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Innovation management strategies for industrial machinery maintenance: Enhancing competitive advantage

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Abstract: In a rapidly evolving technological and business environment, business leaders must adapt quickly to maintain their competitiveness. The main objective of this article is to propose a maintenance management guide with the innovation management process to help organizations develop effective innovation strategies and respond to the challenges of the Industry 4.0 era. It examines the principles and strategies of innovation management in the maintenance of industrial machinery and their impact on competitiveness. It focuses on the integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics into maintenance processes. This article explains that the introduction of modern technologies in the areas of predictive maintenance, condition-based maintenance, and intelligent maintenance significantly reduces machine downtime, increases production efficiency, and lowers operating costs. However, implementing these innovations comes with challenges, including data management, cybersecurity risks, lack of employee skills, and high investment costs, especially for small and medium-sized enterprises (SMEs). This article proposes a structured transition plan for the introduction of innovative maintenance strategies. The approach focuses on upskilling the workforce and cultivating an innovation-oriented corporate culture. By addressing these challenges, companies can strengthen their competitiveness and long-term sustainability in an increasingly digitalized industrial landscape.
Keywords: *Maintenance innovation, Maintenance strategies, Competitiveness, Smart, Maintenance.*

1. Introduction

Today's industry is undergoing a rapid transformation under Industry 4.0 and moving towards Industry 5.0, where digital technology is a key factor that will lead companies to sustainable competitiveness. Safitri [1] have introduced the concept of "DICE World", which describes the current business environment characterized by D (Dynamic), i.e. sudden changes to which companies must quickly adapt to; I (Insecure), i.e. increasing uncertainty and risk due to internal and external factors; C (Complex), i.e. the complexity of managing multidimensional, interrelated factors; and E (Exponential), i.e. exponential growth and technological change forcing management to develop strategies to cope with change. Industrial maintenance has evolved from the traditional model that focuses on repairing damage when it occurs to preventive and predictive maintenance with modern technology and advanced data analytics [2]. Therefore, innovation management in maintenance has become an important factor that helps companies build competitiveness and sustainable growth in a highly uncertain environment [3]. The evolution towards smart maintenance requires the integration of technology, work processes and systematic human resource development [4].

This article aims to explore the strategy for innovation management in industrial machinery maintenance to increase competitiveness in the manufacturing industry. It presents a conceptual framework that combines the level of smart maintenance development with the application of

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technology and innovation. This framework can serve as a guide for companies to create innovations aimed at increasing production efficiency, reducing costs and improving competitiveness in the industry. This conceptual framework is divided into five main components: Development of a maintenance system according to the level of complexity, use of technology and innovation, development of human resources, measurement and evaluation of performance, and organizational adaptation [5].

The main objective of this article is to propose a guide for maintenance management with the innovation management process to help organizations develop effective innovation strategies and respond to the challenges of the Industry 4.0 era. It also provides guidance for organizations that want to transform their maintenance systems into predictive and command-based maintenance [6]. The expected outcomes of this study include increasing the long-term competitiveness of the organization, reducing production costs and improving the quality and standards of production [7].

The strategy of innovative maintenance management of industrial machinery focuses on the application of IoT, AI and big data technologies to analyze and predict machine failures in advance [8]. These strategies respond to the need for companies to adapt to the rapid changes in market conditions while taking into account the development of employees' skills and potential in line with modern technologies [9]. The importance of this topic lies in the potential for long-term business success and machine reliability. The effective implementation of innovative maintenance management strategies enables companies to reduce unexpected downtime, increase machine availability and modernize production processes to meet market demands in the age of Industry 4.0 [10].

2. Literature Review

2.1. Development of Industrial Maintenance

Industrial maintenance management began during the industrial revolution and the transition from manual production to mass production. Initially, the focus was on reactive maintenance, i.e. repairing damage after it had occurred [2]. In the 20th century, production lines and automation technology prompted manufacturers to focus on preventive maintenance to reduce downtime and extend equipment life [3]. In the late 20th century, computerized maintenance management systems were introduced, allowing real-time access to data, tracking of repair history and efficient management of spare parts inventory [4]. Later, Industry 4.0 technology, particularly the Internet of Things (IoT), evolved into predictive maintenance, which uses data analytics to predict damage. Currently, maintenance management is an important element of operations strategy in the manufacturing industry, which focuses on a holistic approach to increase efficiency, reduce costs and maintain safety standards [10, 11].

2.2. Intelligent Maintenance Approaches

Smart maintenance approaches have evolved from traditional approaches to the application of advanced technologies and data analytics and are categorized into three stages of development based on their complexity. The first stage is *Condition-Based Maintenance*, which uses data from sensors or inspections to decide when maintenance needs to be carried out. This strategy is beneficial for increasing competitiveness in the manufacturing industry as it reduces unexpected downtime by continuously monitoring the condition of the machine, reduces costs by avoiding unnecessary maintenance and increases production efficiency by reducing downtime and increasing the reliability of the machines [8]. The second level is *Predictive Maintenance*, which builds on the first level by using advanced analytics and real-time data to predict machine failures before they occur [5]. The highest level is *Prescriptive Maintenance*, which uses artificial intelligence and machine learning to analyze data and recommends the most appropriate course of action [6].

Table 1.
Smart Maintenance Maturity Model.

Development Level	Key features of maintenance systems	Key technologies used
Level 1 - Reactive Maintenance	Fix when machines break down	No technology
Level 2 - Preventive Maintenance	Schedule repairs	CMMS (Computerized Maintenance Management System)
Level 3 - Condition-Based Maintenance	Monitor machines via sensors	IoT, Sensor
Level 4 - Predictive Maintenance	Predict damage with AI and real-time data	AI, Machine Learning
Level 5 - Prescriptive Maintenance	Automated decision-making and data analysis	Digital Twin, Big Data

Source: Anaba, et al. [12] and Maier, et al. [13]

2.3. Proactive Maintenance Strategy and Asset Reliability Management

Proactive maintenance is a strategy that focuses on reducing the need for future maintenance by upgrading or replacing parts to be more durable, including considering designing new machines to repair damage that has occurred in the past [7]. Reliability Centered Maintenance (RCM) is a strategy that complements proactive maintenance with systematic analysis. According to a study by Bohrey and Chatpalliwar [14] companies that applied for RCM were able to increase equipment availability by up to 6 percent and reduce downtime by 15 percent. The RCM process consists of several important steps: Analyzing the system's functional and performance standards, identifying failure modes and their potential impact, prioritizing equipment based on risk levels, determining the appropriate maintenance schedule for each piece of equipment, and continuously monitoring and improving the maintenance schedule for maximum efficiency [14].

2.4. Using Technology and Innovation to Support Modern Maintenance

Maintenance in the digital age has evolved dramatically through the integration of modern technology and traditional maintenance. Three key elements are interlinked and mutually reinforced. Starting with the Internet of Things (IoT), the cornerstone of modern maintenance, studies have shown that IoT-based predictive maintenance systems can significantly extend the service life of machines. The principles of IoT in maintenance include the collection of real-time data from sensors, continuous monitoring of machine performance, providing immediate notification of abnormalities, and the collection of data for in-depth analysis. In the context of industrial systems, the integration of machine learning with IoT sensors has been shown to improve machine uptime by 5.5 percent, highlighting the effectiveness of real-time monitoring in reducing machine downtime [8]. Artificial intelligence (AI) is the second component that works in tandem with IoT by processing big data through advanced algorithms. The application of AI in maintenance includes machine failure prediction, root cause analysis, automatic maintenance scheduling and continuous improvement of work efficiency [6]. The last component is Smart Maintenance, where machines located along the production line can communicate with the relevant personnel to explain the operating status of the machines and the required maintenance intervals, which can be managed in real time for strategic resource allocation via the network. This system can retrieve relevant information instantly. This increases production efficiency and reduces maintenance costs [9].

2.5. Human Resource Development to Support Modern Maintenance Innovations

2.5.1. Training and Skills Development

Training and upskilling staff is an important element in driving innovation in maintenance, especially at a time when technology is changing rapidly. Companies need to develop both technical and digital skills in their employees. Training should cover modern technologies such as IoT, AI and data analytics and develop analytical and problem-solving skills. Training should be evaluated and curricula continuously updated to meet changing needs. A study in a sugar factory found that after training, employees' skills, knowledge and problem-solving abilities increased by 20 percent and the number of work errors decreased significantly [11]. A study on the impact of international labor migration on economic growth in the era of Thailand 4.0 also found that while Thailand has seen an increase in highly skilled workers over the past decade, most research still focuses on studying low-skilled workers. The results show that high-skilled labor has a statistically significant positive impact on regional economic growth and labor productivity [15].

2.6. Knowledge Management and Experience Transfer

Knowledge management is an important process for maintaining and developing maintenance knowledge. Organizations must have a practical system for storing and sharing knowledge. This includes setting up a database of best practice, creating work manuals and recording experience. In addition, knowledge transfer between old and new employees through mentoring systems and the creation of learning communities is also important to maintain continuity of development [16]. The study found that Thailand's higher education reform still has challenges in terms of administrative efficiency and educational equity that need to be addressed to support the development of an informed workforce [17]. King Mongkut's University of Technology North Bangkok has initiated a workplace collaboration project to improve workforce development in line with the 4.0 era [18].

2.7. Skills and Career Path Development

The development of skills and career paths in the age of Industry 4.0 is crucial for the implementation of innovations in maintenance. The study found that organizations with clear skills development plans linked to career paths can increase the retention rate of talented staff [19] and improve work efficiency [20]. Employees who have developed digital skills and data analytics can advance to the position of Smart Maintenance Specialist, which is better paid than that of a general maintenance technician [21]. Creating this career path helps to create motivation and organizational commitment, leading to sustainable development of modern maintenance systems in the long term.

2.8. Creating Organizational Culture

Creating a corporate culture that emphasizes learning, and innovation is an important foundation for the development of modern maintenance systems. Organizations should foster a work culture that is open to change and the introduction of new technologies, create a work environment that encourages knowledge sharing and creativity, reward and recognize employees who contribute to innovation development, and create an understanding of the importance of maintenance to the success of the organization [22]. Creating an organizational learning culture is directly related to the effectiveness of training and knowledge management, as it forms the basis for continuous knowledge sharing and skills development.

2.9. Change Management

Change management is an important process when introducing innovations in the area of maintenance in an organization. Effective planning and communication are required to reduce resistance and gain the acceptance of employees. Clear visions and goals, building a team of change advocates, continuous monitoring and evaluation of the change, and supporting and counseling employees during the transition [23]. Change management strategies such as workshops or training programs for employees and training and knowledge sharing programs are important to improve knowledge management (KM) and knowledge sharing (KS) within the maintenance department. Studies have shown that the use of novice sneakers in the high-tech industry significantly improves KM and KS among employees and promotes a culture of continuous learning [24]. Generative AI or AI chatbots to advise on Predictive Maintenance is another approach to support the transition to modern maintenance [25]. The development of human resources to support modern maintenance innovation must therefore be a process that integrates all five of the above elements, starting with training and development of essential skills, an effective knowledge management and experience transfer system, the creation of a clear career path, the development of an organizational culture that is conducive to learning and innovation, and the systematic management of change that will lead to the success of raising the company's maintenance system to international standards.

Table 2.
The Model of ADKAR (Awareness, Desire, Knowledge, Ability, Reinforcement).

Procedure	Details
Awareness	Create an understanding of the need for Smart Maintenance
Desire	Encourage staff and management to support the change
Knowledge	Train and increase understanding of digital technologies
Ability	Apply knowledge and experiment in real-world applications
Reinforcement	Continuous improvement of processes and promotion of a culture of development

Source: Hiatt [26]

3. Maintenance Performance Measurement and Evaluation

3.1. Key Performance Indicators (KPIs)

Defining suitable key performance indicators is an important basis for evaluating maintenance performance. Leading key performance indicators include Overall Equipment Effectiveness (OEE), Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR) and Planned Maintenance Percentage (PMP), which allow companies to systematically track and evaluate their performance. Research on improving machine maintenance systems based on reliability found that after the improvement, overall equipment effectiveness (OEE) increased by 17 percent, reliability performance (MTTF) increased by an average of 22.68 hours, machine maintenance performance (MTTR) decreased by an average of 7.68 hours and system availability performance increased by 4.2 percent [27].

3.2. Financial Return on Investment (ROI)

Managers must analyze the financial return on investment in a modern maintenance system. Both the direct and indirect costs, such as installing the system, training employees and maintaining the system, should be considered in comparison to the benefits received. Accurate ROI calculations help with investment decisions and appropriate resource allocation. One study found that smart sensors that utilize machine learning have a return on investment (ROI) of 33.3 percent and a positive net present value (NPV) over five years [8]. In addition, the implementation of predictive maintenance systems can increase machine availability from 80 percent to 90 percent [19] with the break-even point for investments in innovative maintenance systems typically being 18-24 months [28].

3.3. Industry Standards and Requirements

Compliance with industry standards is essential to ensure the quality and reliability of maintenance processes. Key standards such as ISO 55000 (Asset Management), ISO 14224 (Collection and Exchange of Reliability and Maintenance Data) [10] and EN 15341 (Maintenance Key Performance Indicators) help in the development and evaluation of maintenance systems. Companies should regularly review their processes and improve them in line with the standards to increase the efficiency and reliability of the production system [29].

3.4. Regulatory Compliance and Safety

Safety and regulatory compliance are key components of effective maintenance [30]. Companies must have a comprehensive safety management system that includes accident prevention [23] employee training and work environment management. Modern technologies such as IoT and AI can help to monitor and control safety more effectively. An effective maintenance system must prioritize safety and compliance with relevant laws and regulations [22].

3.5. Continuous Monitoring and Improvement

The continuous development of a maintenance system is the key to long-term success. Companies should regularly analyze their performance using real-time tracking and analytics data. Applying the concepts of continuous improvement and kaizen helps organizations to effectively improve and evolve their maintenance processes. This continuous improvement should encompass technology, workflows and staff development. To make the maintenance system modern and respond effectively to the needs of the organization [11, 27].

4. Trends and Future of Industrial Maintenance

4.1. Future Technology and Innovation

Future technology and innovation play a key role in the development of maintenance systems, especially the use of advanced analytics and digital twin, which can be used to create virtual models of equipment that enable the analysis of operating conditions, the prediction of failures and the improvement of maintenance efficiency in advance. Advanced data analytics also increases the accuracy of predictive maintenance, reduces unnecessary maintenance and extends the life of machinery [31]. Augmented Reality (AR) and Virtual Reality (VR) technologies allow technicians to see data superimposed on real equipment or practice repairs in a virtual environment before performing them, reducing errors and increasing work efficiency [32]. Edge computing enables data processing from sensors and IoT devices directly at the edge unit, reducing the amount of data transfer to the cloud system and enabling real-time alerts and responses [33]. 5G networks will enable faster and more stable connections between IoT devices and maintenance systems and support efficient remote maintenance [34]. Quantum computing helps analyze large, complex data. Higher accuracy in predicting machine failures [32] and automation and robotics reduce human workload in high-risk tasks, enable continuous maintenance, reduce downtime and increase productivity [35].

4.2. Challenges and Opportunities

The biggest challenges in the development of modern maintenance systems are cyber security and big data management. Companies need to integrate old and new systems and train their employees to keep up with technology. However, there are also opportunities to develop new business areas, such as subscription-based maintenance services and data analytics for business decision making. Using blockchain to track maintenance history and certify parts quality will create a competitive advantage [36]. Challenges faced by Thai SMEs include low digital readiness, lack of skills and the need to invest in new technologies. Overcoming these challenges through targeted strategies can increase productivity and competitiveness, which will contribute to the growth of the SME sector in Thailand [37].

4.3. Organizational Adaptation

Companies must adapt their structures and work processes in order to keep pace with technological change. Investment in digital infrastructure and talent development are essential. Collaboration with technology partners and educational institutions will help to strengthen the organization. Organizational culture should be changed to emphasize innovation and lifelong learning. Developing effective knowledge management systems will help to maintain a competitive advantage [38]. For Thai SMEs, the challenges of digital transformation include the need for new skills, technology investment and process improvements. Studies show that by collaborating with universities and technology development agencies, SMEs can effectively address these challenges and increase their competitiveness in the market [37].

4.4. Industry Trends

The manufacturing industry is moving towards a *"manufacturing-as-a-service"* concept that emphasizes flexibility and responsiveness to specific customer needs. Maintenance will focus more on prevention and prediction and use AI and machine learning for analysis and decision-making.

Maintenance ecosystems will be developed that connect manufacturers, service providers and customers, and maintenance systems will be integrated into the concept of the circular economy for sustainability [39]. These trends reflect a fundamental shift in the way the industry will carry out maintenance in the future. It will be more proactive and connected, focusing on value creation and long-term sustainability.

4.5. Case Study: A Global Leading Company and the Application of Intelligent Maintenance

Siemens Optimization of Production Digital Twins are frequently used in manufacturing to model and optimize production processes. For example, it enables the simulation of worker movements and assembly line operations, which leads to better ergonomic analysis and process optimization [40].

General Electric (GE) uses Big Data Analytics to assess and predict machine maintenance in advance, reducing downtime and increasing production efficiency [41].

The Toyota Production System (TPS) is a well-known method that focuses on continuous improvement and waste reduction to increase production efficiency. It is based on two fundamental pillars: Just-in-Time (JIT) and Autonomation (Jidoka), which aim to improve production processes and ensure quality control. TPS identifies seven types of waste: Waiting, Defects, Transportation, Movement, Excess Inventory, Overproduction and Over/Under processing; and seeks to eliminate them to increase production efficiency [42].

5. Conclusion

Strategy for managing innovative maintenance of industrial machinery in the age of Industry 4.0 The manufacturing industry is facing challenges in the age of the "DICE World", characterized by dynamism, uncertainty, complexity and exponential growth [43]. The maintenance strategy has evolved from a reactive to a more modern strategy. The evolution of maintenance has begun from reactive maintenance to preventive maintenance, condition-based maintenance and predictive maintenance [2] where organizations that implement Reliability-Based Maintenance (RCM) being able to increase machine availability by up to 6 percent [14]. Key technologies driving modern maintenance include the Internet of Things (IoT), which can increase machine availability by 5.5 percent [8] Artificial Intelligence (AI), which can predict breakdowns [6] and Smart Maintenance, which enables machines to communicate with operators [9]. Human resource development is another important factor. Training can increase skills and problem-solving ability by 20 percent [11], and employee engagement significantly improves knowledge management [24]. Business leaders use strategies to measure performance with indicators such as OEE, MTBF and MTTR [27]. Investments in modern maintenance systems have a break-even point of around 18-24 months [28].

Future trends will focus on the use of advanced technologies such as Digital Twin, AR/VR and 5G [31]. Leading companies such as Siemens, General Electric and Toyota have successfully and competitively deployed smart maintenance. Companies that can use the smart maintenance model and the ADKAR model as a framework and invest in innovative maintenance technologies will therefore be able to increase efficiency, reduce costs and maintain sustainable competitiveness in the era of Industry 4.0 and beyond [12].

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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