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Current Scenario of Maintenance 4.0 and Opportunities for Sustainability-Driven Maintenance

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Abstract: Industry 4.0, a shift from Industry 3.0, aims to enhance productivity and efficiency in operations and supply chain management. Maintenance plays a crucial role in this process, and IoT-enabled (Ind. 4.0) condition monitoring is a key component of this technology. However, challenges persist in implementing effective IoT-enabled condition monitoring solutions. The triple bottom line perspective (Economical, Ecological, and Social) is also crucial for realizing Ind. 4.0. This paper investigates the state of IoT-enabled industrial condition monitoring (Maintenance 4.0) and sustainability-driven maintenance (Maintenance 5.0), focusing on the challenges associated with implementing these concepts. The IoT-enabled technologies are divided into three layers: the application layer, the networking layer, and the physical layer. The physical layer, the lowest layer, faces numerous challenges in realizing maintenance 4.0 effectively. A new system configuration for vibration-based condition monitoring in an Ind. 4.0 environment is proposed to address these shortcomings. Wi-Fi technology is found to be the best option for high-throughput communication needs in the current scenario. The literature review reveals that while the economic aspect of maintenance 5.0 has been thoroughly examined, the environmental and social aspects have not been thoroughly assessed. Future research should focus on developing a new sustainable maintenance model that incorporates IoT-enabled technologies and investigates sustainable performance indicators to understand sustainability aspects quantitatively.

Keywords: Industry 4.0, Maintenance 4.0, Sensor, Condition monitoring, Overall equipment effectiveness, Triple bottom line, Sustainability driven maintenance.

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1. Introduction

The first industrial revolution, or Industry 1.0, was the mechanization of industry through the use of steam power and water; the second, or Industry 2.0, was the extensive use of electrical energy for mass production and assembly lines; the third, or Industry 3.0, was the widespread digitalization and automation of industry; and the fourth, or Industry 4.0, was the use of cyber physical systems, the internet of things (IoT), and networking in industry, where everything is connected to everything[1].

More specifically, nine technologies, or "pillars," including Big Data and Analytics, Cloud Computing, Digital Twin, Additive Manufacturing, Augmented Reality, Artificial Intelligence, Block Chain, Simulation, and Industrial Internet of Things (IIoT), make up Ind. 4.0 and turn the factory into a smart, fully automated, and integrated one [2-13].

The growing emphasis on sustainability in Industry 4.0 gave rise to the fifth industrial revolution, or Industry 5.0. Sustainability is built upon three pillars: environmental, social, and economic. The objective of these three pillars is to meet the resource needs of both the current and future generations while avoiding adverse environmental effects [14].

Maintenance plays a critical role in the manufacturing sector since it avoids equipment breakdown, which in turn improves business performance in terms of productivity, quality, and logistics management [15,16]. Breakdown maintenance as well as time-based preventive maintenance practice enhances business performance to some degree, but condition-based predictive maintenance is a superior option. Furthermore, under condition-based predictive maintenance, the maintenance decision is enhanced if the monitoring is done online and continuously for systems that are stochastically deteriorating, which increases the benefits of maintenance even more [17].

In Industry 4.0, condition-based maintenance (CBM) is becoming more and more significant since it reduces maintenance costs and downtime by assisting in the detection of potential asset defects and the precise prediction of the time to breakdown [18]. With time, maintenance transitioned from a CBM strategy to a predictive and prescriptive approach, sometimes referred to as smart maintenance or maintenance. 4.0[19-22]. In the predictive maintenance approach, the impending failure of the asset is predicted using real-time data, and in the prescriptive maintenance approach, a course of action is prescribed based on predictive maintenance. A predictive approach leads to automated or smart maintenance. [23].

Smart maintenance, or Maintenance 4.0, is another term used to refer to the maintenance role in the context of Industry 4.0 [24, 25]. Different authors have different perspectives on the Maintenance 4.0 concept. According to [26], self-learning and intelligent machines that forecast failure, diagnose problems, and initiate maintenance are examples of a subset of the smart manufacturing system. As per [27], smart maintenance is the use of robotics, drones, automated processes, and machine learning in dependability and maintenance tasks. The author [28] suggested that it is the process of applying cutting-edge analytical techniques to large data regarding the technical state, usage, environment, maintenance history, similar equipment elsewhere, and, in fact, anything possibly related to the performance of an asset in order to predict future asset failures and, in the end, prescribe the most effective preventive measure. Smart maintenance represents intelligent and learning maintenance management with an ongoing improvement as its main goal. [29]. According to [30], Maintenance 4.0 does predictive analytics and offers workable solutions. It has significant applications in Industry 4.0, particularly in those areas of maintenance that deal with data collection, analysis, and visualization, as well as asset decision-making, and according to [20], Maintenance 4.0 is an organizational structure intended to handle manufacturing plant maintenance in settings where digital technologies are widely used.

Taking all of the above into consideration, Smart Maintenance refers to a collection of methods for keeping an eye on the state of machines in order to forecast when they will break. These methods include automated real-time analytics and supervised or unsupervised machine learning, which are used to identify potential problems, analyze their interactions, and recommend the best course of action in real time.

The new dimension has been added to Maintenance 4.0, i.e., sustainability, and therefore, Maintenance 4.0 is renamed Maintenance 5.0 [25, 31, 32]. Bruntland Commission (1987) defines Sustainable Development as 'development that meets the needs of the present without compromising the ability of the future generation to meet their own needs.'

After going through the extensive literature survey, it was found that the sustainability dimension includes three aspects: economic, environmental, and social. The analysis reveals that the economic aspect of maintenance systems has been investigated deeply by various authors and practitioners, but it is also essential to meticulously investigate the environmental and social aspects of maintenance systems in order to achieve true development and hence maintenance sustainability (Maintenance 5.0).

The objectives of this article are to present state-of-the-art information on Maintenance 4.0 and Maintenance 5.0 along with a larger understanding of these concepts and the difficulties in implementing Maintenance 4.0. Furthermore, to propose a new system configuration for the IoT-enabled condition monitoring that addresses the shortcomings of the existing setup.

After carrying out the extensive review, it is found that the sustainability performance indicators need to be determined to know the sustainability aspects (economic, environmental, and social) in quantitative form. A new sustainable maintenance model is required to be developed that not only incorporates IoT-enabled technologies and sustainability aspects but also is able to deal with big and heterogeneous data (data related to IoT technologies and economic, environmental, and social impacts), and the performance of currently available IoT-enabled sensors and actuation devices needs to be improved.

The structure of the paper is as follows: In Section 2, a case study of the current Industry 4.0 condition monitoring system configuration is presented, followed by a proposed system configuration. In Section 3, the three-layer IoT architecture for condition monitoring and its challenges are presented; in Section 4, sustainability-driven maintenance is covered; and in Section 5, the results and discussion are provided. Finally, in Section 6, the conclusions of the study are provided.

2. System Configuration of Condition Monitoring under Industry 4.0

Condition monitoring in the industry 3.0 scenario is carried out by installing sensors on crucial machinery, sending the data to an FFT analyzer via a wired network, and then doing analysis to determine the diagnosis and prognosis of the system in question [33, 34].

But in Industry 4.0, smart sensors are being used that collect the machine data, condition it so as to amplify the sensor's output, transfer this data to a multi-log where the data is processed, and then the analysis is sent to the central computer. The information from the central computer is uploaded to the purchased cloud through the internet, and access is given to the management authority and domain experts through a public IP address in order to respond to the anomaly detected in the asset, as shown in (Figure 1).

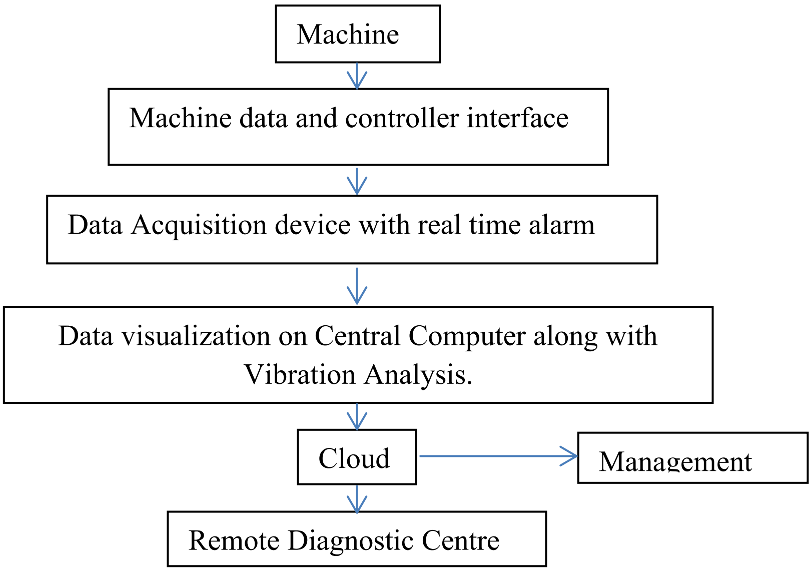

Figure 1. System Configuration of Condition Monitoring under Industry 4.0

In IoT-enabled CM, experts and management can look into the state of the asset from anywhere and anytime and can maintain its health. Therefore, IoT-enabled industries are regarded as smart industries. To extract the features of the asset in Industry 4.0, a wired or wireless sensor network can be utilized. Only a small number of assets, or critical assets, are monitored in a wired sensor network because of the high cost of installation, upkeep, and the space utility problem [35]. Wireless sensors can be considered a good alternative because of their low cost, small size, and no cascading of wires. However, there are still a lot of obstacles and opportunities for sensor makers to improve wireless sensor technology. However, when compared to readings from FFT analyzers, wireless sensors, like accelerometers and piezoelectric sensors, do not produce as exact or precise measurements. For this reason, the FFT analyzer remains the most reliable option for obtaining consistent data from these sensors. The following example is taken into consideration to support it. In Adani Thermal Power Station, Dahanu, Mumbai (India), a sensor is used to monitor the vibrations of the PA fan casing. The online horizontal vibration recorded by the sensor was 4.0 mm/sec. But sometimes it fluctuated between 7 and 8 mm/sec. To confirm this fluctuation and to know the actual reading, the FFT analyzer was used. It was showing a vibration of 4.0 mm/sec with no fluctuation. The reading of the FFT analyzer was correct, and the sensor was showing some deviation, which occurs occasionally but is problematic. Therefore, relying merely on the readings of sensors is not a wise decision, and therefore, an FFT analyzer is used to confirm the readings. Taking this fact into account, a new configuration system is proposed, which is discussed in a subsequent section. Furthermore, wireless sensors have a short lifespan of two to three years, and the technology used does not provide the necessary high resolution of 16 bits, which results in a hazy and blurry vibration spectrum with side bands. Additionally, another significant problem with piezoelectric sensors is the availability of vibration spectrum for very low-speed drives [35,36]. In Industry 4.0, these problems may be mitigated by utilizing accelerometers built on MEMS (Micro Electro Mechanical Systems) [37]. Nevertheless, the effective implementation of Industry 4.0 for asset condition monitoring still faces difficulties with huge data management [38].

2.1 Proposed System Configuration

Considering the inadequacies of the current scenario, a new system configuration is proposed as shown in (Figure 2), which operates as follows:

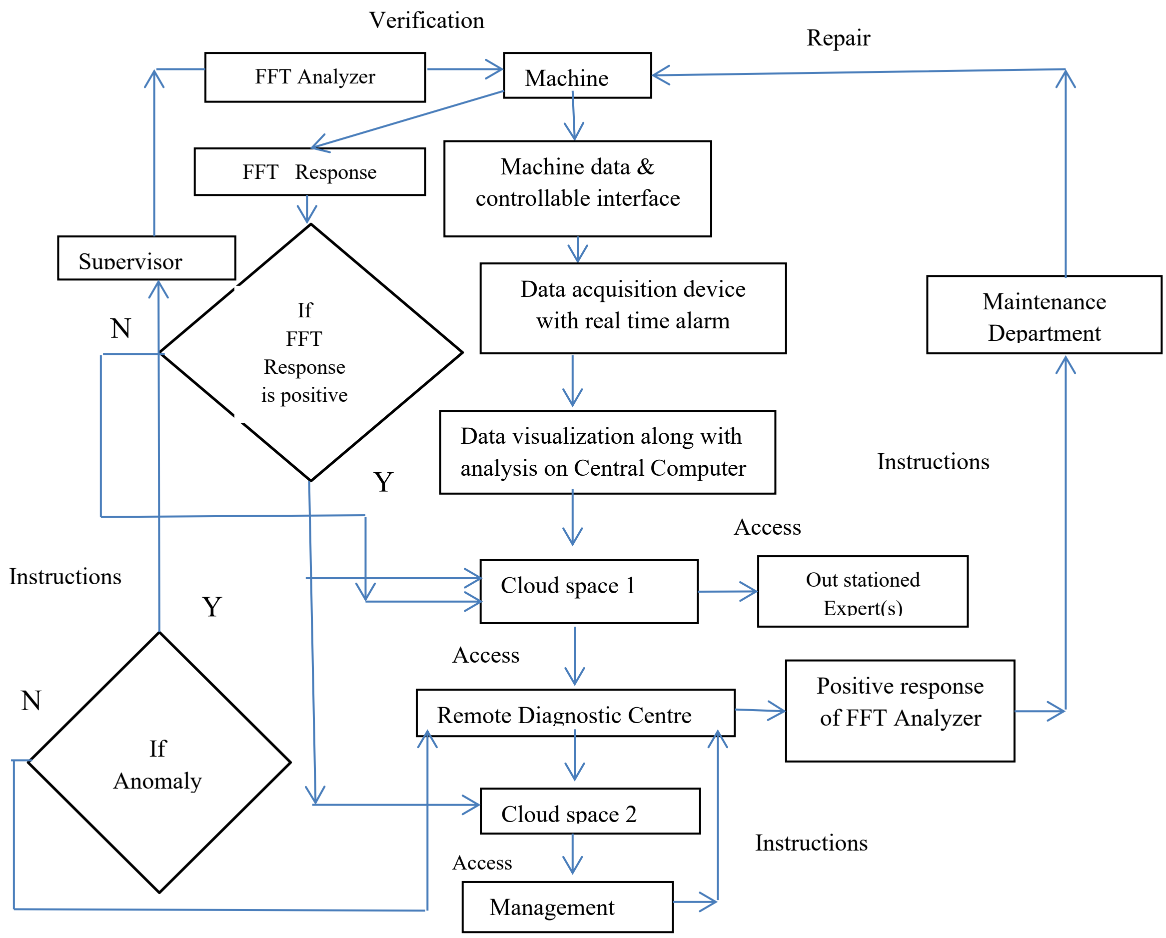

Figure 2. Proposed System Configuration of Condition Monitoring under Industry 4.0

The physical parameter of the machine, such as vibration (a non-electrical signal), is sensed by the sensor, which converts vibration into an electrical signal. This data is continuously fed to the controller through the interface. It is then further given to the DAS (data acquisition system). The DAS acquires the data in its original form. It conditions the signal (amplified, attenuated, or filtered) and then converts the signal to a digital one by ADC (an analog to digital converter). The signal is continuously compared with the reference value, and if any anomaly is detected, the microprocessor will set the alarm 'ON' as shown in (Figure 3). For visualization purposes, the data is sent to the central computer system [36].

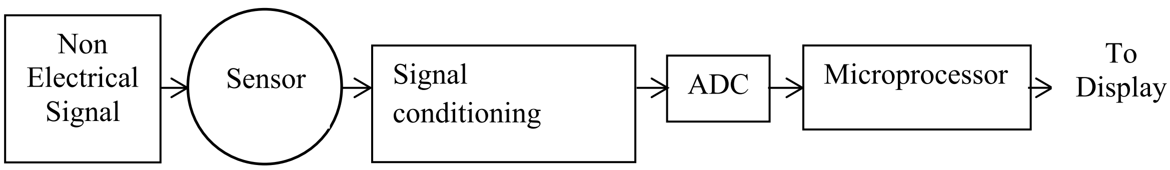

Figure 3. Flow of data acquisition system

The central computer data is sent to cloud 1. Access is given to experts and the Remote Diagnostic Center through a public IP address to assess the anomaly present. But because of the various shortcomings of wireless sensor technology and false-positive alarms, the FFT analyzer is used to verify the vibration readings. If these readings confirm the anomaly, it is sent again to cloud 1 for confirmation to the diagnostic center and experts, and to cloud 2, where access is given to management through a personal IP address. Then the instructions are passed to the maintenance department by the diagnostic center for corrective action. And if the readings do not confirm the anomaly, then the FFT response is sent to cloud 1 only.

3. A three-layer IoT architecture for condition monitoring

Three-layer design has been suggested as an Internet of Things approach [39], as (Figure 4) illustrates. The lowest layer is the physical layer, which is made up of sensors and actuation devices. These devices communicate with the middle layer to send the gathered data for further analysis. The middle layer, known as the network or internet layer, includes all Internet-connected infrastructures and facilitates communication with the application layer to perform back-end functions. These functions include data processing, data storage, analysis, and decision-making. Typically, they are offered on cloud servers that are owned by third parties [40].

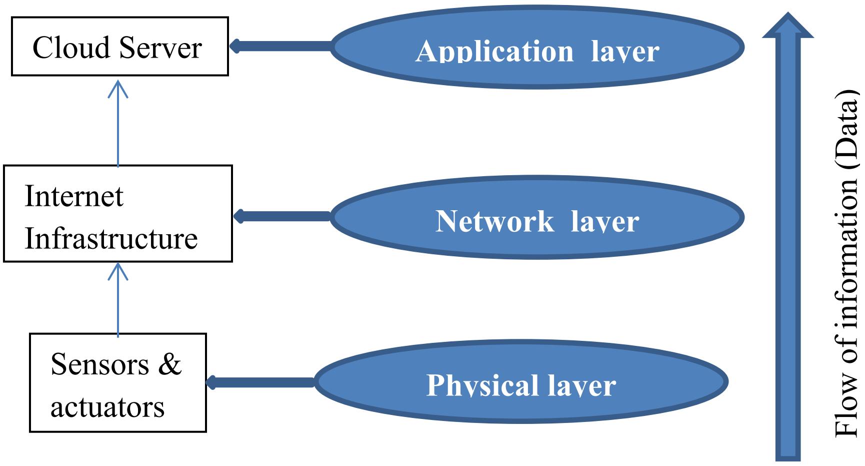

Figure 4. A three-layer IoT-enabled condition monitoring Architecture

In three-layer architecture, the design challenges are mainly attributed to the physical layer; the other layers, i.e., the network layer and the application layer, are well established technologies. In an IoT-based condition monitoring system, the application layer can be managed by having its own servers or by using a cost-effective option, i.e., by purchasing third-party cloud services, is the only question in the present scenario, and the latter is the best option. As the cloud service part is a well-established technology today, it is therefore not considered in our analysis [41].

The middle layer, or internet, is part of a global infrastructure that is effectively distributed and run by many different businesses and individuals [42]. Similar to cloud services, the internet is a highly advanced technology, and the arrival of 5G and 6G has further enhanced its performance. In summary, there are no problems with the technology needed for middle-layer architecture. However, this is not the case for the physical layer; for this reason, the design of the physical layer, which is covered in a later section, is the focus of this work.

3.1 Sensor

To translate physical parameters into electrical signals, sensors are needed. The most popular type of sensor for vibration-based condition monitoring is piezoelectric sensors, also known as accelerometers [36].

A few key features of vibration sensors for Condition Monitoring are: low cost, small size, high resolutions, ability to detect vibrations at very low frequencies, power savings, and simplicity of integration into electronic circuit boards [43-46].

Micro Electro Mechanical Systems (MEMs)-based accelerometers are capable of fulfilling every one of the aforementioned requirements. As such, these accelerometers are suitable for vibration-based CM in an industry 4.0 context. Finding low-noise sensors with bandwidths greater than 2 KHz for multiple axis sensors is still challenging, albeit [37].

3.2 Wireless communication

Wireless technologies such as WI-FI, Bluetooth low-energy [BLE], and ZigBee are available for enabling communication in Industry 4.0 [47-52]. The selection of wireless communication technologies will be based on energy consumption for different payloads and data transmission rates. The energy consumption of various payloads for several wireless communication technologies—Wi-Fi, Bluetooth, and ZigBee - was determined through an experiment; the findings are shown in (Figure 5) and discussed in section 5.

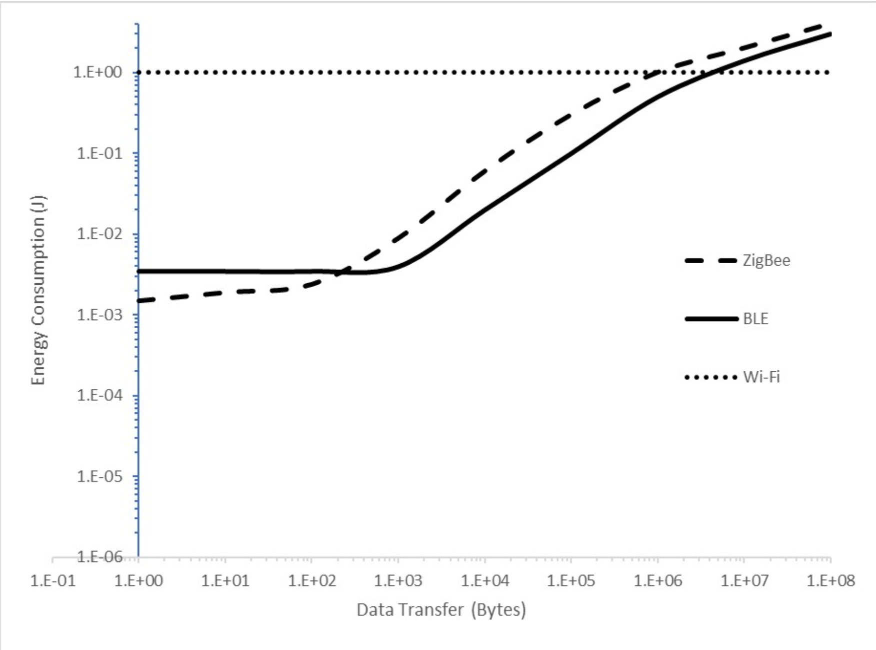

Figure 5. Energy Consumption v/s raw data transmission from an end device

4. Sustainability Driven Maintenance

The contribution of maintenance to sustainable manufacturing has garnered increased attention in the past few years [53-55]. As described by [56], 'maintenance as part of the circular economy can be considered, first, as an enabling system to sustain the artifact throughout its life cycle, then as a key tool to keep the regeneration potential of this artifact, and finally, as a target system that must be sustainable. As per this perspective, one of the primary pillars of sustainable manufacturing might be the "maintenance" function, which is required to guarantee the availability, dependability, and safety of industrial assets [53, 57]. For this reason, traditional maintenance procedures need to incorporate sustainability objectives. [58] defined sustainability maintenance as ‘a set of proactive technical, economic, and management activities implemented throughout the whole life-cycle of a technical facility aimed at realizing the functions of a technical facility, ensuring at the same time the achievement of goals and the ability to create economic, environmental, and social value for all stakeholders in the long-term horizon.’

After going through the extensive literature survey, it was found that the sustainability dimension includes three aspects: economic, environmental, and social. Under the economic aspect, machine performance, maintenance downtime, economic efficiency, spare parts inventories, defects, and unnecessary transportation are the major impacts that affect product quality and the productivity of plants [59-68]. Under the environmental aspect, energy consumption, spare parts and lubricant utilization, emission, production waste, and the and the life span of machinery are the major impacts [27,59,60,62,63,65,67,69,70,71], and under the social aspect, worker safety, working conditions, worker satisfaction level, worker health, worker skill and knowledge, and job security are the major impacts that affect the workers social, physical, and financial health [53,54,72-77].

5. Results & Discussion

Accelerometers are used to extract the features of the asset in IoT-enabled condition monitoring, but the accelerometer, as compared to the FFT analyzer, does not provide the precise and accurate readings of vibration. Therefore, a new system configuration is suggested in order to eliminate this error and rework time of the workforce, and for this, the case of Adani Thermal Power Station, Dahanu, Mumbai, India, is considered. In the new system configuration, the vibration measurements of the accelerometer are verified with the FFT analyzer, and then these readings are sent to the management and remote diagnosis center.

For condition monitoring, three-layer IoT architecture has been proposed. The physical layer is the lowest layer, the network layer is in the middle, and the application layer is at the top. The top and middle layers' underlying technologies are tried-and-true, well-established technologies. The physical layer, which is the lowest layer and is composed of sensors and actuation devices, has numerous design difficulties. Therefore, in this work the authors have focused on physical layer.

Piezoelectric sensors are typically used for condition monitoring; however, they are unable to provide the vibration spectrum required for low-speed drives (35, 36). An accelerometer integrated into Micro Electro Mechanical Systems (REMS) is a viable solution to get around this restriction (36). However, low noise, band width greater than 2 KHz for multiple axes, and large data management sensors are still the prominent challenges.

Wireless communication in Ind. 4.0 can be done by WI-FI, Bluetooth low-energy (BLE), or Zig Bee technologies. The selection of these technologies is based on energy consumption for different payloads and data transmission rates. The aforementioned wireless communication technologies are examined in (Figure 5) for various data transmission rates as well as energy usage. (Figure 5) shows that ZigBee is a more energy-efficient option for sending tiny amounts of data, up to 500 bytes (4 kbits), when it comes to transmission. However, Wi-Fi uses the least amount of energy to send data—up to 800 kB, or 6.4 Mbits—than other networks. At last, the BLE yields an energy-efficient solution for the transfer of 500 bytes to 800 kB [78-82]. Vibration-based continuous condition monitoring needs to transmit a large amount of data, which is possible by means of Wi-Fi technologies only. Therefore, it serves as the best option in the current scenario to meet the high-throughput communication needs of CM in an industry 4.0 setting [83–85].

The sustainability aspect has been studied by many authors along the triple bottom line (TBL), which means three axes: economic, social, and ecological. The analysis reveals that the economic aspect of maintenance systems has been investigated deeply by various authors and practitioners, but it is also essential to meticulously investigate the environmental and social aspects of maintenance systems in order to achieve true development and hence maintenance sustainability (Maintenance 5.0).

The sustainability performance indicators need to be investigated to know the sustainability aspects (economic, environmental, and social) in quantitative form, and once the sustainability impact for each aspect is known, the maintenance activities can be arranged accordingly to achieve the desired sustainability of maintenance systems. Further, the sustainability-cost ratio (e.g., Reduction in Energy consumption to cost incurred ratio) will reveal the cost required to achieve a certain sustainability level in any sustainability aspect. This ratio will assist management in determining how much of some sustainability features are implemented.

In summary, to transform the conventional industry into a smart as well as human-centric industry, research and development is required to further improve enabling technologies.

6. Conclusions

For many years, maintenance was seen as a non-value-adding task, but over time, it became clear that maintaining machinery and devices was also critical to the quality of products produced, and as a result, machine and device maintenance has gained attention. Maintenance progresses from reactive to preventive, then condition-based maintenance (Automation), and finally predictive and prescriptive maintenance (Ind. 4.0) as a result of manufacturing companies' and researchers' constant interest in applying technological advancements to the field of maintenance. The technologies of Industry 4.0 are being applied to the maintenance area, which will further enrich it, and by doing so; the overall equipment effectiveness (OEE) of the plant may increase to all-time highs.

However, putting Industry 4.0 technologies into practice requires significant financial resources, a well-thought-out roadmap, and active participation from all company departments, especially top management [86]. Potential job issues could also surface since maintenance personnel will need to acquire new abilities and knowledge [87, 88].

In this work, the states of the art of Maintenance 4.0 and Maintenance 5.0, along with a larger understanding of these concepts, were investigated. The difficulties in implementing IoT-enabled condition monitoring (i.e., Maintenance 4.0) are also discussed, along with potential solutions.

The study investigated that currently, the physical layer, which is the lowest of the three layers of an Internet of Things solution, is the main barrier and faces numerous challenges to realize maintenance 4.0 in an effective way, which thus requires significant research and development. Nonetheless, in the current setting, IoT-enabled CM can be very beneficial for machinery that is inaccessible and close to heated temperatures.

The literature demonstrates the significant efforts being made by researchers to make maintenance 4.0 (IoT-enabled condition monitoring) human-centric or sustainable. Consequently, the economic, environmental, and social elements of Maintenance 5.0 have been covered in this work. To make Industry 4.0 technology human-centric, it is necessary to thoroughly examine not only the economic aspect but also the other two, namely the social and environmental elements.

The literature review also reveals that maintenance 4.0 is heading towards "remote maintenance," "self-maintenance," or "automated maintenance" [89], which may be possible by the combination of powerful big data analytic tools with autonomous robots and augmented reality, which will make smart factories more attractive.

However, key research opportunities are identified in the present review article, such as the investigation of sustainability performance indicators to know the sustainability aspects (economic, environmental, and social) in quantitative form and hence their associated cost, the development of a new sustainable maintenance model that not only incorporates IoT-enabled technologies and sustainability aspects but also is able to deal with big and heterogeneous data (data related to IoT technologies and economic, environmental, and social impacts), and the performance improvements of IoT-enabled sensors and actuation devices.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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