

Original Article

A Review on Mechanical System Reliability & Maintenance strategies for Maximizing Equipment Lifespan

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Abstract: Reliability assessment is vital to guarantee the effectiveness, safety, and longevity of mechanical systems, particularly in industrial applications where downtime and failures can result in significant operational and financial losses. Mechanical failures, often caused by fatigue, stress corrosion, wear, and brittle fracture, pose challenges to system reliability and maintenance. This study presents a comprehensive approach to reliability optimization by integrating predictive, preventive, and reliability-centered maintenance strategies. Key methodologies include Analysis of Failure Modes and Effects (FMEA), dependability, availability, maintenance, and safety (RAMS), and importance measures to identify critical failure modes and optimize resource allocation. Furthermore, advanced data-driven techniques are employed to enhance failure prediction and optimize maintenance scheduling. By addressing key challenges in mechanical reliability, this research provides a framework for cost-effective and data-driven maintenance strategies, contributing to improved system performance, reduced downtime, and sustainable industrial operations.

Keywords: System Reliability, Maintenance Strategies, Equipment Lifespan, Predictive Maintenance, Preventive Maintenance, Reliability-Centered Maintenance (RCM).

I. INTRODUCTION

The importance of reliability evaluation for the use of mechanical equipment to increase the reliability of equipment through condition-based maintenance and reduce costs has made it a prominent subject for studies on dependability study and life prediction for mechanical equipment[1][2]. Predictive life also benefits from knowing how to evaluate dependability[3]. The ability to evaluate dependability is also beneficial for life prediction[4] and maintenance time[5]. Machine tool stability and overall production effectiveness are affected by performance deterioration, which is one of the most significant factors during machining and closely relates to product accuracy. The primary cause of mechanical equipment failures, which typically results in time and product waste, is performance deterioration. Also, the efficiency and productivity of a machine are directly linked to the state of its equipment; for this reason, studies on the reliability evaluation of mechanical devices based on studies of performance deterioration are essential[6].

The likelihood that a thing will perform its tasks under specific circumstances for a predetermined amount of time is known as reliability[7]. In order to enhance the quality of their goods, businesses conduct dependability assessments so it can plan their products and carry out preventative maintenance[8]. Assessing the risk of structural failures, or the structure's failure probability, is a crucial task for a mechanical system that is subjected to stochastic excitation. In terms of mathematics, importance measures help simplify or approximate the multi-dimensional failure probability integral by focusing on the most critical variables[9].

The impact on system dependability that occurs when one or more of a system's components malfunction or change states depends on the system's structure and component reliability criteria[10]. Importance measurements are a fundamental theory of reliability that permeates every stage of a product's lifecycle, including design, production, testing, marketing, upkeep, and so forth. The most crucial step is to determine the elements affecting system dependability [11][12]. Importance metrics are employed throughout the design process to pinpoint flaws and aid in system enhancement and optimization. To make sure a system is functioning correctly, importance measurements can distribute enterprise resources to its component parts in a reasonable manner. Importance measurements have been widely used in risk analysis, decision-making, and system dependability by detecting and assessing system shortcomings [13][14].

A. Motivation and Contribution of the Study

Ensuring mechanical system reliability is essential for efficiency, safety, and cost-effectiveness. Frequent failures lead to downtime and high costs, making proactive maintenance strategies like preventive, predictive, and condition-based maintenance crucial. However, selecting the optimal strategy requires understanding failure mechanisms, importance measures, and system reliability models. This study aims to integrate reliability assessment techniques with maintenance strategies to minimize failures, optimize resource allocation, and maximize equipment lifespan for sustainable industrial operations. Also include key contributions of the study are as follows:



- Enhances the reliability of mechanical components like gears through advanced optimization techniques.
- Identifies and mitigates common failures such as fatigue and stress corrosion using FMEA.
- Explores preventive, predictive, and reliability-centered maintenance to extend equipment lifespan.
- Integrates RAMS analysis for data-driven, cost-efficient and successful maintenance scheduling.

This paper is formatted as follows: Reliability optimization design for mechanical items was presented in Section II. Models of mechanical system failure were presented in Section III. Mechanical maintenance techniques were employed in Section IV. The literature review and summary are provided in this part. Additionally, section V concludes the conclusion and future work.

II. DEVELOPMENT STATUS OF RELIABILITY OPTIMIZATION DESIGN OF MECHANICAL PRODUCTS

In the field of optimization design, the significance of optimization design based on dependability has increased. used in two mechanical parts, the gear and the gear reducer. China has been at the forefront of designing planetary gear transmissions and gear transmissions with reliability-based optimization, among other things. The problem of communication dependability, radar, and other machine features was proposed in China in the 1960s[15]. The late 1970s saw a surge in economic growth, reform, and openness, which enhanced the reliability of the propulsion system for essential use and civic goods components. Military components are now two orders of magnitude more dependable after years of effort. After a group of academics and the organization's technical core were established in China in the 1980s, state ministries of reliability engineering began to be implemented further. China's military and civil products, along with many civil electrical items, witnessed a significant improvement in 1990, hitting a new high in terms of product quality and dependability.

Mechanical reliability emphasizes the capacity of a system or component to function faultlessly under specified conditions for a certain period of time. The DRM discusses reliability in a number of chapters since a system component failure might lead to a utility service disruption or failure.

A. The Reliability Design Principles of Mechanical Products

Mechanical items have unique design and analysis methods and features when compared to electronic products [16]. In outcome, mechanical product dependability design should adhere to the following guidelines:

a) *Combination of Reliability Design and Traditional Design*

The dependability of mechanical parts may be guaranteed in the majority of situations using the conventional safety coefficient approach, which is straightforward, easy to understand, and requires little effort. However, it is now exceedingly challenging to implement classic dependability design for mechanical goods in certain situations. Therefore, using probability design to refine and enhance the conventional approach appears both sensible and essential. Furthermore, it is possible to carry out the reliability probability design targeted at critical components progressively.

b) *Integration of Quality and Quantity Design*

Quantity design is the study of dependability through quantitative analysis and computation, although it is not able to address every issue related to reliability. Furthermore, dependability may not always be able or be suitable to explain quantitatively. Consequently, the combination of quality and quantity is necessary for reliability.[17]. It is more sensible and efficient to carry out quality design for items that have quality requirements and are challenging to calculate in terms of quantity. Experience has shown that a high-quality design is crucial to ensuring and enhancing the dependability of mechanical goods. Therefore, quantity and quality design should be combined throughout the dependability design process.

c) *Paralleling of Mechanical Reliability and Durability*

In a broad sense, durability and dependability are components of mechanical product reliability. Thus, the two previously stated are part of mechanical dependability design. Reliability design specifically addresses sporadic errors, whereas durability addresses progressive defects. Therefore, their fault mechanisms differ.

d) *Paralleling of System and Parts Reliability*

The designers must create a thorough system and part design since mechanical parts have a complicated functional status and structure and are less standardized and universal. The most basic building block of the entire system is its parts, and their strength is the fundamental assurance of systematic reliability. In this instance, the traditional dependability design should be enhanced by the parts' design.

III. FAILURE MODES IN MECHANICAL SYSTEMS

The definition of a failure is "the condition in which [a device or system] is unable to carry out its intended tasks when subjected to the specified conditions and time". Because of the connection, the mechanical and electrical properties of the whole system determine how well a MEMS device works. That can single out two major categories of errors:

- Catastrophic (or permanent) malfunctions that render the apparatus totally unusable

- Deterioration failure, which alters a local component of the device's characteristics and functions outside of its typical operating range.

The observable impacts (broken structure, fractured surface, plasticity process, etc.) or directly measured degradation that surpass specified limitations can be used to establish failure modes and failure mechanisms.

- Material and residual stress: The kind of materials chosen and their structural compatibility have a big impact on a device's durability and failure rate. A wide variety of materials are employed in the technical MEMS process[18]. The moving components of the gadgets are made of silicon or metal. Both silicon dioxide and silicon nitride have long been employed for thermal and electrical isolation. Other materials, such as polyimide and aluminum oxide, are also utilized for electrical isolation.

A. Common Causes of Mechanical Failures

All machine and structural component failures may ultimately be linked to material failure, which is the foundation upon which the modes of failure were built. Based on this, the analysis of several mechanical failures reveals that brittle fracture, stress corrosion, and fatigue are the main causes of failure. These modes of material failure are the most prevalent because, although proper design procedures exist for designing against simple overload, they are either nonexistent or are only now starting to be used for designing against fatigue, stress corrosion, or brittle fracture. Because there are now no design techniques that can effectively address these types of failure, it remain prevalent.

B. Failure Modes and Effects Analysis (FMEA)

The FMEA discipline was created by the US military. On November 9, 1949, Implemented Military Procedure MIL-P-1629 and Performed a Failure Mode, Impacts, and Criticality Analysis. With its clear reliability and safety criteria, the aircraft industry adopted FMEA as a formal design process in the 1960s. For safety and regulatory reasons, FMEA was introduced to the automotive industry by Ford Motor Company in the late 1970s. They are used to enhance design and production as well. FMEA has been used by many industries, including as the automotive, electrical, mechanical, semiconductor, aerospace, and military sectors. The risk of failure is assessed using the risk priority number (RPN) value in the majority of modern FMEA approaches. The ability to evolve continually is desired. Power plant dependability has become more significant recently in the majority of both developed and developing nations. In the power industry, the importance of risk analysis and reliability, availability, maintainability, and supportability (RAMS) has increased. [19]. Significant reasons for customer discontent stem from unforeseen malfunctions that have caused the thermal power plant to incur unanticipated costs. However, the frequency of failures and their effects may be decreased by appropriately integrating RAMS and risk analysis into each maintenance procedure in the thermal power plant.

The major goal of an FMEA is to eliminate the potential that a new system, technique, or design will not completely or partially satisfy the recommended criteria in specific situations, such as when there is a stated purpose and imposed constraints. With a focus on protecting the security of the systems and the safety and well-being of the employees, the FMEA assesses the needs of the client and develops products and procedures to reduce the likelihood of possible failure modes. The FMEA also aims to build, evaluate, and enhance design development and testing procedures to reduce failures and create competitive, world-class products.

IV. MAINTENANCE STRATEGIES FOR MECHANICAL SYSTEMS

The ability of strategic investments to boost manufacturing performance has led manufacturers to employ effective maintenance approaches like Maintenance that are focused on reliability (RCM), total productivity (TPM), and CBM in order to compete[20]. It's crucial to consider the production department's objectives in addition to the general maintenance development goals when creating a maintenance strategy. A pertinent strategic objective may be created by taking into account the two viewpoints of both components. The most frequent error made in the creation of maintenance is that manufacturers lack the necessary information and are unsure of how to start. This results in the most widespread use of contemporary ideas and theories, such TPM and Lean. The maintenance strategies for maximizing equipment's lifespan are discussed below:

A. Maintenance Strategies for Maximizing Equipment Lifespan

The following section discusses methods for enhancing the life of equipment:

a) Preventive Maintenance

The introduction of preventive maintenance (PM) in the 1950s followed the realization that failures might be avoided [21]. As a substitute for corrective maintenance (CM), PM has gained acceptance since evolving technologies tend to have more complex systems than those that rely on manual tools. The fundamental idea behind a PM system is that it consists of planned maintenance activities that are dictated by the lifespans of component components and the functioning of machinery

or equipment. To replace parts before it break, jobs are therefore planned during machine stoppages or shutdowns. As an advance on PM, condition-monitoring systems are commonly employed in predictive maintenance (PdM).

b) Time-Based Maintenance

Time-based planning involves calculating the topic analysis's length and information distribution.

c) Predictive Maintenance (PdM)

The idea of predictive maintenance (PdM) is used to improve asset maintenance schedules by using data-driven methods to forecast asset breakdowns [22]. Among other positive outcomes, the use of PdM may benefit businesses by decreasing downtime and improving product quality.

d) Reliability-Centered Maintenance (RCM)

A methodical and systematic framework for maximizing maintenance resources for physical assets within their operational environment is called reliability centered maintenance[23]. The goal of reliability-centered maintenance is to maintain system functionality as opposed to physical asset preservation. Reliability Centered Maintenance is a seven-step process that examines the functions and possible failures of spare components in order to assess "reliability" while managing risk.

e) Corrective Maintenance (CM)

To restore a malfunctioning system to operational condition, CM or repair is performed. The dependability community divides maintenance effectiveness into three categories: minimum, imperfect, and perfect. Perfect maintenance returns the system to its pre-failure state, or as bad as it was before, to its good-as-new state by minimum maintenance, and to the intermediate state of maintained imperfectly, good as new and terrible as old[24].

V. LITERATURE REVIEW

This section emphasizes the mechanical system's dependability, with a focus on the techniques that will maximize the lifespan of the equipment, discussed below in Table I:

Li, Zhu and Wang (2020) focus on the test of reliability for component-switching redundancy systems in offshore wind turbines. A component-swapping technique based on survival signatures is used to define the system's new structure-function following the switch. The fault tree and survival signature are also used in the construction of the reliability model for redundant systems. The next step is to examine the impact of component switching on two metrics of reliability significance—Joint reliability importance and marginal reliability significance, both with and without failure rate imprecision taken into consideration[25].

Shittu, Kolios and Mehmanparast (2021) present the latest developments in Structural Reliability Analysis (SRA) techniques with the goal of determining the main uses for each technique as well as its suggested modifications, qualifying traits, benefits, and drawbacks. It is becoming more and more important to provide a precise and effective method for evaluating the uncertainties in the material qualities, geometric dimensions, and operational conditions of contemporary offshore jacket structures because of their growing complexity and scale. A kind of uncertainty analysis, SRA has proven to be an invaluable resource in structural design due to its ability to directly measure the effect of input parameter uncertainty on structural performance[26].

García and Salgado (2021) compare the outcomes provided by various maintenance techniques for industrial production machines with several stages by examining An example of a multi-stage thermoforming process in action. In particular, two innovative predictive maintenance-based techniques, Algorithm Life Optimisation Programming (ALOP) and DBT, are contrasted with two preventive maintenance-based techniques, Preventive Programming Maintenance (PPM) and Improve Preventive Programming Maintenance (IPPM)[27].

Pan et al. (2021) An innovative condition-based opportunistic maintenance approach is suggested for mechanical parts of multi-component systems whose degradation is getting worse with time. The trend of decreasing mechanical component performance is explained by this method using the Gamma process. In order to characterize the maintenance relationship between components and group them repeatedly, intersectionality is proposed as a method based on the current single-component maintenance methodology. The condition-based opportunistic maintenance model at the system level also aims to minimize the average maintenance cost rate[28].

Nithin, Sriramula and Ebinum (2021) provide an RCM-focused framework for cost optimization for the assets by applying statistical and probabilistic analysis. Over time, the failure is predicted by an examination of the most crucial elements using probability. The failure history is used to calculate the mean time to failure, mean time between failures, and mean time to repair parameters. The failure pattern of the failure mode over time is determined by the characteristics of the probability distribution, such as the Weibull distribution's shape and scale parameters[29].

Chen et al. (2019) For intelligent manufacturing systems, a selected maintenance optimization model that takes into account the unpredictable maintenance effect and is mission dependability orientated has been presented. The working mechanism of intelligent manufacturing systems was first thoroughly described using a novel connotation and modeling approach for mission dependability using the idea of multistate systems. Second, a quantitative model reflecting the unknown qualities induced by repairmen and tools was developed based on real-time data and relating maintenance resources to quality[30].

Chen et al. (2017) A Weibull-based imperfect preventative maintenance plan is suggested for the CNC lathe's turret system. The elements that influence the degree of restoration and failure are in line with a steady distribution. However, as the frequency of preventative maintenance grows, so does its expense. Maintenance time should, therefore, be taken into account as well. This study presents a customizable preventive maintenance approach. Reducing the entire cost of maintenance is the goal. To determine the most flexible preventive maintenance plan, the model's preventive maintenance interval was computed using the limited reliability value[31].

Yang et al. (2020) sampling subsystem of CEMS should be maintained using Reliability-Centered Maintenance (RCM). The failure mode and effect analysis (FMEA) serve as the basis for the RCM logic decision, which determines the justifiable maintenance mode. Next, an average availability model is suggested to ascertain the maintenance interval cycles. The creation of the maintenance blueprint is the last step. This information can then be utilized to enhance equipment dependability and create maintenance plans[32].

Table 1: This Table Highlights the Major Results, Primary Areas, Difficulties, and Contributions of the Reliability Analysis, Maintenance Techniques, and Structural Evaluation

References	Focus Area	Key Findings	Challenges	Key Contribution
Li, Zhu and Wang, (2020)	Analyzing the dependability of offshore wind turbines' redundant systems	Introduces a component switching technique based on survival signatures to improve system dependability. Analyzes the influence of swapping on reliability importance measures.	Imprecision in failure rates and complexity in modeling component interactions.	Develops a fault tree and survival signature-based method to evaluate reliability improvement via component swapping.
Shittu, Kolios and Mehmanparast, (2021)	Structural Reliability Analysis (SRA) for offshore jacket structures	Reviews SRA methods, their applications, advantages, and limitations. Highlights the need for accurate uncertainty assessment in material properties and operating environments.	Managing uncertainties in large-scale offshore structures and their impact on performance.	Demonstrates the role of SRA in quantifying uncertainties and optimizing structural design.
García and Salgado, (2021)	Techniques for maintaining industrial production machinery with many stages	Compares preventive maintenance (PPM, IPPM) with predictive maintenance (ALOP, DBT). Predictive maintenance strategies show better performance in optimizing machine life.	Implementing predictive maintenance models requires real-time data monitoring and integration.	Proposes predictive maintenance strategies that enhance machine efficiency and longevity.
Pan et al. (2021)	Condition-driven opportunistic maintenance for systems with many components	Uses Gamma process for degradation modeling; Introduces detection intersectionality for component grouping; Minimizes maintenance cost.	Managing multi-component interactions; Optimal grouping; Cost-effectiveness vs. reliability	Proposed a cost-efficient condition-based maintenance model.
Nithin, Sriramula and	RCM-based cost optimization using	Uses Weibull distribution to predict failure patterns and optimize maintenance costs	Accurate estimation of probability distribution parameters and their	Develops a cost-optimization framework for RCM

Ebinum (2021)	probabilistic analysis	based on failure history.	impact on maintenance strategies.	based on probabilistic and statistical analysis.
Chen et al. (2019)	Optimising Selective Maintenance in Intelligent Manufacturing Systems	proposed a multistate system theory-based selected maintenance model focused on mission dependability; used real-time data to create a quantitative model that relates maintenance resources to quality.	Uncertainty in maintenance effects due to variability in repairmen and tools.	Comprehensive modeling of mission reliability and uncertainty in maintenance for intelligent manufacturing.
Chen et al. (2017)	Ineffective CNC Lathe Turret System Preventive Maintenance Plan	Designed a model for preventative maintenance based on the Weibull distribution, taking into account variables that influence failure intensity and restoration; Minimized total maintenance cost.	Increasing cost with preventive maintenance frequency; Need to balance maintenance time and cost.	Developed an optimal flexible preventive maintenance strategy using a limited reliability value approach.
Yang et al. (2020)	CEMS Sampling Subsystem Reliability-Centered Maintenance (RCM)	Applied FMEA-based RCM logic to determine a reasonable maintenance mode; Proposed an average availability model for maintenance interval cycle determination.	Identifying optimal maintenance cycles for different failure modes, Ensuring effective implementation of RCM decisions.	Established a structured maintenance outline to enhance reliability and inform maintenance strategies.

VI. CONCLUSION AND FUTURE WORK

The importance of reliability assessment in mechanical systems to enhance efficiency, safety, and cost-effectiveness. By integrating predictive, preventive, and reliability-centered maintenance strategies, this research provides a framework for optimizing system reliability and minimizing downtime. The implementation of methodologies, such as Maintenance planning optimization and the identification of critical failure modes, are made feasible by FMEA and RAMS analysis. Additionally, the use of data-driven techniques contributes to improved failure prediction and resource allocation, ensuring sustainable industrial operations. This study relies on historical data, which may not capture unforeseen failures. The effectiveness of predictive models also depends on data quality and availability.

Future research should focus on the use of cutting-edge AI and ML methods to improve maintenance scheduling and failure prediction. The application of digital twin technology can provide real-time monitoring and simulation capabilities, improving decision-making in reliability assessment. Moreover, exploring the impact of environmental and operational conditions on mechanical reliability can help develop more robust maintenance strategies.

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