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The Role of Condition-Based Maintenance in Minimizing Operational Costs

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Abstract. Effective maintenance strategies play a crucial role in reducing costs and enhancing operational efficiency for organizations across various industries. This article presents a review of maintenance strategies aimed at achieving cost reduction objectives. By examining a wide range of research and industry practices, this study aims to identify key strategies and highlight their benefits, challenges, and potential applications. By consolidating existing knowledge and examining the latest trends, this article provides a handful resource for researchers, practitioners, and decision-makers seeking to optimize maintenance strategies for cost reduction. The insights presented in this article serve as a foundation for future research and practical applications in the pursuit of efficient and cost-effective maintenance operations.

Keywords: maintenance, overview

1. Introduction

Condition-based maintenance (CBM) is a maintenance strategy that focuses on monitoring the actual condition of an asset or system in order to determine the appropriate maintenance actions. Instead of relying on predetermined maintenance schedules, CBM uses real-time data and predictive analytics to assess the health and performance of equipment [1].

CBM aims to optimize maintenance efforts by identifying potential issues or failures early on, before they lead to costly breakdowns or downtime [2]. It involves continuously monitoring key parameters, such as vibration, temperature, pressure, fluid levels, and other relevant indicators, to detect abnormalities or deviations from normal operating conditions.

By employing various sensor technologies, data collection systems, and analytics tools, CBM enables organizations to gather and analyze data in real-time or periodically, allowing them to make informed decisions about maintenance activities. This approach helps to minimize unnecessary maintenance actions, reduce overall maintenance costs, and increase the reliability and availability of assets.

CBM can be implemented in various industries, including manufacturing, transportation, energy, aviation, and healthcare. It often relies on advanced technologies such as Internet of Things (IoT), data analytics, machine learning, and artificial intelligence to automate data collection, analyze patterns, and generate insights for maintenance decision-making.

Overall, condition-based maintenance helps organizations move from reactive or preventive maintenance strategies to a more proactive and efficient approach, optimizing resources and improving the overall performance and lifespan of their assets.

2. Maintenance strategies

Maintenance strategies [4][5] refer to the different approaches or methodologies that organizations employ to manage and maintain their assets and equipment. Here is an overview of some commonly used maintenance strategies:

2.1. Reactive Maintenance

Reactive Maintenance: Also known as "breakdown maintenance" or "run-to-failure," this strategy involves addressing maintenance issues and repairing assets only when they fail or break down. It is a reactive approach that can result in unplanned downtime and higher costs due to emergency repairs.

2.2. Preventive Maintenance

Preventive Maintenance (PM): This strategy involves performing routine and scheduled maintenance tasks to prevent failures or breakdowns before they occur. Maintenance activities are performed based on a predetermined schedule, such as regular inspections, lubrication, filter replacement, or equipment servicing. PM aims to reduce the likelihood of unexpected failures and extend the lifespan of assets.

2.3. Predictive Maintenance

Predictive Maintenance (PM): Predictive maintenance relies on real-time or periodic monitoring of equipment to assess its condition and predict when maintenance or repair actions will be required. It uses techniques such as condition monitoring, data analysis, and predictive analytics to identify early signs of deterioration or potential failures. PM helps optimize maintenance efforts, minimize downtime, and reduce costs by addressing maintenance needs at the right time.

2.4. Condition-Based Maintenance

Condition-Based Maintenance (CBM): CBM is similar to predictive maintenance but focuses on continuously monitoring the actual condition and performance of assets using various sensors and data collection systems. It uses real-time data and analytics to determine maintenance actions based on the current condition of the equipment. CBM aims to maximize asset availability, minimize unnecessary maintenance, and reduce costs.

2.5. Reliability-Centered Maintenance

Reliability-Centered Maintenance (RCM): RCM is a comprehensive maintenance strategy that identifies the most critical assets and analyzes their failure modes, consequences, and risks. It aims to optimize maintenance activities by determining the most appropriate maintenance tasks for each asset based on its criticality and potential impact on operations, safety, or the environment. RCM focuses on minimizing the risk of failures while optimizing maintenance costs.

2.6. Total Productive Maintenance

Total Productive Maintenance (TPM): TPM is a holistic maintenance strategy that involves the active participation of all employees to improve the overall equipment effectiveness (OEE). It aims to eliminate all forms of losses, such as breakdowns, setup time, defects, and reduced operating speed. TPM combines preventive and autonomous maintenance with employee involvement and continuous improvement initiatives to maximize equipment availability, performance, and quality.

2.7. Combined Maintenance strategies

These maintenance strategies can be used individually or in combination, depending on the nature of the assets, industry requirements, and organizational goals. Each strategy has its advantages and considerations, and organizations often adopt a mix of approaches to achieve the most efficient and effective maintenance practices for their specific needs.

3. Failure rate

Failure rate in maintenance refers to the frequency or probability of failures occurring within a given system, equipment, or component over a specific period [17]. It is a key metric used to assess the reliability and performance of assets and helps maintenance professionals in planning and implementing appropriate maintenance strategies. The failure rate is often expressed in terms of failures per unit of time, such as failures per hour, failures per month, or failures per year. It represents the rate at which failures or breakdowns happen within a particular asset population. By analyzing the failure rate, maintenance professionals can identify patterns, trends, and potential risks associated with specific assets [18]. This information enables them to develop preventive or predictive maintenance [19] strategies, schedule maintenance tasks, allocate resources effectively, and optimize maintenance activities to minimize downtime and reduce costs.

The failure rate can be determined through various methods, such as historical data analysis, condition monitoring techniques, reliability modeling, and statistical analysis. It is influenced by several factors, including the age and condition of the equipment, operating environment, maintenance practices, and usage patterns.

By monitoring and managing the failure rate, maintenance teams can proactively address potential failures, improve asset reliability, increase uptime, and ultimately enhance operational performance and productivity.

The bathtub curve (see Fig 1.) is a graphical representation of the failure rate of a system or component over its lifespan [3]. It illustrates the three main stages of failure that typically occur: the infant mortality stage, the normal life stage, and the wear-out stage. Here's an explanation of each stage:

Infant Mortality Stage: At the beginning of the component's life, there is a higher likelihood of failures occurring. This stage is called the infant mortality stage or the early failure stage. Failures during this stage are often caused by manufacturing defects, design flaws, or inadequate initial testing. These failures can happen relatively soon after installation or during the initial period of use. The failure rate during this stage is generally higher than the average failure rate over the component's lifespan.

Normal Life Stage: After the initial period of the infant mortality stage, the failure rate of the component decreases and reaches a relatively constant and low level. This stage is known as the normal life stage or the random failure stage. During this stage, the component operates under typical conditions and experiences failures due to random events or normal wear and tear. The failure rate during this stage remains relatively constant and low for a significant portion of the component's life.

Wear-out Stage: As the component ages and accumulates usage, the probability of failures gradually increases. This stage is called the wear-out stage or the end-of-life failure stage. The failure rate starts to rise again, indicating a higher likelihood of failures due to aging, deterioration, or wearing out of critical components. The wear-out stage is characterized by an increasing failure rate, leading to a higher frequency of breakdowns and a decrease in system reliability.

The shape of the bathtub curve resembles the cross-sectional shape of a bathtub, hence the name. It illustrates the idea that failures are more likely to occur at the early stages (infant mortality) and the later stages (wear-out), while the normal life stage experiences a relatively lower and constant failure rate.

Understanding the bathtub curve [21] and its stages is important for maintenance planning and reliability engineering. It helps in determining the appropriate maintenance strategies and intervals, such as implementing preventive maintenance during the early stages and considering replacement or refurbishment options as the system approaches the wear-out stage.

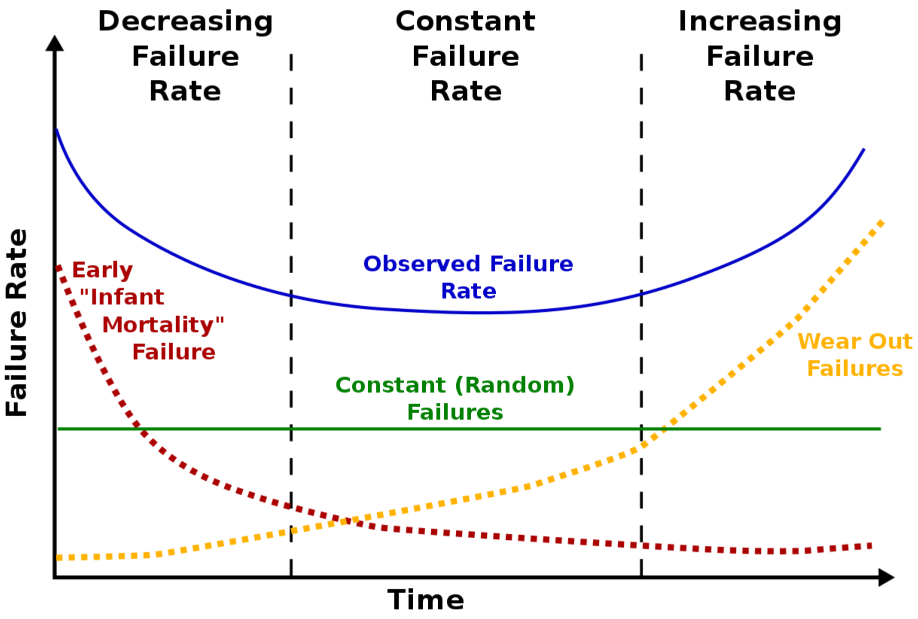

Figure 1. Bathtub curve [3]

4. Maintenance cost

Calculating maintenance costs involves considering various factors related to the assets or equipment being maintained, as well as the resources and activities associated with maintenance.

Here are some key steps to calculate maintenance costs:

Identify Maintenance Activities: Start by identifying and categorizing the maintenance activities required for your assets. This could include:

- routine inspections,
- preventive maintenance tasks,
- corrective repairs,
- replacements, and
- other associated activities.

Gather Data: Collect data on the resources and inputs required for maintenance. This may include the following cost types:

- human cost:
  - labor cost
  - contractor fee
  - administrative cost
- direct cost:
  - spare parts
  - consumable items cost
  - material cost
- indirect cost:
  - overhead expenses

Estimate Labor Costs: Determine the labor hours required for each maintenance activity. Multiply the hours by the hourly rate for the maintenance technicians involved. Consider factors like overtime or shift differentials, if applicable.

To calculate labor costs for maintenance considering shifts and overtime, you can use the following formula:

$$C_L = s \cdot R_{base} \cdot h_{regular} + R_{overtime} \cdot h_{overtime} \tag{1}$$

where R_{base} is the base rate, s is the regular hourly rate of the maintenance technician or worker. It represents the standard wage paid for normal working hours.

$h_{Regular}$ is regular hours which refers to the number of hours worked during the standard shift or regular working hours. This includes the non-overtime hours.

s is a multiplier for shifts (e.g. 1.0 for day shift, 1.5 for night shift).

$R_{overtime}$ is the overtime rate which is an extra rate paid for work performed beyond the standard working hours. It is typically higher than the base rate to compensate for the additional hours worked.

$h_{overtimer}$ is Overtime Hours: Overtime hours represent the number of hours worked beyond the regular hours or outside of the standard shift. These are the hours eligible for the higher overtime rate.

By using this formula, you can calculate the labor cost for maintenance taking into account shifts and overtime hours, providing a more accurate estimation of labor expenses.

Calculate Material Costs: Determine the cost of materials and spare parts (C_{spare}) required for maintenance tasks (C_M). This can involve estimating the quantity of materials needed and their associated costs, including procurement ($C_{procurement}$) and shipping expenses ($C_{shipping}$).

$$C_M = C_{spare} + C_{porcurement} + C_{shipping} \tag{2}$$

Factor in Downtime Costs: Consider the impact of equipment downtime on productivity and revenue. Calculate the cost of lost production, missed opportunities, and potential penalties or customer dissatisfaction resulting from equipment failures or maintenance activities.

Consider Asset Lifespan and Replacement Costs (C_{ALRC}): Assess the expected lifespan of the assets and factor in the costs associated with their eventual replacement or major refurbishment. Include costs such as asset procurement, installation, and any additional modifications or upgrades.

$$C_{ALRC} = C_{replacement} + C_{installation} + C_{upgrade} \tag{2}$$

Upgrade costs refer to the expenses incurred when improving or enhancing an existing product, system, or infrastructure. These costs are associated with the acquisition of new components, software licenses, hardware upgrades, labor, training, and any additional resources required for the upgrade process.

Upgrading can be necessary to keep up with technological advancements, improve efficiency, enhance functionality, or address security concerns. However, it is important to carefully evaluate the costs and benefits of an upgrade before proceeding, as it can involve significant financial investments.

Factors influencing upgrade costs include the complexity of the upgrade, the scale of the project, the compatibility of existing systems with the upgraded components, and any potential disruptions to ongoing operations during the upgrade process. Proper planning and analysis are crucial to estimate and manage the associated costs effectively. Organizations often consider the total cost of ownership (TCO) when evaluating upgrade costs. This includes not only the direct expenses of the upgrade itself but also the long-term costs of maintenance, support, and potential future upgrades. It is recommended to conduct a cost-benefit analysis and assess the potential return on investment (ROI) before undertaking an upgrade to ensure that the benefits justify the expenses. Additionally, exploring different options, such as phased upgrades or alternative solutions, may help optimize costs while achieving the desired improvements.

Account for Maintenance Management Costs: Consider the costs associated with maintenance management software, training, planning, and coordination efforts. These costs include maintenance scheduling, work order management, documentation, and reporting.

Software costs refer to the expenses associated with acquiring, developing, implementing, and maintaining software solutions. These costs can vary depending on several factors such as the type of software, licensing model, complexity, customization requirements, and ongoing support.

- Commercial off-the-shelf (COTS) software often involves upfront licensing fees or subscription costs. These costs may vary depending on the size of the organization, the number of users, and the specific features and functionalities required. Upgrades and updates to the software may also incur additional costs, either as part of ongoing maintenance or through new version releases.
- Custom software development involves the cost of designing, coding, testing, and deploying a software solution tailored to specific business needs. The expenses associated with custom development can include the salaries of developers, project management costs, infrastructure requirements, and ongoing maintenance and support.

Software costs also encompass implementation expenses, which include activities such as installation, data migration, configuration, and integration with existing systems. Training costs for end-users and administrators may also be necessary to ensure effective utilization of the software.

Ongoing maintenance and support costs should also be considered. This includes bug fixes, security patches, feature enhancements, and technical support. Some software providers offer support contracts or service-level agreements (SLAs) that outline the costs and services provided. It is essential for organizations to carefully evaluate software costs by conducting a comprehensive cost-benefit analysis. This analysis should consider factors such as the expected return on investment, productivity gains, cost savings, and long-term scalability and flexibility.

Open-source software can provide cost advantages as it is often freely available, although customization, support, and maintenance costs should still be taken into account.

Analyze Historical Data: Review past maintenance records and expenses to identify trends and patterns. This analysis can help in estimating future maintenance costs and identifying opportunities for cost optimization. A big data solution is described in [20].

Summarize and Analyze: Once you have gathered the necessary data and estimated the costs for each category, summarize and analyze the information. This could involve aggregating the costs by asset, equipment type, or maintenance category to gain a comprehensive view of maintenance expenses.

Periodic Review and Adjustments: Regularly review and update your maintenance cost calculations to reflect any changes in equipment, labor rates, materials costs, or other relevant factors. This ensures that your maintenance cost estimates remain accurate and up to date.

By following these steps and considering the various cost factors associated with maintenance activities, you can calculate an estimation of your maintenance costs. This information can be valuable for budgeting, cost control, and decision-making regarding maintenance strategies and resource allocation.

5. Maintenance cost saving strategies

There are several strategies that organizations can employ to plan and manage maintenance costs effectively. [8] made a review on maintenance optimization Here are a few common strategies collected by [10]:

Preventive Maintenance: Implementing a proactive approach to maintenance can help minimize unexpected failures and reduce overall costs. This strategy [11] involves regular inspections, routine maintenance tasks, and timely replacements or repairs of equipment or software components before they fail or cause significant disruptions.

Predictive Maintenance: Leveraging data analytics and monitoring tools, organizations can predict when maintenance is needed based on the performance and condition of assets. By using predictive algorithms and sensor data, potential failures can be anticipated, and maintenance activities can be scheduled accordingly. This strategy [13] can optimize maintenance efforts and minimize costs by avoiding unnecessary maintenance or replacing components too early.

Asset Lifecycle Management: Taking a holistic view of the asset lifecycle helps in planning maintenance activities and associated costs. By considering the acquisition, utilization, maintenance, and retirement stages, organizations can strategically allocate resources and plan for maintenance expenses throughout the entire lifecycle of an asset or software system. [14] reviews asset management and related standards.

Risk-Based Maintenance: Prioritizing maintenance efforts based on the criticality and risk [15] associated with assets or software components can be an effective cost planning strategy. By focusing on high-risk areas or systems, organizations can allocate resources where they are most needed and ensure that maintenance efforts align with business objectives and risk tolerance.

Continuous Improvement and Documentation: Regularly reviewing maintenance processes, documenting lessons learned, and capturing best practices can contribute to ongoing improvements and cost optimization. By analyzing historical maintenance data and identifying areas for improvement, organizations can streamline processes, reduce downtime, and optimize resource allocation.

Vendor Management and Support Contracts: For software systems or outsourced services, maintaining effective vendor relationships and negotiating comprehensive support contracts can help manage maintenance costs. Clear service-level agreements (SLAs) and well-defined expectations can ensure timely support and minimize unexpected expenses related to maintenance or system upgrades.

6. Maintenance management in MES systems

Maintenance management is an integral part of Manufacturing Execution Systems (MES). MES systems [7] typically include features and functionalities to support maintenance activities and enable effective maintenance management in manufacturing environments. Some common capabilities of MES systems related to maintenance management include:

- Equipment and Asset Management: MES systems often provide tools to track and manage manufacturing equipment and assets. This includes capturing asset information, maintenance history, maintenance schedules, and tracking asset performance metrics. These features help in planning and executing maintenance activities effectively.
- Preventive Maintenance Planning: MES systems support the planning and scheduling [6] of preventive maintenance tasks based on predefined maintenance schedules or condition-based triggers. They enable the creation of maintenance work orders, assignment of tasks to technicians,

and tracking of work progress. This helps organizations proactively maintain equipment and reduce unexpected failures.

- Downtime Management: MES systems help in monitoring and managing equipment downtime, capturing downtime reasons, and analyzing downtime patterns. This information is valuable for identifying recurring issues, improving maintenance strategies, and optimizing production efficiency.
- Maintenance Work Order Management: MES systems facilitate the creation, assignment, and tracking of maintenance work orders. They provide visibility into the status of work orders, capture maintenance activities and associated labor and material costs, and enable real-time communication between maintenance technicians and other stakeholders.
- Spare Parts and Inventory Management: Effective maintenance management requires proper inventory management of spare parts and materials. MES systems often include features to track spare parts inventory levels, reorder points, and facilitate the procurement process. This ensures that necessary parts are available when needed, minimizing equipment downtime.
- Analytics and Reporting: MES systems often provide reporting and analytics capabilities to analyze maintenance data, track key performance indicators (KPIs), and identify opportunities for improvement. These insights help organizations optimize maintenance strategies, identify trends, and make data-driven decisions.

Maintenance management within MES systems contributes to overall equipment effectiveness (OEE), reliability, and operational efficiency in manufacturing environments. By integrating maintenance management functionalities with production data, MES systems provide a holistic view of the manufacturing process, enabling organizations to optimize maintenance activities, reduce costs, and enhance productivity.

7. CBM tools

Condition-Based Maintenance (CBM) software solutions come in various forms, ranging from standalone products to modules integrated into larger Enterprise Asset Management (EAM) or Computerized Maintenance Management System (CMMS) platforms. Here are some notable CBM software options:

- IBM Maximo Asset Health Insights:
  This solution by IBM combines asset performance management, predictive maintenance, and IoT data to provide predictive maintenance capabilities. It integrates with IBM Maximo for asset and work management.
- Bentley AssetWise APM:
  Bentley's AssetWise APM offers predictive maintenance capabilities by combining engineering analysis with real-time data from sensors and other sources. It's designed for asset-intensive industries like oil and gas, utilities, and transportation.
- Schneider Electric EcoStruxure Asset Advisor:
  EcoStruxure Asset Advisor is part of Schneider Electric's IoT-enabled EcoStruxure platform. It offers remote monitoring and predictive maintenance for critical equipment in various industries.
- Fluke Connect:
  Fluke Connect is a cloud-based condition monitoring and predictive

maintenance solution that integrates with Fluke's range of measurement tools and sensors. It's suitable for both small and large organizations.

- ABB Ability™ Asset Vista Condition Monitoring:
  ABB's Asset Vista provides condition monitoring and predictive maintenance capabilities for industrial equipment. It uses advanced analytics to identify potential issues and offers remote monitoring.
- PTC ThingWorx Navigate:
  PTC's ThingWorx Navigate includes a predictive maintenance module that combines IoT data and analytics for predicting equipment failures. It can integrate with various data sources and systems.
- Emaint by Fluke:
  Emaint is a CMMS software with integrated predictive maintenance features. It allows users to monitor equipment conditions and set up preventive maintenance schedules.
- Honeywell Forge Asset Performance Management:
  Honeywell Forge offers asset performance management capabilities, including predictive maintenance, for industrial facilities and critical assets.
- Uptake:
  Uptake is an industrial AI and predictive analytics platform that offers predictive maintenance solutions for various industries, including construction, manufacturing, and transportation.
- SAP Predictive Asset Insights:
  SAP's Predictive Asset Insights is part of the SAP Leonardo IoT portfolio. It uses IoT sensor data and predictive analytics to monitor and predict equipment health.
- National Instruments InsightCM:
  NI InsightCM is a condition monitoring and predictive maintenance solution for industrial machinery and equipment. It integrates with NI hardware and software.

Remember that the choice of CBM software should align with your specific industry, equipment, and business needs. It's essential to evaluate factors such as scalability, integration capabilities, and support when selecting the right CBM software for your organization.

8. Conclusions

Maintenance costs play a critical role in the overall financial performance of organizations. By effectively managing and optimizing maintenance costs, companies can achieve significant savings and improved profitability.

Implementing a robust maintenance management system, such as a Manufacturing Execution System (MES), is essential for streamlining maintenance processes, enhancing asset performance, and reducing maintenance costs. MES systems provide real-time data, automation capabilities, and advanced analytics, enabling better decision-making and resource allocation. Condition-based maintenance (CBM) has emerged as a powerful strategy for cost-effective maintenance. By monitoring equipment health in real-time and utilizing predictive analytics, CBM minimizes unplanned downtime, reduces maintenance expenses, and extends the lifespan of critical assets. The adoption of CBM requires the integration of advanced sensing technologies, data collection systems, and analytics tools within the maintenance framework. This enables early detection of equipment anomalies,

timely maintenance interventions, and optimized maintenance schedules.
Successful implementation of CBM relies on accurate asset condition monitoring, data analysis, and the establishment of meaningful performance metrics. It requires collaboration between maintenance, operations, and data analytics teams to leverage the full potential of CBM and achieve cost reductions. Organizations that prioritize proactive maintenance strategies, such as CBM, experience increased equipment reliability, minimized breakdowns, and improved overall operational efficiency. These benefits translate into reduced maintenance costs, enhanced customer satisfaction, and a competitive advantage in the marketplace.
Continuous improvement is vital in maintenance cost reduction efforts. Regularly reviewing maintenance processes, analyzing data insights, and implementing corrective actions allow organizations to optimize maintenance strategies, identify cost-saving opportunities, and adapt to changing operational needs.

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