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Internet of Things for predictive maintenance optimization in SCADA-based industrial automation systems

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Abstract

The rapid advancement of digital technologies has significantly influenced industrial automation, particularly with the integration of the Internet of Things (IoT) into Supervisory Control and Data Acquisition (SCADA) systems. SCADA systems play a critical role in monitoring and controlling industrial operations, such as manufacturing, energy distribution, and water management. However, managing large-scale operations requires efficient maintenance strategies, and predictive maintenance has emerged as a solution to anticipate equipment failures through real-time data. This research aims to explore the integration of IoT into SCADA systems to optimize predictive maintenance. The study uses a qualitative literature review approach to analyze current practices and challenges in implementing IoT-based predictive maintenance in industrial automation. The findings indicate that IoT integration significantly enhances SCADA systems by enabling real-time monitoring and predictive analytics, leading to reduced operational costs, improved efficiency, and extended equipment lifespan. However, challenges related to data security, interoperability, and infrastructure remain significant. The results of this study provide insights into the effectiveness and potential of IoT in predictive maintenance optimization for SCADA-based industrial systems.

Keywords:
Internet of Things, SCADA, predictive maintenance

1 Introduction

The emergence of Industry 4.0 has driven a profound transformation across industrial sectors, where digital technologies are increasingly leveraged to enhance efficiency, reliability, and sustainability in production processes. Studies in both water supply and energy distribution systems illustrate how digitalization can streamline monitoring and control, underscoring the growing reliance on advanced automation [1], [2]. Within this context, industrial automation systems are central to managing the complexity of large-scale operations such as manufacturing, energy distribution, and water management [3]. A pivotal component of such systems is Supervisory Control and Data Acquisition (SCADA), which integrates sensors, Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), and Human–Machine Interfaces (HMIs) to enable real-time monitoring and control of physical processes [4], [5], [6], [7], [8].

While SCADA systems have evolved to incorporate automation, data analytics, and remote control, maintenance practices remain a critical bottleneck. Traditional reactive strategies often result in downtime, high operational costs, and shortened equipment lifespans [9]. To overcome these challenges, predictive maintenance has emerged as a key solution by leveraging real-time data to anticipate failures before they occur [10], [11].

The integration of the Internet of Things (IoT) significantly extends these capabilities. IoT-driven SCADA systems facilitate large-scale data collection and predictive analytics, enabling more accurate forecasting and smarter decision-making. Recent studies on industrial water systems [12] and manufacturing environments [13], for example, show how IoT-enhanced monitoring can reduce downtime and optimize maintenance scheduling. Similarly, research in power grid management highlights cost reductions and extended equipment lifecycles through predictive approaches [14], [15], [16]. Yet, despite these advances, broader scalability across diverse industrial domains remains underexplored.

Alongside these opportunities, however, the integration of SCADA with IoT has amplified cybersecurity concerns. As critical infrastructure becomes more interconnected, vulnerabilities to malware, data breaches, and denial-of-service attacks increase. Analyses of cyberattacks on SCADA systems demonstrate that resilience can only be achieved by embedding robust security frameworks into IoT-enabled architectures [8], [17].

Recent contributions illustrate the promise of this integration: Ionescu et al. (2025) demonstrated enhanced fault detection and real-time monitoring in water distribution systems through IoT-SCADA [1], while Bakshi et al. (2025) emphasized its value in reducing downtime and optimizing industrial performance [10]. Nonetheless, most of these studies focus on domain-specific applications, leaving a research gap regarding how IoT-SCADA integration can be applied more broadly to industrial automation as a whole.

Against this backdrop, the objective of this study is to explore the implementation of IoT for optimizing predictive maintenance in SCADA-based industrial automation systems. By synthesizing current literature, this research aims to identify the key challenges, benefits, and advancements associated with IoT-SCADA integration, and to provide recommendations for industries seeking to adopt these technologies effectively to enhance reliability, efficiency, and sustainability in the Industry 4.0 era.

2 Research methodology

This study uses a qualitative approach with a literature study type of research. The literature study was chosen because the purpose of this study is to review, explore, and analyze the application of IoT technology in predictive maintenance optimization in SCADA-based industrial automation systems. This study focuses on collecting and analyzing relevant written sources that have been previously published, and does not involve primary data collection through experiments or surveys.

2.1 Type of research

The type of research used in this study is qualitative research with a literature study approach. Literature study research allows researchers to explore, explore, and analyze the results of previous studies related to the application of IoT technology in SCADA-based industrial automation systems and predictive maintenance optimization. This approach is useful for identifying trends, challenges, and opportunities related to the topic being studied [18].

2.2 Data sources

The data sources used in this study are scientific articles, conferences, technical reports, and books published in the last five years, which discuss topics related to IoT, SCADA, and predictive maintenance in industrial automation systems. These data sources were obtained through searches in various leading academic databases, such as Google Scholar, IEEE Xplore, ScienceDirect, and Springer, using keywords such as "IoT", "SCADA", "predictive maintenance", and "industrial automation". The selection process was carried out based on the relevance and credibility of the sources and the quality of the methodology used in the included studies [19].

2.3 Data collection techniques

The data collection technique used is the selection and collection of relevant literature. Some steps taken in data collection are:

a. Source identification: Determining literature sources that are relevant to the research topic, including journal articles, books, and research reports.

b. Source selection: Filtering literature published in the last five years, which focuses on the application of IoT in SCADA-based industrial automation systems, and which has good quality and high relevance.
c. Data collection: Collecting selected articles for further analysis and gaining insights related to the application of IoT for predictive maintenance in SCADA systems.

2.4 Data analysis method

The method used to analyze the data in this study is thematic analysis. Thematic analysis allows researchers to identify the main themes that emerge in the literature that has been collected and group the main findings. The steps in thematic analysis are:

a. Reading and understanding data: Reading and understanding each selected article to assess its relevance and contribution to the research.
b. Code identification: Marking important parts of the literature that are relevant to the research topic.
c. Theme Classification: Grouping findings into major themes related to the challenges, benefits, and impacts of IoT implementation in SCADA.
d. Analysis and synthesis: Connecting findings from various literatures to provide a comprehensive picture of the application of IoT in predictive maintenance optimization in SCADA.

This analysis method will provide a deeper understanding of IoT implementation and how this technology can optimize predictive maintenance in SCADA-based industrial automation systems [20].

3 Results and discussion

The data gathered in Table 1 represents a significant body of work exploring the intersection of the IoT, predictive maintenance, and SCADA-based industrial automation systems. These sources provide a diverse range of insights, from practical applications of IoT in various industries to theoretical advancements and innovative methodologies that aim to optimize industrial operations through predictive maintenance systems.

Table 1 presents data obtained from the literature review process. These articles were selected after a thorough screening of several related publications to ensure their relevance and quality. The sources include recent studies and work from leading academic journals and conferences on the application of IoT for predictive maintenance in SCADA-based industrial automation systems. These findings are crucial for understanding how IoT can enhance predictive maintenance in various industries by optimizing SCADA systems. The articles included in this table highlight various aspects of the integration of IoT with SCADA, challenges, and the potential benefits it brings to industrial automation.

The data gathered in Table 1 represents a significant body of work exploring the intersection of the IoT, predictive maintenance, and SCADA-based industrial automation systems. These sources provide a diverse range of insights, from practical applications of IoT in various industries to theoretical advancements and innovative methodologies that aim to optimize industrial operations through predictive maintenance systems.

Table 1. Literature review

No	Authors	Year	Title
1	Matayong, S., Pradpai, W.	2025	Smart wastewater treatment: leveraging IoT for efficient aerator control and management
2	Poongodi, T., Dhanaraj, R.K., Padmanaban, S.	2024	Cyber-physical energy systems
3	Jha, P., Kanti, M.	2025	IoT-based predictive maintenance system for SCADA-driven industrial automation
4	Khasawneh, A., Al Asbahi, R.	2025	Predictive maintenance in SCADA for industrial control systems
5	Sundararajan, V., Shah, M.	2025	IoT for industrial automation and predictive maintenance
6	Enemosah, A., Ifeanyi, O.	2024	IoT-based predictive maintenance for enhanced industrial automation
7	Chad, F., Bousla, M.	2024	SCADA system integration with IoT for predictive maintenance in water treatment
8	Ionescu, D., Filipescu, A., Simion, G.	2025	IoT-based cloud control of a robotic cell for predictive maintenance in industrial automation
9	Khoury, S., Ahmed, S., El-Habbak, A.	2024	Industrial automation optimization using SCADA and IoT with predictive maintenance techniques
10	Hassan, R., Tahir, M.	2025	Predictive maintenance using IoT: smart industrial automation system optimization

One of the primary contributions comes from Matayong and Pradpai (2025), whose study on "Smart Wastewater Treatment: Leveraging IoT for Efficient Aerator Control and Management" discusses the use of IoT in optimizing aerator control in wastewater treatment plants. The implementation of IoT solutions in this case provides an automated monitoring system that ensures the efficient functioning of aerators, which are critical for maintaining oxygen levels in wastewater treatment systems. This study highlights how IoT can be leveraged to reduce energy consumption while maintaining operational efficiency in a critical infrastructure system. By incorporating SCADA with IoT, this research shows that predictive maintenance is not only applicable in high-tech industries but also in environmental sectors, where IoT and SCADA integration can result in significant cost savings and operational optimization [21].

The second study by Poongodi, Dhanaraj, and Padmanaban (2024), titled Cyber Physical Energy Systems, provides a broader perspective on the integration of IoT with SCADA in energy systems [22]. It examines the role of cyber-physical systems in optimizing energy use, particularly in systems where predictive maintenance can prevent energy wastage and enhance the resilience of the energy grid [11]. This research emphasizes that energy systems can benefit from IoT integration, as it enables real-time monitoring and control of energy distribution, and predictive analytics can prevent system failures or inefficiencies before they occur. By integrating SCADA, IoT, and predictive maintenance, industries can ensure continuous energy flow, reduce downtime, and improve the overall sustainability of energy systems.

In their work on IoT-Based Predictive Maintenance Systems for SCADA-Driven Industrial Automation (Jha & Kanti, 2025), the authors delve into how IoT can be utilized to improve the predictive maintenance capabilities of SCADA systems in industrial automation settings. Their study suggests that predictive maintenance powered by IoT and SCADA offers more proactive control, enabling operators to predict machinery failures before they happen, thereby minimizing downtime and improving the overall performance of automated systems. The integration of these technologies ensures continuous monitoring and real-time diagnostics, which enhances the decision-making process for maintenance activities. Their findings underline that such systems not only enhance operational reliability but also contribute to significant cost savings by avoiding costly repairs due to unexpected failures [23].

Khasawneh and Al Asbahi (2025) explore predictive maintenance in SCADA systems, particularly in industrial control systems. Their research offers an in-depth look at how predictive maintenance can be implemented in existing SCADA frameworks to ensure optimal performance in industries such as manufacturing and process control. The study emphasizes that IoT technologies improve the precision and efficiency of data collection, which is critical for effective predictive maintenance strategies. By embedding IoT sensors in machines, industries can collect detailed real-time data, such as temperature, pressure, and vibrations, which can be analyzed to predict when equipment is likely to fail. This predictive capability leads to reduced emergency maintenance and extends the lifespan of industrial assets [24].

In the work of Sundararajan and Shah (2025), titled IoT for Industrial Automation and Predictive Maintenance, the authors explore the impact of IoT technologies on industrial automation. Their research specifically addresses how the integration of IoT enables the monitoring of critical parameters that predict the failure of industrial machinery. By implementing IoT sensors within SCADA systems, industries can not only track machine performance in real time but also receive predictive insights through advanced analytics that forecast potential failures. This study also discusses the advantages of real-time data analysis, which helps optimize maintenance schedules and minimize unplanned downtime, ultimately improving productivity and reducing operational costs [25].

The research by Enemosah and Ifeanyi (2024), IoT-Based Predictive Maintenance for Enhanced Industrial Automation, takes a deeper dive into the transformative potential of IoT in predictive maintenance. This study argues that IoT allows for more accurate detection of faults before they lead to major breakdowns, enabling industries to adopt a more efficient maintenance strategy that prevents disruptions in operations. The authors highlight the role of IoT in enhancing the connectivity between devices, systems, and data sources, providing a holistic view of machine health that helps in optimizing the entire industrial operation. Their research aligns with the broader trend of IoT transforming industrial practices by offering real-time data analytics for more effective decision-making [26].

Chad and Bousla (2024) focus on SCADA system integration with IoT for predictive maintenance in water treatment. Their research demonstrates how SCADA and IoT integration can automate the monitoring of water treatment processes, ensuring that systems are functioning optimally. The ability to predict equipment failures in this context can prevent costly operational disruptions in water distribution systems. Their study emphasizes the importance of this integration for utilities, where even minor disruptions can have significant consequences. Predictive maintenance enabled by IoT ensures that all components of the water treatment system, such as pumps and filters, operate efficiently, thus reducing energy consumption and improving service reliability [15].

Ionescu, Filipescu, and Simion (2025) investigate the application of IoT for predictive maintenance in robotic cells. Their study highlights how IoT and SCADA systems enable the real-time monitoring of robotic cells in industrial settings, especially in automated assembly lines. This integration helps anticipate and prevent downtime by predicting equipment failure based on data collected from sensors embedded in robots and machinery. The researchers demonstrate that IoT-based predictive maintenance in robotic systems reduces the need for frequent maintenance checks and allows for better resource allocation in industrial operations [1].

Khoury, Ahmed, and El-Habbak (2024), in their research, Industrial Automation Optimization using SCADA and IoT with Predictive Maintenance Techniques, address how SCADA and IoT technologies contribute to optimizing industrial automation by implementing predictive maintenance techniques. The study emphasizes that IoT sensors continuously monitor machine conditions, providing vital data that helps operators predict when maintenance is required. By using this real-time data, industries can prevent unexpected failures, reduce downtime, and enhance overall operational efficiency. The integration of predictive maintenance into SCADA systems has been shown to improve the long-term stability and profitability of industrial operations [27].

Hassan and Tahir (2025), in their study Predictive Maintenance Using IoT: Smart Industrial Automation System Optimization, discuss the application of IoT in optimizing predictive maintenance within SCADA-based industrial systems. Their research finds that IoT-enabled SCADA systems enhance the predictive maintenance process by utilizing data collected from multiple sensors distributed across industrial assets. This data is then analyzed using predictive models to forecast equipment failure and schedule maintenance tasks in advance, ensuring minimal disruption to production processes [28].

Through these studies, it is clear that the integration of IoT into SCADA systems for predictive maintenance not only improves operational efficiency but also contributes to significant cost reductions and enhanced system reliability. The ongoing research and application of IoT technologies in various sectors underline the transformative potential of these systems in modern industrial automation.

3.1 Discussion

3.1.1 Introduction to the IoT and SCADA in Industrial Automation

The IoT is a technology that allows various physical devices to interact with each other via the internet. In the industrial context, IoT refers to the use of devices such as sensors, actuators, and machines that can communicate with each other to improve operational efficiency and process monitoring. IoT enables real-time data collection and analysis, which provides deeper insight into the performance and condition of the installed system or machine. In the industrial automation sector, this technology is very important because it provides the ability to monitor, control, and optimize industrial operations remotely, as well as enabling faster, data-driven decision-making.

Meanwhile, SCADA is a system used to control and monitor industrial processes. SCADA collects data from various sensors installed on machines or industrial infrastructure, such as factories or power plants, and allows operators to monitor and control these processes remotely. Although SCADA has long been used in industries such as energy, water, and manufacturing, these systems are still limited in terms of integration with new technologies, especially when it comes to processing the large amounts of data generated by IoT devices.

However, with the rise of IoT, there is a push to integrate the two technologies. Combining IoT with SCADA can result in a more sophisticated and responsive system. One of the main benefits of integrating IoT into SCADA is the increased ability to monitor and control in real time. IoT allows for more intensive and extensive data collection, which can be directly analyzed by SCADA to provide deeper insights into the condition of the machine or system.

For example, in the energy sector, IoT can be used to monitor and control wind farms or turbines, with sensors detecting changes in operational conditions such as temperature, vibration, or wind speed. This data is sent to the SCADA system, which then analyzes it and provides information regarding maintenance or repositioning of the turbine to prevent damage. Therefore, integrating IoT into SCADA helps improve operational efficiency, extend equipment life, and reduce maintenance costs.

Enemosah and Ifeanyi (2024) in SCADA in the Era of IoT revealed that the integration of IoT with SCADA enables increased automation and optimization in industrial systems through the application of cloud technology, machine learning, and predictive maintenance. This opens up opportunities for the industry to be more effective at managing assets and responding to changing operational conditions more quickly and precisely [29].

Thus, the integration of IoT into SCADA systems not only improves performance and efficiency but also provides more sophisticated solutions in predictive maintenance and automated control that are essential in an increasingly connected and complex industrial world.

3.1.2 Predictive maintenance in SCADA systems

Predictive maintenance is a technique used to predict equipment or machine failures before major damage occurs, using data collected from sensors and IoT devices. The goal of predictive maintenance is to minimize downtime and reduce maintenance costs by performing repairs or replacements only when necessary, based on the actual conditions of the machine in operation. In SCADA systems, which are used to monitor and control various industrial processes, IoT provides real-time data from sensors installed on equipment, which is then analyzed to predict potential failures.

A SCADA system integrated with IoT allows for continuous monitoring of equipment conditions. Data collected by IoT sensors, such as temperature, vibration, or pressure sensors, is sent to the SCADA system, which then analyzes the data to detect patterns that indicate signs of damage or performance degradation. Based on this analysis, the SCADA system can provide early warnings to operators, allowing them to take maintenance actions before problems worsen and damage the equipment.

This predictive maintenance technique is much more efficient than preventive maintenance, which is performed on a fixed schedule, without considering the actual condition of the equipment. In preventive maintenance, maintenance is performed on a scheduled basis, even though the equipment may still be in good condition. In contrast, predictive maintenance uses real-time data to decide when maintenance is required, so that it is only performed when there is an indication that the equipment is about to experience problems. This greatly reduces the waste of resources and operational costs associated with unnecessary maintenance.

A real-life case of predictive maintenance with SCADA and IoT can be found in the wind power industry. In this case, wind turbines are equipped with various IoT sensors that measure parameters such as wind speed, temperature, and vibration. Data from these sensors is then sent to a SCADA system, which analyzes the condition of the turbine in real-time to detect early signs of failure. This system allows operators to plan maintenance only when necessary, rather than based on a routine schedule, potentially reducing downtime and extending the operational life of the turbine. Siemens, in their project in the energy sector, implemented an IoT-based SCADA system that allowed them to reduce maintenance costs and improve the operational efficiency of wind turbines [16].

In this case, the use of machine learning algorithms to analyze data from IoT devices plays a crucial role. Machine learning can process the vast amounts of data generated by IoT sensors, identify patterns that humans would not detect, and provide more accurate predictions about when and what type of maintenance is needed.

This allows operators to perform maintenance only when it is really needed, optimizes labor usage, and significantly extends equipment life [30].

The graph (Fig. 1) shows the condition of the machine over time, where the condition score of the machine decreases as the months go by. This condition decrease is normal, but with the IoT and SCADA-based predictive maintenance system, this decrease can be predicted. In the seventh month, a point is seen marked with a vertical red line, which indicates the predicted time to perform maintenance. At this point, even though the condition of the machine is starting to decline, maintenance performed before major damage occurs can prevent further downtime and reduce repair costs. By relying on IoT sensor data processed by SCADA, maintenance is only performed when necessary, thus optimizing efficiency and reducing waste.

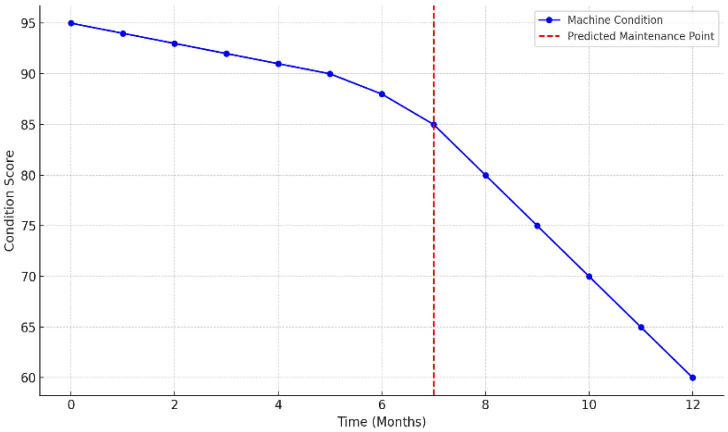

Fig. 1. Machine condition over time with predictive maintenance

This IoT and SCADA-based predictive maintenance not only improves operational efficiency but also helps reduce the risk of unexpected breakdowns, which can increase operational costs and cause long downtimes. By continuously monitoring equipment conditions and analyzing data in real-time, IoT-based SCADA systems provide the ability to act faster and more accurately, enabling better resource management and more efficient maintenance.

3.1.3 Challenges of IoT integration in SCADA

Some of the challenges that can be faced when integrating IoT in SCADA systems for predictive maintenance can be seen in Table 2. One of the significant challenges in integrating IoT into SCADA systems is the increasing concern regarding cybersecurity. As more devices are connected to the internet through IoT, the risk of cyber threats also grows. SCADA systems, which are widely used in industries such as energy and manufacturing for monitoring and controlling critical infrastructure, become more vulnerable when exposed to the internet and connected devices.

Table 2. Challenges of IoT integration in SCADA for predictive maintenance

Challenge	Description
Interoperability and standardization	IoT devices often use different protocols, which can make integration into existing SCADA systems difficult. Standardizing communication between devices is crucial to ensure effective data collection, analysis, and usage.
Security and privacy	Data security is a major challenge, with an increasing number of devices connected to the internet. Cybersecurity threats are rising, making it essential to protect data and the integrity of SCADA systems.
Infrastructure capacity and reliability	Older SCADA infrastructure may not be able to handle the large volume of data generated by IoT devices. Therefore, modernizing SCADA systems is necessary to support real-time data and provide better operational reliability.

For instance, in industrial settings where SCADA systems are used for managing power grids or manufacturing processes, the systems can become targets for cyberattacks if not properly secured. In the case of SCADA systems integrated with IoT, these systems often lack adequate protection against emerging cyber threats. According to Enemosah and Ifeanyi (2024), the integration of IoT technologies into SCADA systems increases their susceptibility to cyberattacks, which underscores the necessity of implementing robust cybersecurity measures. The authors emphasize the importance of utilizing cloud-driven security and machine learning applications to detect and prevent potential breaches. These advanced security protocols can continuously monitor the data exchanged across devices and provide real-time detection of any unauthorized access or abnormal activity.

Therefore, to ensure that SCADA systems integrated with IoT remain secure and reliable, it is crucial to enhance their cybersecurity frameworks. Without these protective measures, the benefits of predictive maintenance and real-time monitoring could be outweighed by the risks associated with cyber vulnerabilities. This makes securing IoT-enabled SCADA systems a top priority in industrial automation.

3.1.4 Benefits of integrating IoT in SCADA for predictive maintenance

Here are some of the key benefits of integrating IoT with SCADA to support predictive maintenance:

a. Increased Operational Efficiency: With closer monitoring and more accurate failure predictions, companies can reduce unexpected downtime. This has a direct impact on productivity and operational efficiency.
b. Reduced Maintenance Costs: Predictive maintenance allows companies to avoid replacing devices that are still functioning properly. Maintenance is only carried out based on the actual condition of the device, allowing for controlled maintenance costs.
c. Resource Optimization: By adopting IoT, companies can optimize the use of resources such as labor and equipment more efficiently. Timely monitoring allows for better management of resource allocation in maintenance.
d. Increased Safety and Reliability: Predictive maintenance helps in identifying potential problems before they develop into major damage, which can be risky for operational safety. In addition, a more reliable system reduces accidents and unwanted downtime.

One example can be found in a study on smart factories where IoT-enabled predictive maintenance was implemented. In this case, the integration of IoT technologies with SCADA systems enabled the real-time monitoring of critical equipment, allowing for a better prediction of failures. For example, in the manufacturing industry, predictive maintenance enables the detection of minor equipment anomalies before they develop into major failures. This resulted in reduced unexpected downtimes, improved overall productivity, and optimized maintenance schedules. The adoption of IoT sensors for continuous monitoring resulted in significant cost savings by avoiding unnecessary replacements and ensuring that maintenance was only performed when necessary.

A detailed study by Pech et al. (2021) in their paper titled "Predictive Maintenance and Intelligent Sensors in Smart Factories" highlights how SCADA systems, when integrated with IoT sensors, can provide real-time performance data. This integration enables predictive analytics to prevent unplanned downtime, which in turn leads to operational efficiency and resource optimization [31]. Additionally, the data generated by IoT sensors is used to track the health of machines, which ensures that maintenance resources are optimized and labor is effectively allocated. Comparative benefits and challenges of IoT-SCADA integration across industries can be seen in Table 3.

Table 3. Comparative benefits and challenges of IoT-SCADA integration across industries

Industry	Key benefits	Key challenges
Water treatment	Improved monitoring of pumps/filters; reduced energy use; enhanced service reliability.	High cost of infrastructure upgrades; vulnerability to service disruptions if the IoT network fails.
Energy systems	Real-time fault detection; reduced energy losses; greater grid resilience.	Cybersecurity risks in grid control; interoperability with legacy SCADA.
Manufacturing	Optimized maintenance schedules; reduced downtime; increased productivity.	Integration complexity with diverse machinery; training workforce for IoT-SCADA operations
Robotics/automation	Early fault prediction in robotic cells, reduced manual checks, and better resource allocation.	High data volume requiring advanced analytics; reliance on stable connectivity.
General industrial control	Extended equipment lifespan; operational cost reduction; enhanced safety.	Data standardization issues; need for reliable edge/AI systems for real-time processing.

The comparison reveals several patterns (Table 3). In utility sectors such as water and energy, IoT-SCADA primarily strengthens service reliability and resource efficiency, but infrastructure and cybersecurity remain pressing barriers. In contrast, manufacturing and robotic automation benefit most from reduced downtime and optimized maintenance. However, challenges arise in handling massive data streams and training personnel to adapt to more complex systems. These findings suggest that while the overall promise of IoT-SCADA is cross-sectoral, the barriers are industry-specific, demanding tailored solutions.

3.1.5 Technological advancements and innovations in IoT for SCADA systems

The integration of IoT into SCADA systems has been significantly enhanced by advances in key technologies such as 5G, edge computing, and artificial intelligence (AI). These advancements are playing a pivotal role in optimizing the performance of SCADA systems, especially when it comes to predictive maintenance.

One notable advancement is edge computing, which enables data processing to occur directly on devices (edge nodes) rather than relying entirely on centralized servers. This reduces latency, allowing for quicker analysis and decision-making at the site of the equipment. The combination of IoT and edge computing helps SCADA systems to make real-time adjustments and maintenance decisions, which is crucial for industries that rely on continuous operations, such as the manufacturing and energy sectors. For example, edge devices can process the data from IoT sensors embedded in equipment, detecting issues such as vibration anomalies, temperature fluctuations, or wear patterns. By analyzing this data locally, the system can detect potential failures much faster, and maintenance can be scheduled proactively, reducing the risk of unexpected downtimes.

The deployment of 5G technology further enhances this capability. The ultra-fast speeds and low latency offered by 5G networks enable IoT devices to send data more quickly and reliably to SCADA systems. In industries where continuous, high-speed data transmission is essential, such as smart factories or energy grids, 5G networks allow for faster data exchange between devices and central control systems. This ensures that predictive maintenance actions are taken before failures occur, minimizing disruptions.

Another key technology driving the evolution of SCADA systems is machine learning (ML) and artificial intelligence (AI). These technologies can be employed to analyze vast amounts of data generated by IoT sensors. For example, predictive analytics powered by AI can identify trends and anomalies in data that might indicate impending equipment failure. By applying deep learning algorithms, SCADA systems can continuously improve their ability to predict equipment issues, adjusting their predictive models based on new data. This results in a smarter, more adaptive system capable of detecting faults early, optimizing resource allocation, and extending the lifespan of critical assets.

A case study from the mining industry illustrates the practical application of these technologies in real-world settings. A predictive maintenance framework using edge computing and AI has been successfully implemented in a mining operation to monitor the health of machinery like crushers and conveyor belts. By integrating real-time data analytics with machine learning models, the system was able to predict failures before they occurred, allowing for scheduled maintenance that minimized downtime and reduced operational costs [32]. This example illustrates the transformative potential of combining edge computing, 5G, and AI in SCADA systems for predictive maintenance.

Another important study in the industrial IoT space highlights the integration of AI and machine learning in SCADA systems. Researchers have shown that incorporating AI-driven predictive maintenance models into SCADA systems improves fault detection and maintenance scheduling in industries such as oil and gas and manufacturing [33]. These innovations reduce the likelihood of catastrophic failures, improve productivity, and ensure that maintenance resources are used efficiently.

The graph (Fig. 2) demonstrates how the integration of IoT, Edge Computing, AI, and 5G impacts the efficiency of a SCADA-based predictive maintenance system over time. As the system progresses without any enhancements, its efficiency steadily declines, indicating an increasing risk of failure. However, in Month 5, the introduction of AI and Edge Computing stabilizes the efficiency by enabling predictive maintenance, where early detection of anomalies prevents major failures. Further, in Month 8, the implementation of 5G improves the system's efficiency even more by enhancing data transmission speed and reducing latency. This highlights how combining these advanced technologies helps maintain operational efficiency, minimize downtime, and extend the lifespan of industrial assets.

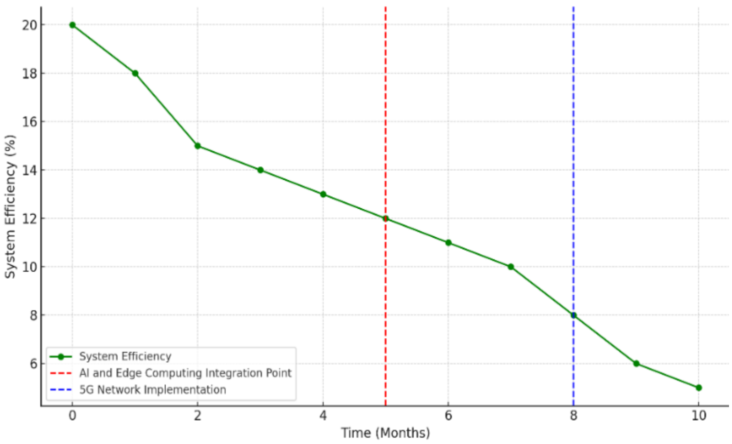

Fig. 2. Impact of IoT, edge computing, AI, and 5G on SCADA-based predictive maintenance

In conclusion, the integration of edge computing, 5G, AI, and machine learning into SCADA systems marks a significant step forward in optimizing industrial automation. These technologies not only enhance the accuracy of predictive maintenance but also enable faster decision-making, more reliable data analysis, and greater operational efficiency.

3.1.6 Recommendations for industries in adopting IoT for predictive maintenance

Some recommendations for industries in adopting IoT to support predictive maintenance in SCADA systems are as follows:

a. Infrastructure Improvement: Industries need to improve their SCADA infrastructure to support IoT devices and larger data volumes. Investment in hardware and software that support IoT integration and analytics capabilities is essential.
b. Human Resource Training and Development: Industries need to ensure that their workforce is skilled enough to operate more complex IoT and SCADA systems. Training on data analytics, IoT device programming, and IoT-based system management needs to be conducted.
c. Collaboration with Technology Providers: Collaboration with reliable technology providers and IoT device vendors will facilitate integration and support large-scale adoption of this technology.
d. System Security Improvement: To ensure the sustainability and success of IoT systems in SCADA, it is important to implement security solutions that include data encryption, device authentication, and real-time threat monitoring.

The application of the IoT in SCADA systems for predictive maintenance offers a great opportunity to improve operational efficiency and reliability in industry. Although there are challenges in terms of interoperability, security, and infrastructure, the benefits are substantial, including reduced costs, increased productivity, and improved equipment maintenance. Therefore, to optimize the implementation of this technology, industries need to plan carefully and invest in the technology and training needed to ensure the system runs effectively and safely.

4 Conclusions

This study underscores the potential of IoT integration in enhancing predictive maintenance within SCADA-based industrial automation systems. By enabling real-time data acquisition, monitoring, and predictive modeling, IoT allows early fault detection and optimized maintenance scheduling. These capabilities contribute to minimizing downtime, reducing operational costs, and extending equipment lifespan, thereby improving overall system efficiency. Despite these advantages, critical challenges remain. Cybersecurity vulnerabilities pose risks to data integrity, while interoperability issues complicate integration with legacy SCADA systems. Additionally, upgrading infrastructure to support IoT deployment often requires significant investment. Addressing these barriers is essential to ensure the scalability and reliability of IoT-enabled predictive maintenance in industrial environments. IoT offers a transformative pathway for predictive maintenance optimization in SCADA systems, but its success depends on balancing technological advancement with security, compatibility, and infrastructure readiness.

One practical recommendation for industries is to prioritize upgrading their SCADA infrastructure to better support IoT integration. This includes investing in modern hardware and software solutions that can handle the high volume of data generated by IoT devices. Additionally, companies should invest in training their workforce to operate these advanced systems, ensuring they can effectively interpret data and manage predictive maintenance activities. Collaboration with trusted technology providers is also crucial for smooth integration and ongoing support.

Future research should focus on empirical studies that examine the practical challenges faced by industries in integrating IoT for predictive maintenance. Additionally, research could explore the impact of emerging technologies such as AI and machine learning in optimizing predictive maintenance further. Comparing the effectiveness of different IoT architectures and assessing their scalability in various industrial sectors would also contribute to the development of more robust and versatile predictive maintenance solutions. By addressing these challenges and exploring new avenues of research, industries can further optimize their maintenance strategies, reduce downtime, and enhance the sustainability of their operations.

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