plant maintenance strategies are essential for operational efficiency, product quality, safety, and long-term sustainability. This study critically reviews plant maintenance strategies adopted by six leading Sri Lankan tyre manufacturing companies. The study examines how these organizations design, plan, implement, and monitor their maintenance frameworks, focusing on proactive maintenance, which includes preventive maintenance, predictive maintenance, reliability-centred maintenance (RCM), total productive maintenance (TPM), and Industry 4.0 technologies. It evaluates their effectiveness in minimizing downtime, optimizing asset utilization, reducing maintenance costs, and ensuring compliance with safety and environmental standards. Using a mixed-methods approach integrating quantitative and qualitative techniques, this study draws on primary and secondary data, including industry reports, structured questionnaires, semi-structured interviews, focus group discussions, and comparative case analysis. This approach identifies best practices, operational challenges, and strategic gaps in the maintenance management systems of the selected tyre manufacturers. The findings examine the relationship between maintenance strategy maturity and overall manufacturing performance, and provide recommendations to enhance maintenance effectiveness, sustainability, technological integration, and the competitive advantage of the Sri Lankan tyre manufacturing sector. The paper concludes that production pressures and management's disregard for new maintenance trends have forced these companies toward reactive maintenance, which is counterproductive to long-term plant operation. The study found that management commitment, maintenance planning, technical competence, digital technologies, and performance measurement are key determinants of maintenance maturity. Shifting from reactive to reliability-based proactive maintenance can improve equipment

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reliability and productivity, reduce costs, and enhance long-term competitiveness.

Keywords: Plant maintenance; Maintenance strategies; Tyre manufacturing; Sri Lanka; Corrective, Preventive and Predictive maintenance; Total Productive Maintenance (TPM) and Reliability-centred maintenance.

1. Introduction

This paper begins by examining the background of the Sri Lankan tyre manufacturing industry, the research problem, the evolution of maintenance philosophies, and relevant literature. It then presents findings from research studies on the maintenance strategies used by six Sri Lankan tyre manufacturing companies. The study concludes that due to production pressures, many companies are bypassing proactive maintenance and turning to reactive maintenance, which ultimately harms the long-term performance and reliability of the plant.

1.1 Background of the Sri Lankan Tyre Manufacturing Industry

The tyre manufacturing industry is an important component of the manufacturing sector of Sri Lanka, contributing to industrial development, employment generation, export earnings, and technological advancement. The tyre industry supports various key sectors and requires highly controlled manufacturing processes, advanced machinery, consistent quality, and strict safety and environmental standards. Therefore, reliable and efficient equipment is essential for uninterrupted production and meeting domestic and international market demands.

Tyre manufacturing is a capital-intensive and process-oriented operation involving complex equipment and interconnected production stages such as raw-material preparation, rubber mixing, component preparation, tyre building, curing, inspection, and finishing. Failures in critical equipment can interrupt production processes, reduce product quality, increase maintenance and production costs, and negatively affect delivery performance. Therefore, effective plant maintenance is a fundamental requirement for ensuring equipment availability, operational

efficiency, product quality, and plant safety. Traditionally, maintenance activities in manufacturing organizations in Sri Lanka have often been dominated by corrective or reactive maintenance, where equipment is repaired after a failure has occurred. Although reactive maintenance can provide an immediate response to equipment breakdowns, excessive dependence on this approach can result in unplanned downtime, higher repair costs, production losses, shortened equipment life, and increased safety risks. Modern manufacturing organizations have therefore increasingly adopted proactive maintenance approaches, including preventive maintenance (PM), predictive maintenance (PdM), reliability-centred maintenance (RCM), and total productive maintenance (TPM). More recently, the emergence of Industry 4.0 technologies, including sensors, condition monitoring (CM), industrial Internet of Things (IIoT), data analytics (DA), artificial intelligence (AI), and digital maintenance systems (DMS), have created opportunities to transform conventional maintenance practices into data-driven and reliability-based systems.

Within the Sri Lankan context, tyre manufacturers operate in an increasingly competitive environment in which productivity, product quality, cost efficiency, equipment reliability, and responsiveness to market requirements are critical to organizational performance. The ability of manufacturers to effectively manage and maintain their production assets is therefore closely linked to their competitiveness and long-term sustainability. However, the extent to which modern maintenance philosophies and digital technologies have been incorporated into Sri Lankan tyre manufacturing remains an important area requiring systematic investigation. The

maintenance maturity of an organization is influenced not only by the technical maintenance methods employed but also by management commitment, maintenance planning, workforce competence, availability of resources, organizational culture, performance measurement, and the effective use of technology. Consequently, assessing maintenance practices across different tyre manufacturing organizations can provide valuable insights into the current state of maintenance management within the sector, identify differences in maintenance maturity, and establish opportunities for improvement.

1.2 Research Problem

Despite the importance of reliable production equipment to the tyre manufacturing industry, there is a concern that most Sri Lankan tyre manufacturing companies continue to rely substantially on reactive maintenance practices. Production pressures, the need to meet delivery targets, limited maintenance resources, inadequate maintenance planning, insufficient management attention to emerging maintenance practices, and gaps in technical competencies may encourage organizations to prioritize immediate breakdown recovery rather than long-term equipment reliability. Such dependence on reactive maintenance can create a cycle in which frequent equipment failures lead to production interruptions, increased maintenance expenditure, reduced asset utilization, and further pressure on maintenance personnel.

Although PM, PdM, RCM, TPM, and Industry 4.0-enabled maintenance practices are increasingly important, limited empirical evidence exists on their implementation and effectiveness in Sri Lanka's tyre manufacturing sector. In particular, there is insufficient understanding of the maturity of maintenance strategies, their integration with production management, and their impact on manufacturing performance. The research problem therefore focuses on the gap between the need for proactive, reliability-based maintenance and the continued reliance on reactive practices, which may contribute to equipment failures, unplanned

downtime, higher maintenance costs, reduced productivity, and compromised quality and safety. A structured comparison of maintenance practices among leading tyre manufacturers is needed to identify mature maintenance systems and the key factors influencing manufacturing performance.

1.3 Concept of Maintenance and Maintenance Strategy.

To begin, it is essential to define the concepts of maintenance and maintenance strategy. Maintenance is the combination of technical, administrative, and managerial activities undertaken to preserve or restore an asset so that it can perform its intended function reliably, safely, and efficiently. A maintenance strategy is a structured, long-term plan that defines how, when, and why maintenance activities are carried out on an organization's physical assets. Its primary objective is to minimize downtime, maximize equipment reliability, and optimize maintenance costs by determining the most appropriate approach, such as reactive, preventive, or predictive maintenance. Plant maintenance, the focus of this study, has evolved in parallel with industrial development, reflecting the technological, organizational, and economic transformations that have occurred throughout industrial history (Poor et al., 2019). From ancient civilizations to contemporary smart factories, the preservation of physical assets has been fundamental to sustaining productivity and operational continuity (Poor et al., 2019). Historical records indicate that maintenance practices date back to early societies; for example, documentation from around 600 BC in ancient Egypt refers to the use of cedar wood for maintaining the sacred boat of the god Amun Ra. Such evidence demonstrates that even early civilizations recognized the necessity of protecting and preserving critical assets to ensure functional reliability (Brugsch-Bey, H., 1881).

With the onset of industrialization, maintenance practices began to change significantly. During the First Industrial Revolution, symbolized by the development of the steam engine by James Watt, industrial machinery became central to

production systems (Henderson, 2013). At this stage, maintenance was largely reactive, commonly referred to as breakdown or corrective maintenance. Equipment was repaired only after failure occurred (Dickinson and Hugh, 1943). While this approach was adequate for relatively simple mechanical systems, it became increasingly inefficient as industrial processes grew more complex and interdependent, leading to higher downtime and productivity losses. Corrective maintenance refers to reactive actions taken after a failure, whereas preventive maintenance involves scheduled interventions to avert breakdowns (Hoffmann et al., 2020). Traditional maintenance, which is still practised to some extent today, can be broadly classified into corrective, preventive, and predictive approaches (Garcia et al., 2021).

The Second Industrial Revolution, characterized by electrification and mass production, introduced more systematic approaches to maintenance. Industrial leaders such as Henry Ford recognized the economic impact of equipment failures in large-scale production environments and promoted preventive maintenance (Zhang and Yang, 2020). This marked a critical shift from reactive repairs toward planned maintenance interventions designed to prevent breakdowns and enhance production stability.

The Third Industrial Revolution, driven by automation, electronics, and programmable logic controllers (PLCs), further advanced maintenance philosophy. As production systems became more technologically sophisticated, maintenance evolved into a more analytical and strategically integrated function (Haradhan and Mohajan, 2021). Concepts such as Total Productive Maintenance (TPM) (Prabowo and Adesta, 2017; Adesta et al., 2018; Mishra et al., 2021) and Reliability-Centred Maintenance (RCM) emerged, emphasizing equipment reliability, risk management, employee involvement, and alignment between maintenance and organizational objectives (Prabowo and Adesta, 2019; Chen et al., 2019; Vaz et al., 2023). During this Third Industrial

Revolution, a form of predictive maintenance called Condition-Based Maintenance (CbM) emerged. It was the foundation for the later development of Predictive Maintenance (PdM) (Ball, Gelman, and Springer, 2020; Mobley, 2002).

The ongoing Fourth Industrial Revolution has transformed maintenance into a data-driven and digitally integrated discipline (Hakeem et al., 2020; Kumar and Singh, 2020). Through the use of sensors, real-time monitoring, artificial intelligence, and big data analytics, predictive maintenance enables organizations to anticipate equipment failures before they occur, thereby reducing unplanned downtime and optimizing asset performance (Shin and Park, 2019). Looking ahead, Industry 5.0 introduces the concept of prescriptive maintenance, which not only predicts potential failures but also recommends optimal corrective actions (Xia et al., 2022). This approach highlights collaboration between human expertise and intelligent systems to achieve enhanced operational efficiency and sustainability.

Today, plant maintenance is no longer viewed as a “necessary evil,” but as a strategic function that directly contributes to competitiveness, profitability, safety, and sustainability. Plant maintenance is increasingly recognized as a strategic function rather than a mere operational necessity (Al-Najjar and Alsyoud, 2004). The progression from reactive to proactive, preventive, predictive, and prescriptive maintenance reflects the broader evolution of industrial systems toward greater efficiency, reliability, competitiveness, and sustainability. Understanding this historical development provides an essential foundation for critically reviewing contemporary maintenance strategies and their effectiveness within modern manufacturing environments. By the year 2000, the term Computerized Maintenance Management System (CMMS) had become widely used in maintenance management. Although implementing a CMMS required considerable financial investment and organizational commitment, it proved to be a

valuable tool for improving maintenance control, streamlining work processes, and increasing productivity. Mather (2002) noted that the growing adoption of CMMS was largely due to its positive impact on maintenance and overall operational performance. At the same time, ongoing developments in maintenance and operations management have introduced more advanced tools and approaches, enabling organizations to manage their resources more effectively and improve overall efficiency (Wireman, 2010).

The economic performance of industrial plants and equipment is largely determined by the effectiveness of the maintenance strategy adopted by an organization. Equipment reliability is a fundamental factor influencing operational performance and can be significantly enhanced through the systematic planning and implementation of effective maintenance practices (Kumar and Kothari, 2018; Gan et al., 2022). Although the financial benefits of structured maintenance programs are substantial and measurable, their advantages extend beyond economic gains. Well-maintained equipment contributes to improved workplace conditions by minimizing unexpected failures, thereby enhancing employee morale and reducing frustration associated with frequent equipment breakdowns (George et al., 2022; Attri et al., 2012; Rahaman, 2022; Masud, 2022). Furthermore, reliable maintenance practices support consistent production schedules and timely product delivery, whereas inadequate maintenance can result in production disruptions, delayed deliveries, customer dissatisfaction, and the potential loss of business opportunities (Ahuja, Khamba, 2008). Despite its strategic importance, maintenance has traditionally been regarded as a secondary function in many industrial organizations, with operations and maintenance management often receiving insufficient attention in operational planning. This perception can contribute to increased production pressures and operational inefficiencies over time. Numerous studies have indicated that these factors have encouraged organizations to adopt predominantly reactive

maintenance approaches, whereby maintenance activities are performed only after equipment failures occur (Hansson et al., 2003). Although reactive maintenance may provide short-term solutions to immediate production requirements, excessive reliance on this approach adversely affects long-term operational performance, asset reliability, equipment availability, and the overall sustainability of industrial operations.

As discussed, unfortunately, many operations managers have traditionally regarded maintenance as an operational burden and have often underestimated its strategic role in improving organizational productivity (Patton, 1980). Consequently, maintenance activities have frequently been perceived as an operational burden rather than a value-adding function. According to Hodges (1996), many industrial organizations have historically neglected the maintenance of both production equipment and physical infrastructure, highlighting the need for a fundamental change in organizational attitudes toward maintenance. Parks (1970) argued that such a transformation should occur through gradual evolutionary changes rather than abrupt revolutionary shifts in maintenance philosophy. He further noted that maintenance management did not receive serious attention as a distinct organizational function until the twentieth century. Since then, however, maintenance has progressively evolved into a recognized discipline that integrates engineering principles with management practices to enhance organizational performance and operational efficiency. As Husband (1986) observed, maintenance is now widely acknowledged as a multidisciplinary function that combines technical expertise and managerial decision-making to support effective business operations. As we understand, each industrial revolution brought about changes in technological, socio-economic and cultural characteristics. Among these technological characteristics, maintenance management in manufacturing contexts is one of the most fundamental factors. The approach to equipment maintenance has changed throughout the revolutions from reactive to predictive/proactive. Instead of fixing

breakdowns, companies try to predict them and minimize the risks and costs associated with them (Nowakowski et al., 2019; Abiodun et al., 2020)

1.4 Evolution of Maintenance Philosophy and Strategies

As described in the above section, the evolution of maintenance strategies has closely followed the development of industrial revolutions, progressing from reactive approaches to intelligent and automated systems. As summarized in Table 1, Industry 1.0 relied primarily on reactive maintenance, where equipment was repaired after failure. Industry 2.0 introduced preventive maintenance through

Table 1: Evolution of Maintenance Philosophy and Strategies

Revolution	Time Period	Characteristics	Maintenance Philosophy/Strategy
Industry Breakdown Maintenance (BM) (Reactive Era)	1.0: Late 18th century to early 20th century (1760-1910)	Introduction of steam power, mechanization, and centralized production systems. Equipment was relatively simple, robust, and easy to repair.	Breakdown Maintenance (BM) or Run-to-Failure strategy. Maintenance was performed only after an equipment failure occurred.
Industry Preventive Maintenance (PM) (Scheduled Era)	2.0: Early 20th century to late 1970s (1910-1980)	Electrification, internal combustion engines, and mass-production lines increased complexity and dependence.	Preventive Maintenance (PM) assembly based on predetermined time intervals or usage schedules to reduce unexpected failures.
Industry Condition-Based and Reliability-Centred Maintenance (RCM) (Digital Era)	3.0: 1980s to early 2000s (1980-2004)	Adoption of computers, PLCs, automation, and industrial software. Greater emphasis on reliability, maintainability, Total Productive Maintenance (TPM), and workforce multi-skilling.	Condition-Based Maintenance (CbM) and Reliability-Centred Maintenance (RCM) . Introduction of Computerized Maintenance Management Systems (CMMS) for maintenance planning and control.
Industry Predictive Maintenance (PdM) (Smart Era)	4.0: 2011-Present	Integration of IoT, sensors, cyber-physical systems, cloud computing, and advanced analytics. Real-time machine learning to predict failures monitoring of temperature, before they occur, minimizing	Predictive Maintenance (PdM) continuous condition monitoring, data analytics, and advanced monitoring to predict failures

Revolution	Time Period	Characteristics	Maintenance Strategy	Philosophy/
Industry Prescriptive and Autonomous Maintenance (PrM & AM) (Cognitive Era)	5.0: and Emerging / Next Generation	vibration, pressure, noise, and other equipment parameters.	downtime and optimizing maintenance schedules.	
		Human-centric integration of AI, advanced analytics, cyber-physical systems, IoT, digital twins, and autonomous decision-making. Focus on collaboration between humans and intelligent systems.	Prescriptive Maintenance (PrM) and Autonomous Maintenance (AM). AI and machine learning not only predict failures but also recommend or automatically initiate optimal maintenance actions by considering equipment condition, operational constraints, safety, cost, and business impact.	

Sources: Hussein and Khayal (2025); Cooke (2003); Lee et al. (2020); Desbalo et al. (2024)

2. Research Design

This study focuses on the maintenance activities of six tyre manufacturing companies in Sri Lanka. The plants are classified as very large, large, medium, small and very small in scale. These companies are named Company1, Company2, Company3, Company4, Company5 and Company6. All of these companies have been operating their plants for more than two decades and operate in a continuous production environment (Piyatissa and Siriwardhana, 2023). The practical case study was conducted between March 2025 and January 2026. Follow-up visits were conducted in April 2026.

Primary data were collected from maintenance personnel and other relevant employees using a combination of quantitative and qualitative data collection methods. A structured questionnaire

survey was administered to obtain quantitative information on maintenance practices, while qualitative data were gathered through focus group discussions (Krueger and Casey,2015), Semi-structured interviews (Brinkmann, 2020), document analysis (Bowen, 2009), direct observations, and informal discussions. Subramaniam (2021) illustrates an instance where a document review was also utilized. The interview participants primarily comprised maintenance technicians, engineers, managers, and supervisors, with additional perspectives obtained from operations managers, human resource managers, and machine operators. The inclusion of participants from different functional levels helped provide a comprehensive understanding of maintenance practices and organizational factors influencing maintenance performance (see Table 2).

Table 2: Survey Details of Selected Companies and Their Respondents

	Company1	Company2	Company3	Compan4	Company5	Company6
Total number of target personnel	360	197	183	134	114	50

Number of survey respondents	72	39	31	26	19	10
Response rate (%)	20	20	17	19	17	20
Number of interviews conducted	22	14	12	10	8	4

This study adopted a mixed-methods multiple case study research design, integrating both quantitative and qualitative approaches to investigate maintenance management practices in six tyre manufacturing companies in Sri Lanka (Ferdous Azam et al., 2021). The mixed-methods approach was selected to provide a comprehensive understanding of maintenance activities by combining the strengths of quantitative data, which enable statistical analysis and comparison, with qualitative data, which offer in-depth insights into organizational practices, experiences, and perceptions (Oranga and Matere, 2023; Teddlie and Tashakkori, 2009; Creswell and Plano Clark, 2017). Creswell and Plano Clark (2018) further explain that a mixed methods research approach provides more comprehensive answers to complex research questions that cannot be fully addressed by a single method alone.

The quantitative component involved a structured survey administered to maintenance personnel across six tyre manufacturing companies. The survey collected numerical data on maintenance practices, organizational characteristics, and maintenance performance indicators. The selected companies represent different organizational scales, ranging from very small to very large manufacturing plants, thereby allowing comparisons across different production environments.

The qualitative component consisted of semi-structured interviews (Brinkmann, 2020), direct observations, documentary analysis, and informal discussions with key personnel involved in maintenance and production activities (Merriam

and Tisdell, 2015). Participants included maintenance managers, maintenance engineers, supervisors, technicians, operations managers, human resource managers, and machine operators. These qualitative methods provided detailed information on maintenance policies, implementation challenges, decision-making processes, and organizational culture, which could not be adequately captured through the questionnaire alone.

A multiple case study strategy was adopted because it enabled an in-depth examination of maintenance management practices across several organizations operating within the same industrial sector (Abadir et al., 2020). Abadir et al. (2020) further emphasized that the multi-case study design is a valuable research tool for studying the relationships between personal, social, behavioural, psychological, organizational, cultural, and environmental factors that guide management and leadership development. Therefore, the integration of quantitative and qualitative data facilitated methodological triangulation, thereby improving the validity and reliability of the study. Quantitative findings were used to identify trends and relationships, while qualitative evidence was employed to explain and interpret these findings within the operational context of the participating organizations. This mixed-methods research design therefore provided a comprehensive assessment of maintenance management practices in the Sri Lankan tyre manufacturing industry.

3. Interview Questions

Semi-structured interviews were employed as a qualitative data collection technique to obtain

detailed insights into maintenance practices, challenges, and organizational factors from participants with relevant knowledge and experience. This approach provided a consistent framework for comparison across interviews while allowing participants to elaborate on issues relevant to their specific roles and organizational contexts. Accordingly, the interviews were guided by a predetermined set of questions; however, minor variations were made where necessary to accommodate the specific circumstances and issues that arose during each interview. The following questionnaire item uses a quantitative survey technique, specifically a structured ordinal-frequency measurement based on descriptive statistics. It is designed to collect numerical data about how frequently different maintenance strategies are used in the respondent's workplace.

Q1. Which of the following maintenance strategies are used in your workplace?

(Respondent's perceived frequency of use: Always / Sometimes / Rarely / Never)

Reactive Maintenance (breakdown maintenance-BM), Proactive Maintenance (Preventive Maintenance-PM, Autonomous Maintenance-AM), Predictive Maintenance-PdM, Condition-Based Maintenance-CbM, Reliability Centred Maintenance-RCM, Total Productive Maintenance-TPM.

Q2. To what extent are the following maintenance management best practices implemented in your organization?

(Respondent's perceived frequency of use: Fully Implemented / Partially Implemented / Planned / Not Implemented)

PM adherence measure (%), Machine release to PMs, Annual maintenance plans availability and functioning, Shutdown maintenance practices, Operator involvement in AM, Predictive Maintenance (PdM) practices, Condition-Based Maintenance (CbM) practices, CMMS availability and utilization, Understanding and use of RCM,

Maintenance planning function, Weekly maintenance meetings, Monthly maintenance reviews, Management commitment to maintenance improvement.

Q3. Are maintenance activities supported by documented procedures, maintenance plans, and digital systems?

(Respondent's perceived frequency of use: Fully Implemented / Partially Implemented / Planned / Not Implemented)

Monthly maintenance reviews-action log, KPI reviews (MTBF, MTTR, PM Compliance), Benchmarking /maintenance audits, Problem-solving reports (5 Why, mFMEA, RCFA)

Q4. To what extent are employees involved in maintenance improvement activities?

(Respondent's perceived frequency of use: Highly Involved / Moderately Involved / Rarely Involved / Not Involved)

Execute AM function, Problem-solving meeting function, Kizen in maintenance.

4. Analysis and Results

This section presents the analyses and findings of the study based on the data collected. The analyses are organized into the following Quantitative and Qualitative analyses subsections.

4.1 Quantitative Analyses

Quantitative data obtained through structured questionnaires were analyzed using appropriate statistical techniques (descriptive statistics) to identify trends, relationships, and variations in maintenance management practices. As presented in Table 3.1, the survey results for Question 1 (Q1) indicate considerable variation in the maintenance strategies perceived to be used across the six companies. The findings demonstrate differences in the extent to which proactive, reactive, and non-specific maintenance practices are adopted within the organizations.

Table 3.1: Quantitative Analysis of Survey Results for Q1

Q1. Which of the following maintenance strategies are used in your workplace?

(Respondent's perceived frequency of use)

	Company1	Company2	Company3	Company4	Company5	Company6
Declaring that proactive maintenance strategies are being used	84.72 %	52.38 %	57.60 %	68.69 %	34.08 %	20.27 %
Declaring that reactive maintenance strategies are used	14.28 %	14.29 %	11.9 %	14.28 %	13.29 %	15.06 %
Declare that no specific maintenance strategy is used	0 %	33.3 %	30.42 %	17.03 %	52.63 %	64.67 %

The quantitative ordinal-frequency statistics, shown in Table 3.1, indicate that proactive maintenance strategies are most strongly embedded in Company1, where 84.72% of respondents reported that proactive maintenance is consistently practiced. This suggests a highly structured maintenance culture focused on prevention, reliability, and continuous improvement. Company4 also demonstrates a strong commitment to proactive maintenance, with 68.69% of respondents indicating its use. Moderate levels of proactive maintenance adoption are evident in Company3 (57.60%) and Company2 (52.38%), suggesting that preventive and predictive maintenance practices are present but may not yet be fully integrated across all operations. In contrast, Company5 (34.08%) and particularly Company6 (20.27%) report substantially lower levels of proactive maintenance implementation. These findings imply that systematic preventive maintenance practices are less established in these

organizations, potentially affecting equipment reliability and operational efficiency.

The use of reactive maintenance strategies appears relatively consistent across all six plants, ranging from approximately 11.9% to 15.06%. This suggests that while breakdown-based maintenance remains a necessary component of maintenance management, it is not the dominant strategy in any of the surveyed organizations. The similar percentages indicate a common reliance on corrective actions when unexpected failures occur. A notable distinction emerges in responses indicating no specific maintenance strategy. This response was absent in Company1, where no respondents reported a lack of maintenance strategy, reflecting a mature and well-defined maintenance management system. Conversely, more than half of the respondents in Company5 (52.63%) and Company6 (64.67%) stated that no specific maintenance strategy is employed. Similarly, considerable proportions were reported in Company2 (33.3%), Company3 (30.42%), and Company4 (17.03%). These

findings suggest varying levels of maintenance management maturity across the organizations, with some plants relying on informal or inconsistent maintenance approaches.

Overall, the data reveal a spectrum of maintenance management practices. Company1 and Company4 exhibit the highest levels of proactive maintenance adoption and the strongest maintenance frameworks, while Company5 and Company6 demonstrate the

lowest levels of structured maintenance strategy implementation. The relatively uniform use of reactive maintenance across all plants indicates that corrective maintenance remains a common operational requirement, regardless of the overall maintenance philosophy adopted by the organization. These findings suggest that organizations with higher proactive maintenance adoption tend to exhibit greater maintenance system maturity and strategic alignment toward equipment reliability and operational excellence.

Table 3.2: Quantitative Analysis of Survey Results for Q

Q2. To what extent are the following maintenance management best practices implemented in our organization?
(Respondent's perceived frequency of use)

	Company1	Company2	Company3	Company4	Company5	Company6
Responses received stating that the best maintenance management practices are being implemented	96.79 %	27.54 %	28.53 %	34.79 %	30.30%	7.69 %
Responses received stating that the best maintenance management practices are not implemented	3.21 %	72.46 %	71.47 %	65.21 %	69.70%	92.31 %

Table 3.2 reveals substantial differences among the six companies regarding the perceived implementation of maintenance management best practices. Among all the organizations surveyed, Company1 demonstrated the highest level of implementation, with 96.79% of respondents indicating that maintenance management best practices are being practised within the organization. Only 3.21% of respondents reported otherwise, suggesting a highly mature maintenance management system characterized by well-established processes, standardization, and continuous improvement initiatives.

In contrast, the remaining organizations reported considerably lower levels of implementation. Company4 recorded the second-highest level of positive responses, with 34.79% of participants

indicating that the best maintenance management practices are implemented. This was followed by Company5 at 30.30%, Company3 at 28.53%, and Company2 at 27.54%. Although these organizations exhibit some degree of maintenance management practice adoption, the majority of respondents in each plant perceived that such practices are not fully implemented. Specifically, the percentages of respondents indicating non-implementation ranged from 65.21% in Company4 to 72.46% in Company2, highlighting opportunities for further improvement in maintenance planning, execution, monitoring, and performance management. Company6 recorded the lowest level of implementation, with only 7.69% of respondents confirming that maintenance management best practices are in place, while an

overwhelming 92.31% reported that such practices are not implemented. This finding suggests a relatively low level of maintenance management maturity and indicates the potential need for significant improvements in maintenance systems, policies, and organizational practices. Overall, the results suggest that Company1 has established a significantly stronger maintenance management framework compared to the other organizations surveyed. The high level of perceived implementation in Company1 reflects a culture of proactive maintenance and operational excellence.

Conversely, the predominance of negative responses in the remaining organizations indicates that maintenance management best practices have not yet been fully institutionalized, emphasizing the need for greater focus on strategic maintenance planning, workforce development, performance measurement, and continuous improvement initiatives to enhance maintenance effectiveness and organizational performance.

Table 3.3: Quantitative Analysis of Survey Results for Q3

Q3. Are maintenance activities supported by documented procedures, maintenance plans, and digital systems?

(Respondent's perceived frequency of use)

	Company1	Company2	Company3	Company4	Company5	Company6
Responses received that it has been implemented	83.62 %	43.95 %	45.62 %	39.56 %	22.55 %	0 %
Responses received that it has not been implemented	16.38 %	56.05 %	54.38 %	60.44 %	77.45 %	100 %

The survey results in Table 3.3 indicate considerable differences among the six companies in terms of the implementation of documented maintenance procedures, maintenance plans, and digital maintenance systems. These elements are widely recognized as essential components of effective maintenance management, as they facilitate standardization, planning, monitoring, and continuous improvement of maintenance activities. Among the organizations surveyed, Company1 demonstrated the highest level of implementation, with 83.62% of respondents indicating that maintenance activities are supported by documented procedures, maintenance plans, and digital systems. Only 16.38% reported that such practices are not implemented. This result reflects a highly structured maintenance environment in which

maintenance activities are systematically planned, documented, and supported by digital technologies, contributing to enhanced operational reliability and maintenance efficiency. Liu et al. (2024) emphasized that, in the current landscape, smart manufacturing facilities can achieve efficient production output by integrating advanced scientific technologies, specifically Internet of Things (IoT) applications, into traditional manufacturing processes.

Moderate levels of implementation were observed in Company3 and Company2, where 45.62% and 43.95% of respondents, respectively, confirmed the existence of documented maintenance procedures and digital support systems. However, slightly more than half of the respondents in these organizations indicated that such systems are not implemented, suggesting that maintenance documentation and

digitalization initiatives may be present only in selected departments or have not yet been fully integrated across the organizations. Company4 reported a comparable level of implementation, with 39.56% of respondents acknowledging the use of documented maintenance procedures and digital systems, while 60.44% reported their absence. This finding suggests that although certain maintenance management practices have been adopted, there remains substantial scope for further formalization and digital transformation of maintenance processes. Lower levels of implementation were reported in Company5, where only 22.55% of respondents indicated that maintenance activities are supported by documented procedures and digital systems, while a significant majority (77.45%) stated that such practices are not implemented. This result points to limited use of formal maintenance management frameworks and highlights the need for greater emphasis on documentation, planning, and technological support.

The most notable finding was observed in Company6, where none of the respondents reported the implementation of documented procedures, maintenance plans, or digital

maintenance systems. Instead, 100% of respondents indicated that these elements are not implemented. This suggests the absence of a formalized maintenance management structure and indicates a significant opportunity for improvement through the development of maintenance documentation, planning mechanisms, and digital maintenance support systems. Overall, the results reveal a clear disparity in the maturity of maintenance management systems across the surveyed organizations. Company1 exhibits the highest level of maintenance system formalization and digital integration, reflecting a strong commitment to best maintenance management practices. In contrast, the lower implementation levels observed in the other organizations, particularly Company5 and Company6, suggest that maintenance activities are less structured and less supported by formal documentation and digital technologies. These findings underscore the importance of adopting documented maintenance procedures, comprehensive maintenance planning, and digital maintenance management systems to enhance maintenance effectiveness, equipment reliability, and overall operational performance.

Table 3.4: Quantitative Analysis of Survey Results for Q4

Q4. To what extent are employees involved in maintenance improvement activities?

(Respondents' perceived frequency of involvement)

	Company1	Company2	Company3	Company4	Company5	Company6
Responses received indicating that employees are engaged in maintenance improvement activities	63.88 %	30.12 %	6.45 %	17.30 %	7.89 %	0 %
Responses received indicating that employees are not engaged in	36.11 %	69.87 %	93.54 %	87.50 %	92.10 %	100 %

Q4. To what extent are employees involved in maintenance improvement activities?

(Respondents' perceived frequency of involvement)

maintenance improvement activities						
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Table 3.4 presents the results on the extent of employee involvement in maintenance improvement activities. The results identified that employee participation is widely recognized as a critical element of effective maintenance management, as it promotes continuous improvement, enhances problem-solving capabilities, and fosters a culture of shared responsibility for equipment reliability and operational performance. Among the organizations surveyed, Company1 demonstrated the highest level of employee engagement in maintenance improvement activities. A substantial 63.88% of respondents indicated that employees actively participate in such initiatives, while 36.11% reported otherwise. This finding suggests that Company1 has established mechanisms that encourage workforce involvement in maintenance-related decision-making, problem identification, and continuous improvement efforts, which are characteristic of advanced maintenance management systems. Company2 recorded the second-highest level of employee involvement, with 30.12% of respondents indicating that employees participate in maintenance improvement activities. However, the majority of respondents (69.87%) reported a lack of employee engagement, suggesting that opportunities for workforce participation exist but are not yet widespread throughout the organization. The remaining organizations reported relatively low levels of employee involvement. Company4 recorded 17.30% positive responses, while Company5 and Company3 reported only 7.89% and 6.45%, respectively. In each of these organizations, more than 85% of respondents indicated that employees are not engaged in maintenance improvement activities. These findings suggest that maintenance improvement efforts may be

largely driven by management or maintenance personnel, with limited participation from the broader workforce.

The lowest level of employee involvement was observed in Company6, where none of the respondents reported employee engagement in maintenance improvement initiatives. Instead, 100% of respondents indicated that employees are not involved in such activities. This result points to the absence of structured employee participation mechanisms and highlights a significant opportunity for the organization to strengthen workforce involvement in maintenance-related continuous improvement programs. Overall, as demonstrated in the literature, the findings indicate that employee participation in maintenance improvement activities is strongest at Company1 (Au-Yong et al., 2022) and considerably weaker in the other organizations surveyed. The high level of participation reported in Company1 reflects a maintenance culture that values employee contributions and continuous improvement. On the other hand, the high number of negative responses from the remaining organizations indicates that employee involvement in maintenance improvement activities is still relatively limited. These results emphasize the importance of fostering employee participation through suggestion schemes, cross-functional teams, autonomous maintenance programs, and continuous improvement initiatives, as greater workforce engagement can contribute significantly to maintenance effectiveness, equipment reliability, and organizational performance.

4.1.1 Synthesis of Quantitative Findings

The quantitative findings demonstrate substantial variation in maintenance management practices

across the six tyre manufacturing organizations. These differences reflect varying levels of organizational maintenance maturity, from structured, reliability-centred systems to predominantly reactive, breakdown-driven approaches. Higher levels of proactive maintenance, best-practice implementation, documentation, digitalization, and employee involvement in the leading organization indicate that maintenance maturity is multidimensional. Effective maintenance requires the combined development of maintenance planning, reliability engineering, management systems, employee participation, performance measurement, and organizational commitment rather than reliance on a single technique such as preventive or predictive maintenance. This aligns with maintenance literature emphasizing the integration of technological, organizational, and human factors. PM implementation is an important indicator of maturity, but formal PM schedules do not always ensure effective execution. Production pressures and difficulties in releasing equipment often postpone PM until equipment failure, reinforcing reactive maintenance and increasing equipment deterioration, unplanned downtime, emergency repairs, and costs. Therefore, PM compliance should be considered both a maintenance performance measure and an indicator of coordination between production and maintenance functions.

Differences in maintenance documentation and digital-system adoption further show that maintenance maturity is linked to the availability and systematic use of maintenance information. A Computerized Maintenance Management System (CMMS) supports work-order management, PM scheduling, asset history, spare-parts management, and performance analysis. However, technology alone cannot create maintenance maturity; CMMS effectiveness depends on organizational processes, data quality, user engagement, management support, and maintenance discipline. This is consistent with Wienker et al.

(2015), who identified challenges in CMMS implementation, and Muraliraj et al. (2018), who highlighted computerized systems' role in improving the speed, accuracy, and timeliness of maintenance decisions.

Employee involvement is also significant. Higher participation reflects a shift from maintenance department responsibility toward shared equipment-reliability ownership, consistent with TPM, where operators participate in basic care, inspection, cleaning, lubrication, and early fault identification. Limited participation in less mature organizations indicates centralized maintenance within engineering departments, restricting early fault detection and collective equipment-reliability culture. Yang and Yang (2024) also further highlighted the importance of the relationship regarding employee participation in maintenance functions. Overall, maintenance maturity should be viewed as an organizational capability rather than a collection of technical practices. More mature organizations combine structured maintenance planning, technological support, employee involvement, performance measurement, reliability engineering, and management commitment, while organizations lacking these capabilities remain vulnerable to reactive maintenance despite introducing preventive or predictive techniques.

4.2 Qualitative Analyses

Qualitative data gathered from semi-structured interviews, focus group discussions, observations, and documentary analysis were examined to provide deeper insights into organizational practices, challenges, and strategic approaches to maintenance management. The results, as shown in Table 4, are presented through comparative case analysis, highlighting best practices, operational challenges, and opportunities for improving maintenance effectiveness, sustainability, and competitiveness within the Sri Lankan tyre manufacturing industry. Using these qualitative assessments and classification, relatively Company1 demonstrates world-class maintenance performance; Company2, Company3, and Company4 exhibit moderate PM effectiveness with reactive

maintenance dominance; Company5 shows poor maintenance maturity; while Company6 operates

in a critical, breakdown-driven maintenance environment.

Table 4: Summary of Qualitative Survey Results

Criteria	Company1	Company2	Company3	Company4	Company5	Company6
PM adherence level (%)	Excellent World-Class PM compliance (95-98%)	/ Moderate to Good PM compliance (65-70%)	Moderate PM compliance (60-65%)	Moderate to Good PM compliance (65-70%)	Poor PM compliance (25-30%)	Very Poor / Critical PM compliance 10%
Proactive vs Reactive Maintenance	Highly proactive, strong preventive maintenance culture (65:35%)	Predominantly reactive, limited proactive maintenance (20:80%)	Predominantly reactive, maintenance mainly driven by breakdowns (20:80%)	Predominantly reactive, with some preventive practices (20:80%)	Highly reactive, low preventive maintenance effectiveness (20:80%)	Extremely reactive, maintenance is largely breakdown-based (10:90%)
Machine release issues	Very Low	Moderate	Low	High	Moderate	Not at all
Annual maintenance plans	Fully established	Fairly treated	Fairly treated	Fairly treated	Available-poorly treated	Not at all
Shutdown maintenance practices	Highly structured	Planned	Structured	Periodic	Planned	Basic
Autonomous Maintenance (AM) involvement	Excellent TPM culture	Learning TPM culture	Learning TPM culture	Developing TPM culture	Learning TPM culture	Not at all
Predictive Maintenance (PdM)	Advanced digital PdM	Occasional PdM	Occasional PdM	Emerging PdM	Occasional PdM	Not at all

Criteria	Company1	Company2	Company3	Company4	Company5	Company6
Condition-Based Maintenance (CbM)	Extensive	Occasional	Occasional	Limited–Moderate	Occasional	Not at all
Thermography	Extensive	Used on critical assets	Occasional	Limited	Used on critical assets	Not at all
Vibration analysis	Extensive online monitoring	Critical equipment only	Occasional	Limited	Critical equipment only	Not at all
Oil analysis	Routine	Selected assets	Occasional	Rare	Rare	Not at all
Laser alignment	Standard practice	Used during overhauls	Used during overhauls	Used during overhauls	Used during overhauls	Not at all
CMMS availability	Enterprise-wide	Learning	Learning	No interest	No interest	Not at all
Understanding and use of RCM	Mature implementation	No intension	No intension	No intension	No intension	Not at all
Maintenance planning resources	Dedicated planners reliability engineers	& Centralized planners	Centralized planners	No planners	No planners	Not at all
Weekly maintenance meetings	Yes	No	No	Moderate	Rare	Not at all
Monthly maintenance reviews	Comprehensive	Occasional	Occasional	Conducted	No	Not at all

Criteria	Company1	Company2	Company3	Company4	Company5	Company6
KPI reviews (MTBF, MTTR, Compliance)	Highly data-PM driven	Regular	Low	Developing	No	Not at all
Management commitment to maintenance improvement	Very High	High	Moderate	Moderate	Moderate	low
Benchmarking / maintenance audits	Global internal & external audits	Internal benchmarking	Regular audits	ISO-driven audits	Internal audits	Not at all

4.2.1 Synthesis of Qualitative Findings

The qualitative findings provide important explanations for the differences observed among the six organizations. In particular, they indicate the factors in shaping maintenance maturity.

Management Commitment and Maintenance Strategy: Senior management commitment is a critical factor in achieving mature maintenance practices. Maintenance transformation requires sustained organizational support, including resources, training, technology, dedicated personnel, structured implementation, and continuous improvement. While employees in less mature organizations may understand concepts such as PM, PdM, RCM, and TPM, individual knowledge alone does not create organizational capability. Management must establish the necessary structures, responsibilities, resources, targets, and accountability to embed these practices. Therefore, strong leadership commitment is essential for moving organizations from reactive maintenance toward a sustainable, mature maintenance system. It also explains why employees who have previously worked in more mature organizations may possess considerable maintenance knowledge without necessarily

being able to reproduce those practices in their new organizations.

Maintenance Planning and Organizational Structure:

The qualitative evidence demonstrates that maintenance planning capability is a major determinant of maturity. The mature organization clearly separates maintenance planning, reliability engineering, execution, and project responsibilities, enabling maintenance personnel to prepare work in advance rather than continuously responding to breakdowns. In contrast, maintenance engineers in less mature organizations often perform multiple functions, including breakdown response, procurement, spare-parts management, planning, and operational support. This role overload limits time for systematic maintenance planning and reliability improvement, reinforcing reactive behaviour. Therefore, maintenance planning is an important organizational capability rather than merely an administrative activity. Dedicated planning resources enable organizations to develop job plans, schedule work, coordinate production releases, prepare materials and manpower, and monitor maintenance backlogs, supporting the transition from firefighting to proactive maintenance.

Production Pressure and the Reactive Maintenance Culture:

A recurring qualitative theme across less mature organisations is the conflict between production continuity and maintenance requirements. Production departments often prioritize immediate manufacturing output, causing scheduled maintenance to be postponed or restricted to critical assets. This explains why some organizations have preventive maintenance schedules but still demonstrate weak maintenance performance. The issue is not necessarily a lack of awareness of preventive maintenance, but the absence of an organizational mechanism for protecting scheduled maintenance time. The findings suggest that this production-maintenance conflict can institutionalize reactive maintenance. When production interruptions are considered more costly than preventive interventions, maintenance is deferred until failure occurs, creating a self-reinforcing reactive cycle through additional maintenance demands and production pressure. Breaking this cycle requires maintenance to be treated as a strategic contributor to production reliability. Maintenance and production objectives should therefore be aligned through shared performance indicators, planned shutdowns, cross-functional decision-making, and management-level review.

Reliability-Centred Maintenance and Advanced Maintenance Practices:

The mature organization, by contrast, uses RCM, RCA, mFMEA, criticality assessment (CA), PM, PdM, and CbM as interconnected elements of an overall reliability strategy. This supports the argument by Kharbanda et al. (2023) that FMEA provides an important analytical foundation within RCM, while Arakulasuriya et al. (2023) emphasize the role of RCM in improving maintenance decision-making and optimizing maintenance resources. The findings indicate significant differences in the institutionalization of RCM, RCA, FMEA, CBM, and PdM. The mature organization incorporates these practices into a broader reliability framework rather than treating them as isolated technical activities. The occasional use of thermography, vibration

analysis, oil analysis, or laser alignment does not necessarily constitute a mature predictive maintenance programme. Advanced maintenance technologies become strategically valuable when linked to asset criticality, failure modes, maintenance decision rules, data analysis, defined performance targets, and systematic follow-up. In intermediate organizations, advanced techniques are available but are often performed only when specific equipment problems occur or through external service providers, representing technology adoption without full organizational integration.

Digitalization and Maintenance Information:

Another important qualitative finding concerns the relationship between maintenance maturity and information management. The mature organization has an integrated CMMS and extensive use of maintenance data, whereas less mature organizations rely on manual records, spreadsheets, incomplete documentation, or experience-based decision-making. The absence of systematic maintenance information limits the ability to identify recurring failures, analyze equipment history, calculate reliability indicators, manage maintenance backlogs, and make evidence-based decisions. Labib (2004) and Labib (2008) emphasized that computerized maintenance systems can support multiple organizational levels, from operators and maintenance workers to planners, managers, and senior management. The findings also suggest that poor documentation is both a technical and cultural problem. In some organizations, maintenance personnel did not perceive documentation improvements as directly contributing to maintenance effectiveness. Therefore, documentation needs to be understood as part of the maintenance process rather than simply an administrative requirement for audits. The distinction between documentation for compliance and documentation for decision-making is particularly important. Where records are primarily generated to satisfy audits, their value for reliability analysis remains limited. Mature organizations instead use maintenance information to support planning, failure analysis,

performance evaluation, and continuous improvement.

Employee Involvement and Autonomous Maintenance: The qualitative evidence demonstrates that employee involvement differentiates mature and less mature maintenance systems. The mature organization has established TPM, AM, Kaizen, and cross-functional improvement activities, enabling operators to participate in equipment care and problem identification. In less mature organizations, operators generally focus on production and report equipment failures to maintenance personnel. This creates a narrow definition of responsibility where equipment reliability is viewed primarily as the responsibility of engineers and technicians. The findings suggest that AM is important because operators continuously interact with equipment and can identify abnormalities at an early stage. However, successful AM requires training, clearly defined responsibilities, standardized procedures, and management support. Simply assigning maintenance tasks to operators without these supporting conditions is unlikely to produce sustainable improvement.

Performance Measurement and Continuous Improvement: The qualitative findings indicate that mature maintenance systems are characterized by systematic performance measurement. Indicators such as PM compliance, MTBF, MTTR, PdM performance, and other reliability measures are regularly reviewed and linked to management decision-making. The Engineering and Maintenance Management Council (EMMC) mechanism demonstrates how performance measurement can become part of organizational governance by creating accountability, enabling comparison between units, and identifying areas requiring corrective action. This supports Parmenter's (2015) argument that KPIs connect operational activities with strategic objectives. However, the usefulness of KPIs depends on how they are used. Measuring PM compliance without addressing production constraints, resource limitations, technical competence, or

maintenance planning weaknesses may have limited effect. KPIs therefore need to be embedded within a broader performance-management and improvement system. The mature organization's use of internal benchmarking and periodic external audits is particularly significant. These practices create an organizational learning mechanism for comparing maintenance practices, identifying weaknesses, and institutionalizing improvements. This continuous-learning capability appears to be a major difference between mature and developing maintenance systems.

The qualitative evidence indicates that the six organizations occupy different stages of a maintenance maturity continuum rather than representing completely separate maintenance models. The most mature organization demonstrates a strategically managed, RCM system supported by management commitment, dedicated maintenance planning resources, RCM and TPM, advanced maintenance technologies, CMMS, employee involvement, KPI monitoring, benchmarking, and continuous improvement. The three intermediate organizations show a partial transition from reactive to proactive maintenance. Although they possess some PM practices and selected advanced technologies, these are not fully institutionalized due to limited planning resources, production pressures, insufficient employee involvement, weak digitalization, and inconsistent performance review. The relatively low-maturity organization demonstrates a policy-practice gap, where maintenance plans and modern maintenance concepts exist but are not consistently implemented. This shows that formal adoption of maintenance terminology does not necessarily represent actual maintenance maturity. The least mature organization has a predominantly failure-driven maintenance system, characterized by limited planning, weak PM capability, minimal documentation, absence of digital maintenance systems, limited KPI monitoring, and dependence on emergency and outsourced repairs.

Overall, the cross-case pattern suggests that maintenance maturity develops progressively. Organizations cannot move directly from breakdown maintenance to advanced predictive maintenance without first establishing foundations such as asset registers, preventive maintenance schedules, maintenance planning, documentation, competent personnel, performance measurement, and management commitment. Advanced technologies are therefore most likely to generate sustainable benefits when these foundational capabilities are already established.

5. Discussion

The mixed-methods findings demonstrate substantial differences in maintenance management maturity across the six tyre manufacturing organizations. Quantitative results consistently identified Company1 as the benchmark organization, with the highest adoption of proactive maintenance (84.72%), maintenance management best practices (96.79%), documented procedures and DMS (83.62%), and employee involvement (63.88%). In contrast, Company6 recorded the lowest levels, including 20.27% proactive maintenance and 0% implementation of maintenance documentation, digital systems, and employee involvement. These findings are consistent with Gholipour et al. (2025), who highlighted that the limitations of reactive maintenance, including unplanned downtime, increased repair costs, and security risks, have driven organizations toward preventive approaches. Interview findings strongly corroborated the quantitative results by demonstrating that Company1 has a mature PM culture supported by CMMS, PdM technologies, reliability engineering, structured shutdown planning, AM, TPM, and systematic KPI reviews. Conversely, Company6 relies predominantly on breakdown maintenance and lacks formal maintenance planning, digital systems, documented procedures, predictive technologies, and structured performance management. Thus, the qualitative findings provide organizational explanations for the quantitative differences.

The intermediate-performing organizations Company2, Company3, and Company4, demonstrated moderate levels of maintenance maturity. Their quantitative results were supported by qualitative evidence showing partial implementation of PM, limited PdM, moderate management commitment, restricted CMMS utilization, and developing TPM practices. These organizations are transitioning from reactive toward proactive maintenance but have not yet achieved the level of integration and organizational maturity observed at Company 1. Company 5 demonstrated relatively weak maintenance maturity, with annual maintenance plans and some PM activities existing but being inconsistently implemented. The qualitative findings indicated that weak management commitment, production priorities, inadequate equipment release, limited AM, and insufficient performance monitoring were major barriers to proactive maintenance implementation.

Company 1 emerged as the most mature organization because of its long-term strategic commitment to maintenance excellence. Its maintenance transformation began in 2013 with the introduction of RCM and TPM, supported by external Certified Maintenance and Reliability Professional (CMRP) expertise, comprehensive training, organizational change, and strong senior-management commitment. Since 2018, continuous improvement has been institutionalized through internal RCM benchmarking across North American and Sri Lankan operations and periodic external audits. RCA and mFMEA were introduced as important components of the RCM framework. FMEA has been identified as a basic application of RCM and a widely used critical assessment method (Kharbanda et al., 2023), while RCM supports spare-parts optimization and the elimination of inefficient maintenance practices (Arsakulasuriya et al., 2023). The analytical nature of RCM also strengthens evidence-based asset management and maintenance decision-making (Arsakulasuriya et al., 2023). Company 1's integrated framework incorporates PM, PdM (Nunes et al., 2023; Zonta et al., 2020), CBM (Ahmad and Kamaruddin, 2012), CA (Lopes et

al., 2020), RCM, and CMMS (Hoffmann et al., 2023).

A major contributor to Company1's superior performance is its organizational structure, particularly the separation of maintenance planning from maintenance execution. Dedicated maintenance planners and reliability engineers support systematic planning and reliability improvement, while project responsibilities are separately managed. Company1 has established a long-term objective of eliminating reactive maintenance, achieving zero breakdowns, and reaching 100% PM compliance. Maintenance performance is systematically reviewed through monthly and quarterly EMMC meetings, supported by KPI monitoring of PM compliance, PdM performance, MTBF, MTTR, and other reliability indicators. KPI monitoring enables organizations to align operational activities with strategic objectives, identify improvement areas, and support informed decision-making (Parmenter, 2015). Company1 is also progressively transitioning from traditional time-based maintenance toward performance-based maintenance, consistent with the approach discussed by Gerum et al. (2019). Although CbM and PdM performance is currently approximately 75% against an 80% target, the organization demonstrates continuous progress toward advanced maintenance practices. Only minor deficiencies, particularly incomplete updating of the asset register, were identified in its maintenance documentation.

Company2 demonstrates a genuine intention to develop PM through annual schedules and planned monthly shutdowns. PM compliance is estimated at approximately 65–70%, although formal records were unavailable to validate this figure. PM is concentrated mainly on critical equipment, while operator involvement, maintenance review meetings, reliability analysis, and continuous improvement remain limited. Planning responsibilities are also combined with procurement activities, unlike Company1's dedicated planning structure. Company2 uses selected predictive techniques, including thermography, oil analysis, and laser alignment,

although several are outsourced and are not fully integrated into a systematic maintenance strategy. Limited organizational commitment to RCM and CMMS was also identified. Maintenance documentation is generally available but requires improvements in completeness, revision control, and record-keeping. Well-designed and technically accurate procedures can improve technician compliance and maintenance execution (Kanse et al., 2018). Strengthening documentation and maintenance planning could therefore improve Company2's overall maintenance effectiveness.

Company3 continues to rely mainly on a reactive approach to maintenance, even though it recognizes the importance of PM practices. Preventive activities are concentrated on highly critical equipment and are often aligned with production shutdowns rather than controlled through a comprehensive plant-wide PM programme. Operator involvement in AM is limited, while maintenance engineers must simultaneously manage planning, procurement, spare parts, and breakdown response. Selected PdM and CbM techniques, including thermography, vibration analysis, oil monitoring, and laser alignment, are available but remain fragmented and reactive. Limited adoption of RCM and CMMS restricts reliability analysis, asset history utilization, failure trend analysis, and data-driven decision-making. Computer-based maintenance support is important for effective operational maintenance management, although CMMS implementation has historically experienced low success rates (Wienker et al., 2015). CMMS can support multiple organizational levels, including operators, maintainers, planners, managers, accountants, and senior management (Labib, 2004; Labib, 2008). The absence of regular strategic maintenance review meetings further reinforces the reactive nature of maintenance decision-making (Bloch and Geitner, 1990). Consequently, Company3 can be classified as an intermediate-maturity organization requiring stronger planning, AM, reliability engineering, PdM, CMMS implementation, and formal performance reviews.

Company4 has maintained a preventive maintenance programme since 2018, with PM compliance estimated at approximately 65–70%; however, the organization still relies largely on a reactive approach to maintenance. Production pressures frequently prevent scheduled equipment release, while shortages of technically competent technicians constrain maintenance execution. Maintenance performance monitoring is largely limited to PM compliance and breakdown records maintained in Microsoft Excel. The absence of a CMMS limits effective work-order management, asset history tracking, reliability analysis, and timely decision-making, despite the importance of computerized systems for data accuracy and maintenance effectiveness (Muraliraj et al., 2018; Zahir et al., 2025). The organization also shows limited interest in data-driven maintenance approaches, although such approaches can support anomaly detection, failure-mode classification, degradation estimation, and failure analysis (Mohammad and Ara, 2023; Mohammad and Sazzad, 2023; Rajesh, 2023; Bakri et al., 2021). RCM, CBM, PdM, criticality assessment, and failure-mode analysis remain largely undeveloped. The future adoption of online PdM within TPM/RCM environments, supported by cross-functional teams and real-time condition monitoring, is therefore important (Arsakulasooriya et al., 2023). Overall, Company4 represents a transitional maintenance organization requiring improved PM compliance, machine release practices, technician competencies, CMMS adoption, reliability methodologies, and strategic maintenance reviews.

Company5 demonstrates relatively low maintenance maturity. Both maintenance and production personnel possess limited understanding of PM maturity and industry benchmarks (Au-Yong et al., 2022). Maintenance remains predominantly reactive, with production priorities frequently overriding scheduled maintenance. Annual maintenance plans are available but appear to be weakly implemented and, in some cases, primarily maintained for audit purposes. TPM is visible within the organization, but no structured Autonomous Maintenance

programme was identified. PdM and CbM activities are occasional and fragmented, while thermography, laser alignment, and other techniques are generally outsourced. No CMMS or RCM implementation was identified, and there are no dedicated maintenance planners or regular weekly or monthly maintenance review meetings. Although engineers understand indicators such as MTBF, MTTR, and PM compliance, these are not systematically reviewed. PM compliance was estimated at approximately 30%, confirming the organization's predominantly reactive maintenance culture. The major barrier to improvement is weak management commitment.

Company6 represents the lowest level of maintenance management maturity. Maintenance is almost entirely breakdown-driven, with no structured PM, PdM, AM, reliability engineering, maintenance planning, CMMS, formal SOPs, maintenance audits, or systematic KPI monitoring. The organization operates largely according to a failure-to-failure strategy and frequently relies on outsourced contractors for emergency repairs. Although some engineers understand PM concepts and the recently appointed Managing Director has experience from Company1, no formal implementation strategy, targets, or timelines have been established. Knowledge of PdM, CbM, RCM, TPM, and other advanced methodologies is extremely limited. Bakri et al. (2021) emphasized the importance of AM, while Mouhib et al. (2024) highlighted technical readiness and infrastructure as prerequisites for effective PdM and TPM implementation. Similarly, Meddaoui et al. (2023) emphasized the importance of PdM and CbM for reducing planned and unplanned downtime through failure prediction. Company6 currently lacks the organizational and technical foundation necessary for such approaches. Its immediate priority should therefore be establishing basic maintenance planning, documentation, PM programmes, performance measurement, staffing capabilities, and management commitment before progressing toward advanced reliability practices.

Overall, the six organizations form a clear maintenance maturity continuum. Company1 represents the benchmark organization, characterized by strategic leadership, high PM compliance, dedicated maintenance resources, advanced predictive technologies, structured planning, systematic KPI monitoring, and continuous organizational learning (Bakri et al., 2021; Antosz et al., 2021; Tortorella et al., 2021). Company2, Company3, and Company4 occupy an intermediate or transitional position, with some preventive and predictive practices established but constrained by reactive cultures, limited planning capabilities, inadequate digitalization, and insufficient reliability engineering. Company5 demonstrates low maturity, while Company6 represents the earliest stage, characterized by near-total dependence on BM. Poor maintenance practices can also generate hidden losses such as excessive downtime and spare-parts overstocking (Antosz et al., 2021).

The integration of quantitative and qualitative evidence produced strong convergence across the six organizations. Both datasets independently identified Company1 as the benchmark and Company 6 as the least mature organization, while consistently positioning Company2, Company3, and Company4 at intermediate levels and Company5 at a relatively weak level. The qualitative findings explained the numerical differences by revealing the organizational, managerial, technological, and cultural conditions underlying maintenance performance. This convergence strengthens the credibility and trustworthiness of the findings through methodological triangulation. Overall, the mixed-methods approach enabled the study to move beyond measuring maintenance implementation levels and to explain why significant differences exist among organizations. The findings indicate that management commitment, organizational structure, maintenance planning capability, technological adoption, performance measurement, employee involvement, and continuous benchmarking are the principal factors shaping maintenance

management maturity within the Sri Lankan tyre manufacturing industry.

5.1 Triangulation and Mixed-Methods Integration

The integration of quantitative and qualitative findings provides a more comprehensive explanation of maintenance management maturity across the six organizations. The quantitative analysis established the extent and relative magnitude of differences, while the qualitative evidence explained the organizational mechanisms underlying those differences. In accordance with the convergent mixed-methods approach described by Creswell and Plano Clark (2017) and Teddlie and Tashakkori (2009), the quantitative and qualitative datasets were therefore compared during interpretation. The triangulation revealed a high degree of convergence between the two datasets. The quantitative survey established substantial differences in maintenance management implementation among the six organizations, while the qualitative evidence provided contextual explanations for these differences. In particular, the organization identified quantitatively as having the strongest maintenance management performance was also characterized qualitatively by the most developed maintenance planning, reliability practices, digital systems, employee involvement, performance monitoring, and continuous improvement mechanisms. Conversely, the organization with the weakest quantitative performance was also found qualitatively to have the least developed maintenance planning, documentation, digital infrastructure, proactive maintenance practices, and performance management.

5.2 Convergence of Quantitative and Qualitative Evidence

A strong convergence was observed between the two datasets. Organizations that demonstrated higher quantitative levels of proactive maintenance, best-practice implementation, documentation, digitalization, and employee involvement also demonstrated corresponding qualitative characteristics. For the most mature

organization, quantitative evidence was supported by qualitative evidence of structured PM, CMMS utilization, PdM, RCM, TPM, dedicated planning resources, KPI monitoring, benchmarking, and continuous improvement. Thus, the qualitative findings provide explanatory depth to the quantitative indicators rather than simply repeating them. Similarly, the low quantitative performance of the least mature organization was supported by qualitative evidence of breakdown-driven maintenance, absence of formal maintenance planning, limited documentation, lack of CMMS, minimal predictive maintenance, weak KPI monitoring, and limited employee involvement. The three intermediate organizations also demonstrated convergence. Their moderate quantitative scores were consistent with qualitative evidence of partial PM implementation, limited PdM, inadequate planning resources, weak digitalization, and developing but incomplete proactive maintenance cultures. The convergence was also evident in the intermediate organizations. The quantitative results positioned Company2, Company3, and Company4 between the highest and lowest-performing organizations. The qualitative evidence supported this position by demonstrating that these organizations had introduced selected preventive and predictive maintenance practices but had not yet fully institutionalized the organizational systems required for advanced reliability-centred maintenance. Thus, the qualitative findings did not merely reproduce the quantitative ranking; they explained why these organizations occupied an intermediate position.

5.3 Complementarity of the Two Methods

The most important contribution of the mixed-methods design is not simply that the two datasets produced similar rankings. Rather, the qualitative findings explain why similar or different quantitative scores occurred. For example, a PM compliance level can indicate whether scheduled maintenance is being completed, but it cannot by itself explain whether poor compliance results from production pressure, insufficient manpower, lack of

planning, weak management support, or poor operator cooperation. The interviews and observations provided this contextual explanation. Likewise, a low score for digital maintenance implementation does not explain whether an organization lacks financial resources, technical competence, management interest, or organizational readiness. The qualitative evidence revealed that these factors varied between organizations. The mixed-methods approach therefore transformed the quantitative results from descriptive indicators into evidence of underlying organizational processes.

5.4 Absence of Major Contradictions

No major contradictions were identified between the quantitative and qualitative datasets. Instead, the qualitative findings generally confirmed and contextualized the quantitative results. Some differences arose because certain qualitative estimates were based on interviews or observations rather than formal records. For example, PM compliance in organizations without reliable maintenance records was estimated by engineering personnel. Such cases highlight an important methodological finding in themselves: weak maintenance information systems can reduce the reliability of organizational performance measurements. Therefore, apparent uncertainty in some quantitative estimates does not necessarily weaken the overall findings. Rather, it provides additional evidence of weaknesses in maintenance documentation, performance measurement, and information management within the less mature organizations.

5.5 Explanatory Mixed-Methods Interpretation

The overall mixed-methods interpretation indicates that maintenance maturity is determined by an interconnected set of organizational, managerial, technical, and cultural factors. Management commitment provides the strategic direction and resources; maintenance planning provides the organizational mechanism for executing proactive work; CMMS and documentation provide the information

infrastructure; reliability methodologies provide analytical support; employee involvement provides operational ownership; and KPI monitoring and benchmarking provide mechanisms for accountability and continuous improvement. The absence or weakness of one or more of these elements can restrict the development of maintenance maturity. Conversely, their integration creates the conditions required for sustained transition from reactive maintenance toward proactive and RCM.

This interpretation is consistent with the broader literature showing that maintenance improvement depends not only on technical methods but also on organizational capability, management systems, human involvement, digital infrastructure, and continuous improvement (Antosz et al., 2021; Tortorella et al., 2021).

Table 5: Convergence of Quantitative and Qualitative Evidence of The Study

Research Question	Quantitative Evidence	Qualitative Evidence	Mixed-Methods Interpretation
Maintenance strategies	Survey percentages (Table 3.1)	Interview themes on PM, PdM, TPM, RCM	Explains why Company1 is proactive while Rovince remains reactive.
Maintenance practices	Survey percentages (Table 3.2)	Interviews, observations, documents	Confirms differences in maintenance maturity across companies.
Documentation and digital systems	Survey percentages (Table 3.3)	CMMS use, maintenance plans, maintenance records	Explains the relationship between digitalization and maintenance effectiveness.
Employee involvement	Survey percentages (Table 3.4)	TPM, autonomous maintenance, Kaizen, management practices	Shows how organizational culture influences maintenance performance.

The triangulation revealed a high degree of convergence between the two datasets. The quantitative survey established substantial differences in maintenance management implementation among the six organizations, while the qualitative evidence provided contextual explanations for these differences. In particular, the organization identified quantitatively as having the strongest maintenance management performance was also characterized qualitatively by the most developed maintenance planning, reliability practices, digital systems, employee involvement, performance monitoring, and continuous improvement

mechanisms. Conversely, the organization with the weakest quantitative performance was also found qualitatively to have the least developed maintenance planning, documentation, digital infrastructure, proactive maintenance practices, and performance management. This structure clearly demonstrates integration, which is the defining feature of a mixed-methods study, and aligns well with the guidance of Creswell and Plano Clark (2017) and Teddlie and Tashakkori (2009).

6. Conclusions and Recommendations

Overall, the findings demonstrate that management commitment, organizational structure, maintenance planning capability, technical competence, adoption of digital maintenance technologies, systematic performance measurement, and continuous benchmarking are the principal determinants of maintenance management maturity within the Sri Lankan tyre manufacturing industry. Organizations that invest strategically in these areas are more likely to achieve higher equipment reliability, improved operational performance, lower maintenance costs, and greater long-term competitiveness.

The study therefore recommends that organizations currently operating under reactive maintenance regimes should progressively adopt

reliability-based maintenance strategies by strengthening preventive maintenance planning, implementing CMMS and PdM, establishing dedicated maintenance planning functions, increasing operator participation through AM, developing maintenance performance measurement systems, and fostering stronger management commitment toward continuous maintenance improvement. Such initiatives would facilitate the transition from reactive maintenance toward world-class maintenance practices and improve the long-term sustainability of manufacturing operations. Several recommendations are summarized here for each of the case study companies involved in this study (see Table 6) that can provide guidance for improving their maintenance management.

Table 6: Recommendations for the Case Study Organizations

Company	Recommendations
Company1	1. Continue the long-term reliability-centred maintenance strategy as an integral part of the business strategy.
	2. Continue internal and external maintenance benchmarking to sustain world-class performance.
	3. Increase the application of Condition-Based Maintenance (CbM) and Predictive Maintenance (PdM) to reduce reactive maintenance further.
	4. Continue developing maintenance competencies through continuous training and knowledge sharing.
	5. Strengthen data-driven maintenance decision-making using CMMS and reliability analytics.
	6. Continue the autonomous maintenance practice and increase operator involvement
Company2	1. Increase preventive maintenance compliance through dedicated maintenance planning resources.
	2. Separate maintenance planning from procurement and breakdown maintenance responsibilities.

	3. Develop a formal long-term maintenance strategy aligned with business objectives. 4. Increase management commitment toward Reliability-Centred Maintenance (RCM) and CMMS implementation. 5. Expand Predictive Maintenance (PdM) activities from selective applications to a structured maintenance programme. 6. Introduce regular maintenance performance review meetings and systematic root cause analysis. 7. Continue the autonomous maintenance practice to increase operator involvement
Company3	1. Reduce dependence on reactive maintenance through improved maintenance planning and scheduling. 2. Increase operator involvement by implementing Autonomous Maintenance (AM). 3. Establish dedicated maintenance planning personnel. 4. Expand Predictive Maintenance (PdM) and Condition-Based Maintenance (CbM) programmes across critical equipment. 5. Implement a comprehensive CMMS to improve maintenance planning and asset history management. 6. Introduce regular maintenance performance reviews based on reliability KPIs. 7. Continue the autonomous maintenance practice to increase operator involvement
Company4	1. Improve preventive maintenance compliance by increasing machine availability for planned maintenance. 2. Increase the number and competency of skilled maintenance technicians. 3. Implement a CMMS to improve maintenance planning, scheduling and work-order management. 4. Introduce Reliability-Centred Maintenance (RCM), Predictive Maintenance (PdM) and Condition-Based Maintenance (CbM). 5. Strengthen maintenance performance measurement using KPIs such as MTBF, MTTR and proactive-to-reactive maintenance ratios. 6. Shift organizational focus from breakdown maintenance to long-term reliability improvement. 7. Implement Autonomous Maintenance (AM) and strengthen operator participation.
Company5	1. Move away from the existing firefighting maintenance culture toward proactive maintenance management.

	2. Increase senior management commitment to preventive maintenance implementation. 3. Develop a structured Planned Preventive Maintenance (PPM) programme supported by measurable KPIs. 4. Implement Autonomous Maintenance (AM) and strengthen operator participation. 5. Introduce CMMS, Reliability-Centred Maintenance (RCM), Predictive Maintenance 6. (PdM) and Condition-Based Maintenance (CbM). 7. Conduct regular maintenance review meetings and continuous maintenance training for engineers and technicians.
Company6	1. Develop a formal maintenance strategy as part of the overall business strategy. 2. Replace the current failure-to-failure maintenance approach with a structured preventive maintenance programme. 3. Establish annual maintenance plans, maintenance KPIs and regular maintenance review meetings. 4. Develop maintenance planning capability by assigning dedicated maintenance planning responsibilities. 5. Implement Autonomous Maintenance (AM) and strengthen operator participation. 6. Increase management awareness and employee training in modern maintenance techniques, including RCM, CbM, PdM and CMMS. 7. Strengthen technical staffing and progressively reduce dependence on outsourced emergency maintenance services. 8. Implement a CMMS to support maintenance planning, equipment history, work-order control and reliability improvement.

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