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EFFICIENCY AND THE HUMAN FACTOR IN INDUSTRIAL MAINTENANCE SYSTEMS

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Abstract: Industrial maintenance has evolved from reactive repairs to strategic, digitalized approaches integrating technical, organizational and human factors. This paper reviews modern maintenance strategies such as TPM, RCM, CBM and CMMS, outlining their benefits, limitations and implementation challenges. Special attention is given to the human factor, as employee attitudes, motivation and organizational culture strongly influence maintenance efficiency and digital transformation success. Current trends are discussed, including Industry 4.0–based predictive maintenance, integration with energy efficiency and sustainability, and the importance of leadership in the modern industrial context.

Keywords: industrial maintenance, human factor, organizational culture, digital transformation, energy efficiency

INTRODUCTION

The maintenance of industrial systems is one of the key activities ensuring the reliability, safety, and longevity of technical equipment. Throughout the course of industrial development, maintenance approaches have undergone a significant transformation — from traditional reactive failure repairs to modern predictive and digitized strategies that integrate technical, organizational, and human factors. Contemporary challenges, such as global competitiveness, high downtime costs, energy efficiency, and sustainability requirements, further emphasize the strategic importance of maintenance for the success of industrial organizations.

In addition to technical solutions, the efficiency of maintenance is increasingly influenced by employees' attitudes and perceptions, whose readiness to adopt new technologies and organizational changes largely determines the success of modern approaches. In this context, the paper focuses on analyzing different maintenance strategies, their efficiency and limitations, as well as examining the factors that shape employees' perception. Special emphasis is placed on future development directions, which include digitalization, energy efficiency, and the role of the human factor in a digital environment.

The purpose of this review paper is to provide a critical overview of existing strategies and trends in industrial system maintenance and to highlight the importance of integrating technical innovations and human resources to improve the efficiency and sustainability of industrial processes.

THEORETICAL CONSIDERATIONS

Maintenance as a Process in Industrial Systems

Maintenance in industrial systems plays a crucial role in ensuring production reliability and efficiency and requires planned activities, clearly defined indicators, and effective resource management. Historically, maintenance has evolved from a reactive approach focused on repairing failures toward modern strategies based on planning, monitoring, and the use of digital tools. By definition, maintenance includes technical and administrative activities aimed at preserving or restoring equipment and systems to their functional state (Dzulkifli, 2021).

The main categories are corrective maintenance, carried out after a failure occurs, and preventive maintenance, which includes planned activities at predefined intervals and predictive approaches based on monitoring the actual condition of equipment (Erbiyik, 2022). Industrial development has led to advanced methods such as Reliability–Centered Maintenance (RCM) and Total Productive Maintenance (TPM), with the aim of reducing downtime and optimizing costs.

Efficiency and Quality of the Maintenance Process

The efficiency of maintenance processes in modern industrial systems is measured using clearly defined performance indicators that enable monitoring equipment condition and making timely decisions. The most commonly used key indicators are:

- MTBF (Mean Time Between Failures) – the average time between equipment failures,
- MTTR (Mean Time To Repair) – the average time required to repair a failure,
- OEE (Overall Equipment Effectiveness) – a combination of availability, performance, and quality to identify bottlenecks.

Reliable monitoring of these indicators forms the basis for increasing productivity, reducing downtime, and optimizing costs, although many companies still lack sufficient automation and standardized procedures. Planned maintenance approaches generally lead to fewer failures, shorter downtimes, lower costs, and a safer working environment (Erbiyik, 2022).

The integration of maintenance management systems with Industry 4.0 technologies enables real–time data collection and processing, schedule optimization, and reduced risk of unplanned stoppages. Among the most successful models are Total Productive Maintenance (TPM) and Reliability–Centered Maintenance (RCM), as they provide high equipment availability and engage employees in preventive activities (Andriulo, 2015).

Digital tools such as the Computerized Maintenance Management System (CMMS) contribute to cost reduction through improved work planning and spare parts management. Although technical solutions play a key role, efficiency also depends on organizational and human factors, such as employee competencies and the ability to adapt processes to change (Irwin, 2017).

Factors Influencing Employees' Perception

Employees' perception of maintenance processes is shaped by a combination of technical, organizational, social, and individual factors. Attitudes are influenced by work experience, education, type of employment contract, and integration into the safety culture; more experienced and permanently employed workers tend to have a more positive view of maintenance processes, while external contractors often show greater dissatisfaction. A significant portion of professional knowledge is transferred informally, meaning that younger employees without mentoring support find it harder to access the necessary information (Carcel–Carrasco, 2021). Risk perception depends on expertise and communication; a lack of clear procedures and training can reduce understanding of potential hazards (Amundrud, 2015).

Organizational and managerial factors play a crucial role: lack of leadership support, unclear procedures, and weak strategic planning reduce trust and motivation. The implementation of digital tools such as CMMS can face resistance when the organization is not ready or lacks adequate IT resources. High–quality communication and employee involvement in improvement initiatives increase the sense of belonging and motivation (Bakotić, 2017; Dzulkifli, 2021).

Table 1 presents the factors that influence employees' perception of maintenance processes.

Table 1. Factors influencing employees' perception of maintenance processes

Factor category	Examples	Effect on perception
Technical factors	Equipment reliability, spare part availability, MTBF/MTTR indicators	Higher reliability and shorter downtimes increase trust in the maintenance system
Organizational factors	Management support, clear procedures, strategic planning, CMMS implementation	Lack of support and unclear procedures create resistance and dissatisfaction
Social & cultural factors	Safety culture, teamwork, leadership style, communication transparency	Positive culture and participative leadership strengthen engagement and motivation
Individual factors	Work experience, education, prior knowledge, type of contract (permanent/temporary)	Experienced and permanent staff tend to show more positive attitudes; younger employees need mentoring
Technological factors	Introduction of new IT solutions, process digitalization (CMMS, IoT, AI)	Without training and support, resistance occurs; with education, trust and perceived efficiency increase

The review of the literature shows that employees' perception is not solely a result of technical working conditions but is also strongly shaped by the organizational and social environment. This combination of factors determines employees' readiness to embrace new maintenance strategies and actively contribute to process improvement.

Employees' attitudes and their role in improving maintenance processes

Employees' attitudes toward maintenance processes are shaped by a combination of individual, organizational, and sectoral factors. These attitudes can be measured using both quantitative and qualitative methods, with surveys and interviews most commonly applied to reveal differences between formally documented and personal knowledge. Research shows that a significant portion of maintenance–related expertise stems from personal experience, especially among more seasoned workers (Carcel–Carrasco, 2021).

A positive attitude toward training and innovation enhances employees' awareness of the importance of maintenance and their willingness to participate actively. Management support, effective communication, and employee involvement in decision–making strengthen motivation, trust, and participation, while their absence leads to resistance and reduced engagement. Employees' attitudes can also serve as leading indicators of system reliability, as they reflect risk perception and operational efficiency (Osman, 2016).

Work experience and job satisfaction significantly affect process stability and quality — experienced workers often show greater commitment and responsibility, although some studies indicate that a long tenure within the same organization may reduce enthusiasm (Inayat, 2021).

Attitudes are also influenced by sectoral affiliation — employees from different sectors or positions may have varying perspectives on maintenance processes, highlighting the need for management strategies tailored to specific work environments (Christodoulou, 2020).

DISCUSSIONS

The literature review indicates that no single maintenance strategy is universally applicable and that their success depends on a combination of technical, organizational, and human factors. TPM relies most heavily on organizational culture and employee engagement, while RCM and CBM require substantial technical and financial resources. CMMS has proven to be a solid foundation for transitioning from traditional to modern approaches, but its effectiveness depends on the organization's readiness for digital transformation.

The literature presents several maintenance strategies that differ in focus, advantages, limitations, and potential applications. Their comparison is shown in Table 2.

TPM is most often recognized as the model that achieves the greatest improvement in Overall Equipment Effectiveness (OEE) by involving employees and promoting autonomous maintenance (Andriulo, 2015). However, its implementation requires a strong organizational culture, continuous training, and management support, which often leads to employee resistance (Chibu, 2018).

Table 2. Comparison of key maintenance strategies

Strategy	Focus	Advantages	Limitations	Typical application
TPM (Total Productive Maintenance)	Involvement of all employees in maintenance, autonomous maintenance, and continuous improvement	Increase in OEE (often >10%), higher motivation and employee knowledge, reduction of failures and downtime	Requires strong organizational culture and management support; employee resistance during introduction	Manufacturing industry, energy sector, companies striving for high–reliability culture
RCM (Reliability Centered Maintenance)	Criticality analysis of systems and components; focus on reliability and safety	Cost and priority optimization, extended equipment life, risk reduction	Complex and expensive analysis process, requires experts and time	Complex technical systems (energy, oil & gas, aviation)
CBM (Condition–Based Maintenance)	Monitoring actual equipment condition and predictive analysis	Reduced unplanned downtime, rational planning of interventions, lower costs compared to excessive maintenance	Requires high–quality monitoring systems, high initial cost of sensors and software	Systems with critical equipment and frequent failures, Industry 4.0 environments
CMMS (Computerized Maintenance Management System)	Digitalized maintenance management: planning, monitoring, and analysis	Better cost control, work transparency, spare parts stock optimization, cost reduction 5–10%	Requires investment in software and IT infrastructure; employee resistance without adequate training	Widely used in all industries, especially in large organizations with complex equipment

RCM has proven effective for complex and critical systems because it allows detailed reliability analysis and activity prioritization, but its implementation demands significant financial and expert resources. CBM offers flexibility by relying on the actual condition of equipment, thus reducing both planned and unplanned downtime, but its use is limited by the availability of reliable monitoring systems and high initial costs. CMMS is an important digital platform for integrated maintenance management, enabling more precise planning and cost reduction by 5–10% over three years; however, its success depends on employee training and readiness for change (Dzulkifli, 2021).

The human factor shows that technical solutions cannot deliver maximum results without considering employees' attitudes and perceptions. Length of service, experience, and job satisfaction directly influence views on maintenance processes, while management support and communication quality shape trust and employees' willingness to engage in innovations. Contradictions in the literature are particularly noticeable regarding the effect of tenure — some authors confirm a positive correlation with engagement (Inayat, 2021), while others find no statistically significant link (Yusuf, 2015), suggesting that this relationship depends on sectoral and organizational context.

The review also highlights gaps in research. Most studies come from large multinational companies. Additionally, technical aspects of strategies are frequently emphasized, while the human factor and organizational culture receive less attention. Practical implications suggest that selecting an optimal maintenance strategy cannot rely solely on technical parameters (MTBF, MTTR, OEE) but must also include an analysis of employee attitudes, readiness for change, and the organization's cultural capacity to support innovation. Integrating TPM and CMMS strategies with systematic training programs and participative management can represent a sustainable path for process improvement.

Future directions are focused on digitalization and predictive models based on big data, but their success will depend on companies' ability to align technical innovations with human potential and organizational structure. In practice, challenges most often arise due to a lack of resources and employee resistance, suggesting that digitalization should be implemented gradually and adaptively. Continuous training and trust–building among employees create the foundation for success. In this way, modern maintenance transcends its role as a purely technical task and evolves into a strategic function that connects technology, organization, and people.

TRENDS AND FUTURE DIRECTIONS IN INDUSTRIAL SYSTEM MAINTENANCE

Digitalization and Smart Maintenance

Industry 4.0 has opened new opportunities for the development of smart maintenance, based on the integration of IoT sensors, Big Data, and Artificial Intelligence (AI). These tools enable the collection and analysis of equipment condition data in real time, contributing to more accurate failure prediction and optimized intervention planning. The use of Machine Learning (ML) makes it possible to create algorithms that detect degradation patterns and provide predictive recommendations, reducing the need for scheduled downtimes and "blind" interventions.

Key components of Predictive Maintenance (PdM) include sensors, data processing modules, algorithms for assessing Remaining Useful Life (RUL), decision–making modules, and integration with ERP (Enterprise Resource Planning) systems. However, challenges arise in terms of reliability and explainability (XAI – Explainable Artificial Intelligence), highlighting the need to build trust in digital tools (Ucar, 2024).

The application of AI in predictive maintenance brings three major benefits: remote monitoring and increased system availability, objective data–driven decision–making, and cost optimization by reducing labor hours and enabling more efficient analysis. Limitations include a lack of high–quality data and employee resistance to new technologies, which is why gradual implementation and the development of a trust–based organizational culture are recommended (Scaife, 2024).

It is clear that the adoption of AI and IoT tools offers significant advantages, but aside from technical barriers, the key challenge remains economic. Most companies lack the resources for such investments. This problem can only be overcome through systemic support and long–term investment; until then, digitalization may remain insufficiently effective.

Integration with Energy Efficiency and Sustainability

Maintenance is increasingly linked to sustainable development and reducing the ecological footprint. Integrating Maintenance Management Systems (MMS) with Energy Management Systems (EMS) enables better resource consumption control and emission reduction. In this way, maintenance becomes a key element of the circular economy, extending equipment life cycles, enabling part recycling, and ensuring rational resource use.

Sustainable Maintenance (SMA) acts as a moderator between Sustainable Manufacturing Practices (SMPs) and overall Sustainability Performance (SP). This ensures a balance of economic, environmental, and social goals in accordance with the "triple bottom line" principle (TBL – people, planet, profit) (Ibrahim, 2019).

Various strategies such as preventive and predictive maintenance, Condition–Based Maintenance (CBM), and advanced Fault Detection and Diagnosis (FDD) significantly contribute to energy efficiency in industrial systems. A particular focus is placed on Energy–Centered Maintenance (ECM), where energy consumption becomes a key criterion for planning and implementing maintenance activities (Firdaus et al., 2019).

The integration of energy and sustainability aspects into maintenance represents a long–term strategic priority. This trend is especially relevant for energy–intensive industries, where the adoption of sustainable maintenance strategies can lead to substantial energy savings and emission reduction.

The Human Factor in the Digital Environment

Digital transformation brings new challenges in human resource management. Although predictive models and digital platforms reduce manual labor, they increase the need for employees to develop new skills — primarily in data analytics, software usage, and understanding complex digital systems. Along with technical abilities, soft skills such as collaboration, leadership, and adaptability to change play a crucial role. Organizations that fail to invest in employee training face resistance, low trust, and poor utilization of new technologies.

Effective leadership and Emotional Intelligence (EI) directly impact maintenance efficiency by improving key indicators such as MTBF (Mean Time Between Failures), MTTR (Mean Time To Repair), downtime hours (DT), and failure rates. Implementing leadership and EI development programs not only reduces downtime and costs but also fosters an organizational culture based on collaboration and motivation (Okirie, 2024).

In the context of Industry 4.0, the role of maintenance managers is shifting from purely technical to broader coordination functions. Their responsibilities now include connecting people, technology, and processes, overcoming employee resistance, and developing new digital skills. The success of digital maintenance strategies depends on balancing technological innovation with socio–organizational factors (Lundgren, 2023).

As previously emphasized, the human factor is crucial. Without continuous training and motivation, digital models remain only theoretical potential. Real success lies in achieving a balance between technical innovations and human competencies. Managerial support, trust–building, and the development of soft skills can determine the success of digital transformation in maintenance.

CONCLUSIONS

Maintenance in industrial systems today represents far more than a technical activity aimed at fixing breakdowns. It has evolved into a strategic function that integrates technical, organizational, and human factors, directly influencing the reliability, productivity, and competitiveness of enterprises. The literature review shows that no single maintenance strategy is universally applicable: TPM provides benefits through employee involvement and continuous improvement, RCM is suitable for critical and complex systems, CBM and predictive approaches enable condition–based decision–making, while CMMS provides a digital foundation for managing and controlling processes.

The findings also indicate that the success of implementation does not depend solely on the choice of technical strategy but equally on employee readiness, managerial support, and organizational culture. Employee attitudes and perceptions shape how new technologies and procedures are adopted, making the human factor just as important as technical solutions. Training, communication, and leadership based on collaboration and emotional intelligence play a particularly significant role.

Current trends highlight the growing importance of digitalization (IoT, AI, Big Data), integration with energy efficiency and sustainability, and the increasing significance of the human factor in the digital environment. The future of maintenance will be directed toward systems that combine technical innovations and organizational aspects, creating models that simultaneously improve equipment reliability and efficiency, reduce the environmental footprint, and foster employee engagement. Digital tools offer great potential, but their implementation faces economic and organizational barriers. Sustainable maintenance opens opportunities to reduce costs and environmental impact, while the human factor remains crucial for overcoming resistance and building trust.

The purpose of this review paper was to present various maintenance strategies, their effects and limitations, and the role of employees in their application — in order to highlight the need for an integrated approach to industrial system maintenance. Maintenance is of key importance because it ensures the stability and safety of production processes, extends equipment life, reduces costs, supports sustainability, and strengthens the competitiveness of industrial organizations in the global market. Therefore, the findings of this research emphasize that a balanced approach — connecting technology, organization, and employees — is essential for improving maintenance processes in modern industrial environments. The author concludes that the true success of implementing modern maintenance strategies depends on achieving the right balance between technical innovations and human competencies.

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