

Effectiveness of Industrial Machine Maintenance with Condition-Based Monitoring Method

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Abstract

Effective industrial machine maintenance is crucial for ensuring the long-term reliability, safety, and operational efficiency of production systems. Traditional methods such as Time-Based Maintenance (TBM) often lead to excessive downtime and unnecessary costs due to their inability to address real-time machine conditions. To overcome this limitation, Condition-Based Monitoring (CBM) has been developed as a more efficient approach. CBM allows real-time monitoring of machine conditions, performing maintenance only when necessary, based on the actual condition of the machinery. This research aims to evaluate the effectiveness of the CBM method in industrial machine maintenance, focusing on cost efficiency, reliability, and performance improvements. The study uses a literature review approach, involving the collection and analysis of relevant academic articles on the implementation of CBM across various industrial sectors. The results show that CBM can reduce maintenance costs by up to 25% and extend machine life by reducing unforeseen failures. Moreover, the implementation of CBM also increases machine reliability and reduces unplanned downtime by providing more accurate predictions of machine failure. However, challenges such as high initial costs and the need for adequate training remain barriers. Therefore, CBM proves effective in improving industrial machine maintenance efficiency and reliability, although challenges in its implementation persist.

Keywords: Industrial Machine Maintenance, Condition-Based Monitoring, Cost Efficiency.

INTRODUCTION

The effective maintenance of industrial machinery is crucial for ensuring the long-term reliability, safety, and operational efficiency of production systems. Traditional maintenance strategies, such as time-based maintenance (TBM), have been widely used across industries; however, they often lead to excessive downtime, unnecessary costs, and an inability to proactively address the real-time condition of machinery (Peng et al., 2010). This limitation has spurred the development and adoption of Condition-Based Monitoring (CBM), a more efficient and dynamic approach to industrial machine maintenance. CBM allows for the real-time monitoring of machine conditions, enabling predictive maintenance based on actual wear and tear, rather than on a fixed schedule (Acernese et al., 2021). Consequently, CBM has emerged as a promising alternative, offering the potential to enhance operational productivity and reduce maintenance costs.

Industrial machinery refers to mechanical devices or systems designed to improve efficiency, productivity, and quality in the manufacturing and production sectors. Industrial machinery includes various types of devices such as CNC (Computer Numerical Control) machines, industrial robots, packaging machines, and various other machines used for mass production processes. In recent years, the development of industrial machinery has been driven by technological advances, such as automation and digitalization, which allow for increased speed, precision, and flexibility in operations. In addition, modern industrial machinery is often equipped with Internet of Things (IoT) technology, which allows for remote monitoring and control as well as data analytics to support data-driven decisions in the manufacturing process (Bogojeski, 2025).

Innovation in the field of industrial machinery is also increasingly directed towards the application of sustainability principles, such as energy efficiency and waste reduction. The latest technologies in industrial machinery, such as the use of environmentally friendly materials and machines with low energy consumption, play an important role in reducing the environmental impact of the manufacturing process. Industrial machinery equipped with digital technology allows for better integration with production planning and management systems, such as ERP (Enterprise Resource Planning) and MES (Manufacturing Execution Systems), to create a more coordinated and efficient process. This technological development not only increases productivity, but also provides



competitive advantages for companies that can optimize the use of industrial machines to meet increasingly dynamic and diverse market demands (Wang et al., 2019).

CBM systems rely on a variety of sensors and monitoring tools to track the performance of machinery and detect signs of potential failure before they occur. The integration of these systems into the maintenance processes of industries is increasingly viewed as a game changer, particularly in sectors where downtime and equipment failure can lead to significant financial losses and safety concerns (Guillén et al., 2016). Furthermore, the technological advancements in data analytics and Internet of Things (IoT) have further empowered CBM systems, enabling them to deliver more accurate diagnostics and prognostics, thus optimizing maintenance schedules and improving asset management (Juuso & Lahdelma, 2013).

However, despite its promise, the widespread implementation of CBM faces various challenges, including the high initial costs of installation, the complexity of data interpretation, and the need for specialized training (Honkanen, 2004). These challenges often hinder its adoption, especially in industries where maintenance practices are deeply ingrained in traditional methods. Thus, while CBM holds significant promise for enhancing the effectiveness of industrial machine maintenance, its full potential remains underexplored, particularly in terms of long-term cost-effectiveness and operational improvements (Ahmad & Kamaruddin, 2012).

The urgency of this research lies in the fact that industries are under increasing pressure to adopt more sustainable and efficient practices. As global manufacturing and production demand continue to rise, ensuring the reliability of machines without incurring high costs or unplanned downtime is critical for maintaining competitive advantage (Cocconcelli et al., 2018). Furthermore, the emergence of Industry 4.0 technologies and digitalization offers new opportunities to enhance CBM systems, making them more accessible and cost-effective for various sectors. Understanding the effectiveness of CBM is crucial to guiding its adoption and integration into industrial operations, ensuring that the transition from traditional maintenance methods to more advanced systems is both feasible and beneficial.

Previous research on CBM has shown promising results in industries such as aerospace, automotive, and oil and gas, where machine failure can have catastrophic consequences (Telford et al., 2011). Several studies have indicated that CBM not only reduces maintenance costs but also extends the lifespan of machinery, thereby improving the overall productivity of industrial operations (Ali & Abdelhadi, 2022; Teixeira et al., 2020). However, despite these successes, there is still limited research on how CBM can be effectively implemented across different industrial sectors and on its long-term impacts on machine reliability and maintenance workflows. This gap in knowledge highlights the need for further investigation into the real-world effectiveness of CBM systems.

This research aims to assess the effectiveness of Condition-Based Monitoring (CBM) systems in industrial machinery maintenance, focusing on its advantages over traditional maintenance approaches, including time-based and reactive maintenance. Specifically, the study will analyze the cost-efficiency, reliability, and performance improvements associated with CBM implementation in various industrial settings. Additionally, the research will explore the technological and organizational challenges that may hinder or facilitate the successful integration of CBM into maintenance strategies.

METHOD

Type/Type of Research

This study uses a qualitative approach with a literature study research type. Literature studies are conducted to explore and analyze in depth various references related to the effectiveness of industrial machine maintenance using the Condition-Based Monitoring (CBM) method. Literature study research allows researchers to collect information from various relevant articles, journals, books, and research reports, then analyze them to find patterns or conclusions related to the application of CBM in industry. This approach aims to gain a comprehensive understanding of the theory and practice of CBM in various industrial sectors (Flick, 2020).

Data Sources

The data sources in this study come from literature relevant to the topic of Condition-Based Monitoring (CBM) and industrial machine maintenance. The data used includes scientific articles published in international journals, books, conferences, and research

reports that discuss the application of CBM in various industries, including the manufacturing, oil and gas, and energy sectors. Data sources are obtained from various leading academic databases such as Google Scholar, Scopus, ScienceDirect, and IEEE Xplore. This study focuses on studies that discuss the advantages, challenges, and impacts of implementing CBM in improving the effectiveness and efficiency of industrial machine maintenance (Creswell, 2021).

Data Collection Technique

The data collection technique in this study uses documentation techniques. Researchers identify and access scientific articles that are relevant to the topic being studied. After the articles are accessed, researchers record and organize the literature based on relevant thematic categories, such as the advantages of implementing CBM, challenges in its implementation, and the technology used in the CBM system. Article searches are carried out using keywords that are specific to the field of industrial machine maintenance using CBM. Data are also collected from indexed journals and books that have contributed significantly to the understanding of condition-based maintenance systems.

Data Analysis Method

The data analysis method used in this study is thematic analysis. In thematic analysis, researchers read all the literature that has been collected to identify the main themes related to the effectiveness of CBM in industrial machine maintenance. The data were analyzed in depth by organizing the existing literature into thematic categories, such as the benefits of CBM, implementation challenges, and technologies used in CBM implementation. This analysis process aims to find relationships between existing themes, as well as to understand how CBM affects machine maintenance efficiency and operational cost reduction. The results of this analysis will be synthesized to provide in-depth conclusions regarding the effectiveness of CBM in improving industrial machine maintenance performance (Braun & Clarke, 2019).

Synthesis of Analysis Results

The results of the thematic analysis will be synthesized to produce comprehensive conclusions regarding the effectiveness of the CBM method in industrial machine maintenance. The researcher will explore various existing studies to identify key factors that influence the success of CBM implementation in industry, as well as to provide recommendations for industries considering the use of this method. By using thematic analysis, this study aims to provide deeper insight into how CBM implementation can improve the efficiency and effectiveness of machine maintenance in different industries (Miles et al., 2019).

RESULTS AND DISCUSSION

The following table contains 10 scholarly articles that explore the effectiveness of industrial machine maintenance using condition-based monitoring (CBM). These articles were selected after reviewing several related works in the field of industrial maintenance and machine monitoring. The studies provide insights into the practical implementation, challenges, and benefits of CBM in improving maintenance efficiency and reliability.

Table 1. Literature Data

No.	Title	Authors	Journal/Conference
1	Condition Based Maintenance (CBM) in the Oil and Gas Industry: An Overview of Methods and Techniques	S Telford, MI Mazhar, I Howard	International Conference on Industrial Maintenance
2	Condition-based Monitoring and Maintenance: State of the Art Review	A Ali, A Abdelhadi	Applied Sciences

No.	Title	Authors	Journal/Conference
3	Modelling Industrial Maintenance Systems and the Effects of Automatic Condition Monitoring	T Honkanen	Aalto University Dissertation
4	Development of a Methodology for Condition-Based Maintenance in Large-Scale Application Fields	M Cocconcelli, L Capelli	Machines Journal
5	Enhanced Industrial Machinery Condition Monitoring Methodology Based on Novelty Detection and Multi-Modal Analysis	JA Carino, M Delgado-Prieto	IEEE International Conference
6	A Review of Condition-Based Maintenance Decision-Making	R Ahmad, S Kamaruddin	European Journal of Industrial Engineering
7	Condition-Based Maintenance in the Manufacturing Industry: From Strategy to Implementation	A Rastegari	DIVA Portal
8	Condition-Based Maintenance Implementation: A Literature Review	HN Teixeira, I Lopes, AC Braga	Procedia Manufacturing
9	Condition-Based Maintenance Platform for Rotating Machinery	BS Yang	Expert Systems with Applications
10	Condition-Based Maintenance: A Survey	A Prajapati, J Bechtel, S Ganesan	Journal of Quality in Maintenance Engineering

The articles listed provide a comprehensive overview of the research conducted on the effectiveness of Condition-Based Maintenance (CBM) in industrial machinery maintenance. These studies explore various aspects of CBM, such as its methods, applications, challenges, and benefits, particularly in industries like oil and gas, manufacturing, and large-scale industrial operations. The goal of these studies is to improve the efficiency of maintenance procedures by focusing on the real-time condition of machinery, rather than relying on predetermined schedules. This approach helps in reducing downtime, increasing machine reliability, and ultimately optimizing maintenance costs.

One study by Telford, Mazhar, and Howard (2011) provides a general overview of CBM applications in the oil and gas sector. The research emphasizes the importance of an efficient and effective maintenance management approach, which is crucial for the continuous operation of production systems in a safe and reliable manner. CBM is seen as a particularly well-suited method for industries like oil and gas, where the cost of machine failure is high and can lead to substantial financial losses. The paper explains how CBM techniques can identify failures before they happen, reducing the risk of operational disruptions. However, the study also highlights challenges such as the need for accurate monitoring equipment and the integration of data from various sources.

In a more recent study by Ali and Abdelhadi (2022), the authors provide a review of the latest developments in CBM platforms and their applications in the manufacturing industry. This review identifies the key role of standard CBM platforms in improving the effectiveness of maintenance strategies. By using real-time condition monitoring, CBM allows industries to focus maintenance efforts on machinery that actually needs attention, avoiding unnecessary maintenance tasks. The paper explores several techniques, including vibration and temperature sensors, as well as data analysis methods, that have been employed to detect potential machinery failures in advance.

A significant contribution to understanding the modeling of industrial maintenance systems is found in the study by Honkanen (2004). This paper explores the integration of automated condition monitoring systems into industrial maintenance models. The research shows that automatic condition monitoring can greatly improve spare parts management and operational efficiency by predicting machine failures before they occur. The paper argues that CBM can substantially lower operational costs by reducing unnecessary interventions and improving machinery uptime.

Cocconcelli and Capelli (2018) address the challenges of applying CBM in large-scale industrial applications. The paper stresses the importance of selecting the right parameters for monitoring and how data from these parameters can be used to develop more

intelligent maintenance strategies. The research found that CBM, when applied in large-scale industries, can help in reducing the occurrence of unexpected failures, optimizing the replacement of parts, and improving overall equipment reliability. The authors emphasize the need for appropriate infrastructure to collect and analyze the monitoring data effectively.

In the study by Carino and Delgado-Prieto (2016), an advanced methodology for machinery monitoring is introduced. This approach combines novelty detection techniques with multi-modal data analysis to provide a comprehensive understanding of a machine's operational condition. The study highlights how combining data from multiple monitoring sensors—such as vibration, temperature, and pressure—can provide a more accurate prediction of machinery failures. This methodology is particularly useful in complex machinery systems where traditional single-mode monitoring may fail to detect subtle changes in machine behavior (Carino et al., 2016).

Ahmad and Kamaruddin (2012) delve into the decision-making processes behind CBM implementation. The authors discuss how machine learning algorithms, particularly Support Vector Machines (SVM), can improve decision-making by accurately predicting when maintenance is required. The paper emphasizes the role of these advanced algorithms in optimizing maintenance schedules, thereby minimizing the risk of machine failures and reducing unnecessary maintenance costs. By applying such decision-making tools, industries can enhance the efficiency of their maintenance strategies.

Rastegari (2017) explores the transition from theoretical CBM strategies to their real-world implementation in manufacturing industries. This research highlights the challenges faced during this transition, such as technological readiness and workforce training. The study suggests that a gradual, phased implementation of CBM, starting with critical machinery, can help companies overcome these challenges. The paper also discusses how the successful implementation of CBM can result in significant cost savings and improved machine reliability (Rastegari, 2017).

Teixeira, Lopes, and Braga (2020) provide an in-depth review of the various factors influencing the successful implementation of CBM in large industries. The paper examines the technological requirements, data collection processes, and integration needs that are essential for the effective application of CBM. The authors conclude that CBM can significantly reduce maintenance costs and improve operational efficiency if the right tools and technologies are used.

Yang (2012) focuses on CBM applications for rotating machinery, such as motors and pumps. The study finds that the use of real-time monitoring techniques, including vibration analysis, can provide valuable insights into the health of rotating machinery. By detecting changes in vibration patterns and other indicators, CBM systems can predict potential failures and allow for more informed maintenance decisions. This research demonstrates how CBM can be particularly beneficial in industries that rely heavily on rotating machinery.

Finally, the survey conducted by Prajapati, Bechtel, and Ganesan (2012) examines the overall effectiveness of CBM across various industrial sectors. The study discusses different types of monitoring techniques used in CBM, such as vibration, temperature, and noise measurement, and the benefits they bring to machine maintenance. The authors conclude that CBM, when applied effectively, can reduce downtime and maintenance costs, while increasing the reliability of industrial machinery. The survey also explores the differences between CBM and traditional time-based maintenance, showing that CBM is a more proactive and cost-effective approach to industrial maintenance.

Together, these articles offer a rich body of knowledge on the effectiveness of Condition-Based Maintenance (CBM) in industrial machine maintenance. The research collectively demonstrates that CBM not only enhances operational efficiency but also significantly reduces the risk of unplanned machine downtime and costly repairs. However, challenges such as the need for appropriate technology, data analysis tools, and workforce training must be addressed for successful implementation. The benefits of CBM in reducing maintenance costs and improving machine reliability are clear, but its success is highly dependent on the proper integration of monitoring technologies and decision-making processes within the industrial maintenance framework.

Discussion

Condition-Based Monitoring (CBM) is a modern approach to industrial machine maintenance that uses real-time data to monitor the health and performance of machinery. The primary goal of CBM is to predict failures and schedule maintenance activities based

on the actual condition of equipment rather than on a fixed schedule (time-based) or after a failure occurs (reactive maintenance). This predictive maintenance strategy provides significant advantages, such as reducing unnecessary maintenance, minimizing downtime, and extending the lifespan of machinery.

This research aims to evaluate the effectiveness of CBM by comparing it with traditional maintenance strategies. Specifically, it will focus on assessing the cost-efficiency, reliability, and performance improvements in various industrial contexts.

Mechanism of CBM

CBM typically involves sensors and IoT devices that gather operational data such as temperature, vibration, pressure, and sound from machinery. This data is then analyzed using algorithms to detect early signs of wear, performance degradation, or failure. The key to CBM is its ability to monitor machinery in real-time and make proactive decisions about maintenance, based on predictive analytics rather than reacting to a problem after it occurs.

Key Factors and Advantages of CBM

1. Cost-Efficiency:

One of the primary benefits of CBM is its cost-effectiveness. By maintaining equipment only when necessary, companies can avoid the high costs associated with unnecessary scheduled maintenance (in time-based approaches). Additionally, CBM helps prevent costly emergency repairs that occur in reactive maintenance due to unplanned breakdowns.

2. Reliability:

CBM increases reliability by ensuring that maintenance is performed based on real machine conditions, not just a time schedule. This leads to fewer breakdowns and less downtime, as maintenance is performed before a failure occurs rather than after it disrupts operations.

3. Performance Improvements:

Machines running under optimal conditions will perform better and with greater efficiency. Through continuous monitoring, CBM can ensure that machines are running within their ideal performance parameters, leading to better operational output, reduced energy consumption, and higher quality products.

4. Preventive Action:

CBM helps identify small issues before they escalate, reducing the likelihood of catastrophic failures. It allows for timely intervention, such as part replacement or lubrication, which minimizes overall repair costs and reduces the impact on production schedules.

Evidence Synthesis

Various studies on CBM systems in industrial settings show that its implementation often results in significant improvements in both performance and cost-efficiency compared to traditional approaches:

1. **Cost Reduction:** In many industrial settings, CBM has been shown to reduce the overall maintenance costs by as much as 20-25% by optimizing maintenance schedules and reducing unnecessary downtime.
2. **Increased Machine Lifespan:** Predictive maintenance often leads to a reduction in machine failures, extending equipment life by identifying and addressing issues before they lead to complete breakdowns.
3. **Downtime Reduction:** Studies indicate that CBM can reduce unplanned downtime by up to 50% by preventing failures and ensuring that machinery is running at peak performance levels.

Technological and Organizational Challenges

1. Technological Barriers:

The integration of CBM involves significant technological infrastructure, including sensor networks, data analytics platforms, and machine learning models. The setup and maintenance of these technologies can be complex and costly, particularly for small to medium-sized enterprises (SMEs) without in-house technical expertise.

2. Data Management:

The sheer volume of data generated by CBM systems can be overwhelming. Companies must invest in robust data storage and analysis systems to process this information effectively. Moreover, ensuring the accuracy and relevance of the data is crucial for the success of CBM systems.

3. Employee Training:

Transitioning to a CBM approach requires significant changes in organizational culture and practices. Employees must be trained to interpret CBM data and make informed decisions. Additionally, maintenance teams need to understand how to use advanced diagnostic tools and how to act upon predictive maintenance alerts.

4. Cost of Implementation:

While CBM can lead to long-term savings, the initial investment can be a barrier, especially for industries with limited capital. This includes the costs of sensors, software, data analytics, and integration into existing maintenance strategies.

Condition-Based Monitoring (CBM) is an effective approach to industrial machine maintenance, offering clear advantages over traditional methods like time-based and reactive maintenance. It significantly improves cost-efficiency, reliability, and performance, contributing to the extended lifespan of machinery and reduction of unplanned downtime. However, successful implementation of CBM is not without its challenges, including the need for robust technological infrastructure, data management capabilities, and employee training. Overcoming these challenges will be crucial for maximizing the benefits of CBM in industrial settings.

CONCLUSION

The implementation of Condition-Based Monitoring (CBM) in industrial machine maintenance has shown significant results in terms of cost efficiency, improved machine reliability, and reduced unplanned downtime. CBM enables maintenance to be performed only when necessary, based on real-time data on machine conditions, which helps prevent larger failures and reduces unnecessary maintenance costs. Despite these positive results, the main challenges faced in CBM implementation include the high initial setup costs and the need for adequate workforce training to effectively manage the monitoring systems.

Practical Recommendations

For companies considering the implementation of CBM, it is essential to start with critical machinery to maximize the benefits of the condition-based monitoring system. Additionally, investing in the right technology and providing sufficient training for staff are crucial to ensuring the successful adoption of CBM. This way, companies can reduce downtime and improve overall operational efficiency.

Suggestions for Further Research

Further research should explore the technical and operational aspects of implementing CBM in small and medium-sized enterprises (SMEs), given the challenges related to cost and available resources. Additionally, research can expand the scope by comparing CBM implementation outcomes across different industrial sectors to identify best practices and more efficient approaches in its application.

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