



Vol. XVIII &amp; Issue No. 02 February - 2025

INDUSTRIAL ENGINEERING JOURNAL

## SYSTEMATIC LITERATURE REVIEW ON DIGITAL TWINS IN PREDICTIVE MAINTENANCE

**Ms. Seema Nagrani**

Research Scholar, Department of Mechanical Engineering, K. J. Somaiya college of Engineering, Mumbai – 400 077. And Assistant Professor, Department of Mechanical Engineering, Thakur College of Engineering and Technology, Mumbai

**Vaibhav S. Narwane**

Associate Professor, Department of Mechanical Engineering, Somaiya Vidyavihar University, K.J. Somaiya College of Engineering, Vidyavihar, Mumbai – 400 077  
Email: vsnarwane@somaiya.edu

### Abstract

*Predictive maintenance plays very important role in fourth revolution of Industry to improve the productivity and to reduce the maintenance cost. The Digital Twin model is used in design, manufacturing, and maintenance work. The main purpose of this study is to conduct systematic literature review on predictive maintenance using Digital Twin model. The research articles selected from year 2017 to 2023 and 46 articles are shortlisted for detailed study. The research articles are divided into three categories. The research articles help to find the relation between predictive maintenance, Digital Twins and Machine Learning algorithms. The study is limited to research articles from peer reviewed articles of reputed journals published in English. Book chapters, white papers and unpublished work are not considered for the study. This research article is one of the few articles which highlight the application of Digital Twins in Predictive Maintenance.*

**Keywords:** Digital Twins, Predictive Maintenance, Machine Learning, Industry 4.0, vibration analysis, condition-based monitoring.

### I. INTRODUCTION AND BACKGROUND

In the competitive world it was essential to increase the efficiency and productivity of the industry. Sudden failure of machines reduces the production and increase the cost [1, 2]. The three commonly used maintenance techniques are reactive maintenance, preventive maintenance, and predictive maintenance [3]. Predictive maintenance predicts the trend of the machine and performs the maintenance shortly before the failure occurs in the machine [2, 4]. Compared to reactive and preventive maintenance, predictive maintenance avoids the unscheduled machine stoppage [3]. Predictive maintenance was nothing but its continuous monitoring of the system to prevent the sudden failure. So, it reduces the time interval between the maintenance operations and therefore definitely cost will be minimized [5]. Predictive maintenance was enhancement of condition-based monitoring, which describe the current state of the health of machinery [6]. Condition based monitoring was done through the Machine Learning algorithms. Machine Learning was essential and fundamental techniques of Industry 4.0 [7]. Most frequently machine learning algorithms used in predictive maintenance were linear regression [5,8], random forest regression [5], decision tree [9,10] Bayesian Networks [11], Support Vector Machines [12,13,14], Artificial Neural Networks [12,15,16], K-nearest neighbour [8,9,12,14]. Digital Twins (DT) means to create the software version of the real system [17]. It allows the user to do the things which were not

practically possible to understand the actual behaviour of the system. The DT was used in Design, manufacturing, and predictive maintenance [17, 18, 19]. Without using many sensors DT model can give more reliable and accurate real time data which can be used for the predictive maintenance of the system [20]. With DT model, extreme harsh conditions can be predicted without any damage because it was simulation tool [21]. The current literature survey studies discuss Industry 4.0 for predictive Maintenance [4,22], Machine Learning for Predictive Maintenance [23,24], DT for maintenance [25], maintenance in Industry 4.0 [26], DT in Industry 4.0 [27] and condition based monitoring using machine learning [7]. However, these papers did not discuss the DT for predictive maintenance and thus this said addresses following research questions (Rqs).

**RQ1:** What previous studies are conducted on application of DT in Predictive Maintenance?

**RQ2:** What are the categories of these studies of DT in Predictive Maintenance?

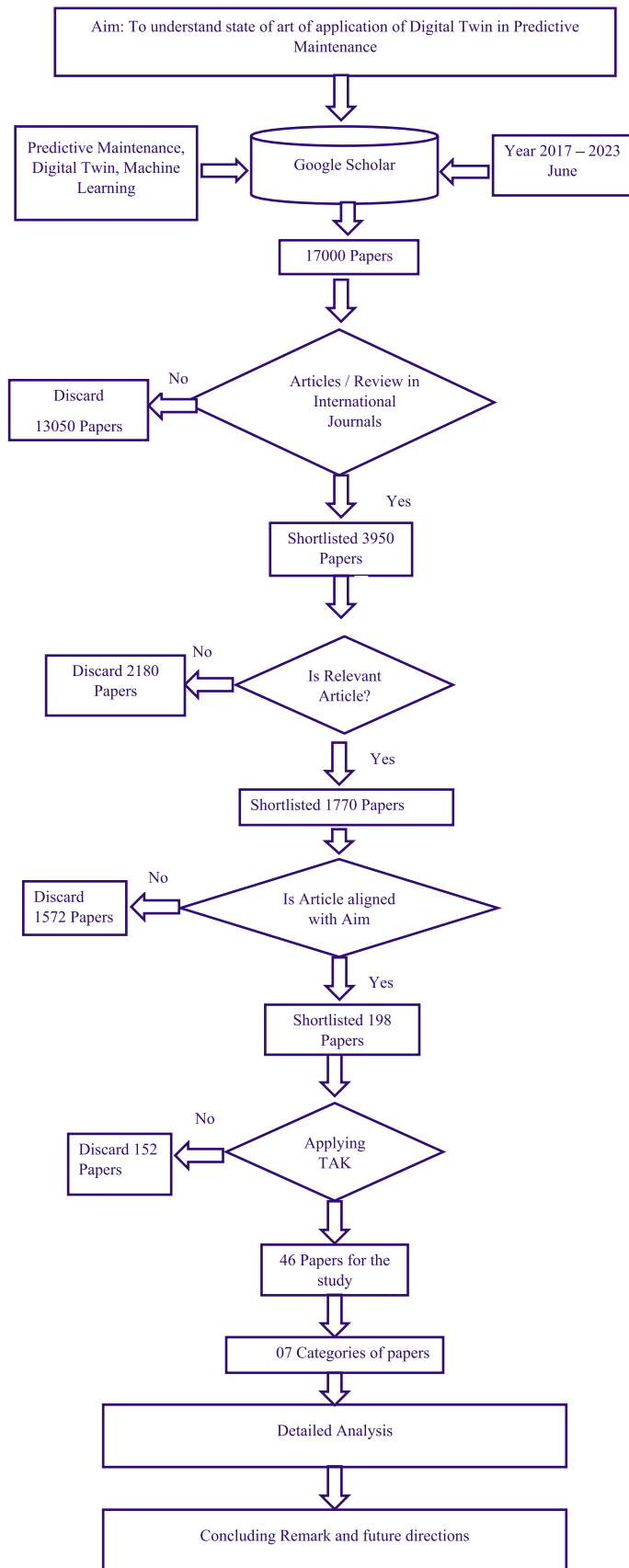
**RQ3:** What are the future directions of DT in Predictive Maintenance?

The organization of the manuscript was as follows: Section 2 gives the methodology adopted for the study to address RQ1. Section 3 gives Detailed Analysis for RQ2. Discussion and Concluding Remarks is given in Section 4 for Rqs.

II. METHODOLOGY ADOPTED FOR SLR

The Methodology adopted for SLR is shown in Figure 1.

Figure 1: Methodology adopted for SLR [Source- Author]

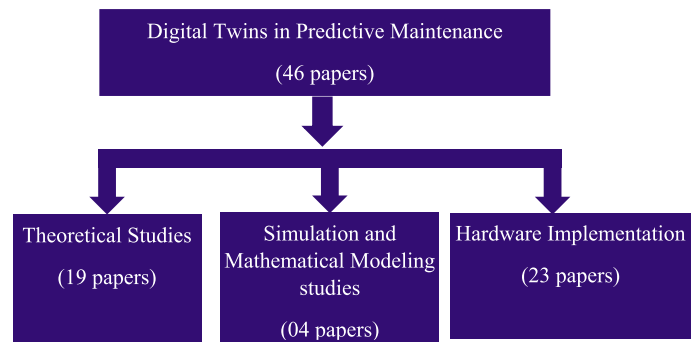


The keywords finalized were predictive maintenance, DT and machine learning. The search was conducted on 15 June 2023 on Google Scholar database to find the relevant papers from year 2017 to 2023 June. Initial 17,000 papers were analysed based on the review and articles category and 3950 papers were found. Further screening of the papers was done on the bases of relevant articles and alignment with the aim of the study. Then, 198 papers were shortlisted. These studies were again filtered using the TAK principle to remove the unrelated articles. After that, 46 papers were found.

III. DETAILED ANALYSIS

The research articles on DT for predictive maintenance are categorized into the three different categories as shown in Figure 2.

Figure 2: Structure of categorization of Papers [Source- Author]



**3.1 Theoretical studies:** The theoretical studies are subcategorized into the literature survey (13 papers), theoretical (04 papers) and conceptual framework (02 papers). The contribution of literature survey articles in theoretical studies is 68.42%. In Industry 4.0 the predictive maintenance plays a very important role in sustainable production and manufacturing system by including digital version of machine maintenance [28]. It is necessary to predict the requirement of maintenance in Industry 4.0 to reduce the downtime, cost and to improve the productivity [4]. Vibration analysis is used for the predictive maintenance. It requires the data acquisition method, feature extraction method and AI techniques to identify the fault in the system [29]. Maintenance Management strategies were changed due to Industry 4.0 [26]. It is observed that DT was used in design, manufacturing, production and maintenance in industry [25]. The conventional simulation process considers the present dataset and gives the output, but the DT model contains the past and present data to predict the behaviour of the physical system [27]. The industry 4.0 techniques like cloud computing, Augmented Reality, Big Data, IoT, and AI-ML were used in Maintenance 4.0 [22]. Machine Learning algorithms were used in predictive maintenance to reduce the maintenance cost [12, 24], but there were no single algorithms which can be implemented. As per Industry and type of fault different algorithms were used [24]. Machine Learning algorithms, data acquisition device, type of data, size of data was required to mention for a particular system [23]. Supervised algorithms

were mainly used in predictive maintenance [30]. Condition Based Monitoring can be done by Supervised, unsupervised and semi supervised algorithms [7]. Knowledge based model, model-based model and data driven based models were used for predictive maintenance, SVM and ANN were mostly used ML algorithms [16]. Maintenance was closely related to production process. Quality of maintenance determines the quality of the product [31]. Maintenance 4.0 techniques were discussed like Failure Based Maintenance (FBM), Condition Based Maintenance (CBM), Total Productive Maintenance (TPM), Predictive Maintenance (PM) and Total Quality Maintenance (TQMain). CBM and TQMain were most important techniques in Maintenance 4.0 [32]. In Industry 4.0 the predictive maintenance plays a very important role especially in manufacturing industry. Author has mentioned the theoretical concept of predictive maintenance in automotive industries of Germany [6]. Knowledge based system can used in predictive maintenance [33]. DT was used for designing, manufacturing and maintenance [20]. DT was used in different industries for number of applications. Industries like E-commerce, food, textile, education; electronics was used to improve the customer satisfaction by changing the design of the product. Industries like production, manufacturing, steel was used to reduce the time and cost, and in aerospace and healthcare industries were used DT to reduce the cost as well as risk [34].

**3.2 Simulation and Mathematical Modelling Studies:** The research study of DT in predictive maintenance contains the 19.56% research articles on mathematical modelling and simulation. The simulation and mathematical modelling were further subcategorized into the managerial survey, mathematical modelling and simulation which show the relationship between the industry 4.0 and predictive maintenance effects the socio- economic factor of industry [35]. To increase the performance of the predictive maintenance, supervised machine learning algorithms were used. Modelling and simulations were done on the Gas turbine by using the K-nearest Neighbour (KNN), decision tree and random forest algorithms. It was proved that KNN gives good result for large dataset and random forest was better for small size of dataset [5]. Efeoğlu and Tuna [2] used predictive maintenance dataset from University of California, Irvine (UCI) library, and it was concluded that Support Vector Machine (SVM) gives 99% accurate result with the combination of Kernal Function. Combination of Jaya algorithm and Sea lion optimization algorithms were used for the predictive maintenance of aircraft engine and lithium-ion battery. Different accuracy level was achieved by using different algorithm and it was observed that ANN gives high accuracy [36].

**3.3 Hardware implementation:** A comprehensive study of the research articles selected during the literature survey revealed that hardware implication studies of DT for predictive maintenance were in abundance, compromising 50% of the selected research articles. Hardware implementation studies include the hardware implementation and case studies. To improving the sustainability of the system Industry 4.0 and

Industry 5.0 technologies were used in European Industries for the mechanical vibration analysis. Short Time Fourier Transform (STFT) gives better results than Fast Fourier Transform (FFT) and Continuous Wavelet Transform (CWT) gives better than STFT. For frequency domain FFT was used but for Time- frequency domain STFT was used. STFT uses fixed-length time window, but CWT uses varied-length time window [37]. The techniques of industry 4.0 were used to reduce the cost of predictive maintenance [38]. For the high frequency defect, there was high amplitude and for low frequency defect there was low amplitude. Vibration amplitude was increased due to increment in load, size of defect and speed. The SVM algorithm was used for the experimental purpose [39]. KNN and SVM algorithms were used to identify the fault in wind turbine system [14]. Real time monitoring was done on motor by using low-cost hardware component and open-source software [40]. For the predictive maintenance of Textile machinery, energy data were used to identify the fault in the system [3]. Predictive maintenance was done in Bottling plant manufacturing small scale industry to identify fault in conveyor motor. Siemens S2-1200 PLC was used for vibration Analysis. Cloud based decentralization system was implemented to send report by email immediately [41]. Predictive maintenance was used continuously in ventilation equipment to identify the misalignment and bearing fault [42]. The accuracy and the reliability of fault diagnosis in machine centre was based on the data mining. The study contains the framework of fault analysis which consists of the sensor and data acquisition, data processing, fault diagnosis and prognosis, performance indicator analysis [15]. The DT was the virtual representation of the physical model. It was used for predicting the tool condition [17]. DT was used for the vibration analysis in manufacturing process to improve the efficiency and the accuracy [43]. It was used for vertical CNC milling machine for the hybrid predictive maintenance o estimate the tool life [21]. For improving the maintenance strategy of the electric motor, the control charts of the vibration analysis were used to generate the DT model of the system [44]. MATLAB software was used to make the DT of ventilation system for fault identification [18]. DT and IOT were used for the predictive maintenance of electric motor. Conductivity and temperature analysis were done through the FEA software and these data were given to the DT to predict the behaviour [45]. Health of the machine was predicted by using the Machine Learning algorithm like Design Support System [9]. Maintenance cost was reduced by using Machine learning algorithms such as Decision Support System was used in predictive maintenance [9]. Machine Learning algorithms were used for the drift detection [8]. SVM was the most popular classification method which was used in vibration analysis of unbalance fault identification. SVM can be used for small number of samples [13]. ANN and Decision Tree (DT) classifiers were used for predictive maintenance of ball bearing. Anysis software was used to feed the data into the Digit Twin model of the bearing. ANN gives 87% and DT gives 89% accurate results [46]. The 84% success was achieved when considered 3 axis vibration data, but 99% success was achieved

while including speed, current, temperature and sound data for predictive maintenance of Bearing. Kappa and accuracy matrix were calculated to find the best machine learning algorithm for the bearing analysis. KNN gives best result for bearing fault identification [10]. Modal analysis of the Airbus Helicopter motor was done through the machine learning algorithm like clustering [47]. The behaviour of the steel plant was observed by using cyber physical system, Internet of things and big data technologies and by applying Discrete Bayes Filter Machine Learning algorithm [11].

**Table 1: Brief analysis of research papers of Digital Twin in Predictive Maintenance of different categories.**

S. N.	Author	Country	Year	Type of Paper	Remark
1	Jasiulewicz et al.[31]	Poland	2023	Theoretical	Economic, social and environmental challenges were described in Maintenance 4.0
2	Costa et al. [3]	Germany	2023	Hardware Implementation	Predictive maintenance was used for textile machinery
3	Łuczak, et al. [37]	Poland	2023	Hardware Implementation	Vibration analysis was done through STFT and SWT algorithms
4	Dos Santo et al. [45]	Brazil	2023	Hardware Implementation	DT was used for predictive maintenance of motor
5	Abbate et al. [44]	Italy	2022	Case Study	Concept of DT was discussed in vibration analysis
6	Abidi et al. [36]	Soudi Arabia	2022	Modelling and Simulation	Different algorithms were used in aircraft engine and lithium-ion battery
7	Achouch et al. [28]	Canada	2022	Literature Survey	Study was based on Industry 4.0 in predictive maintenance
8	Arena et al. [9]	Italy	2022	Case Study	Predictive maintenance of gearbox was done through machine learning
9	Cao et al. [33]	UK	2022	Conceptual framework	Knowledge based system was implemented
10	Efeoğlu and Tuna [2]	Turkey	2022	Modelling and Simulation	SVM algorithm was used for predictive maintenance
11	Es-sakali et al. [16]	France	2022	Literature Survey	Supervised learning algorithms were implemented in predictive maintenance
12	Khair and Phalle [46]	India	2022	Hardware Implementation	Vibration analysis of bearing was done through machine learning
13	Liang et al. [43]	China	2022	Hardware Implementation	DT was used in Gantry machining centre
14	Mugnaini et al. [47]	Italy	2022	Case Study	Modal analysis of motor was carried out through machine learning
15	Muñiz et al. [42]	Spain	2022	Hardware Implementation	Misalignment fault was identified
16	Ouahad et al. [5]	London	2022	Modelling and Simulation	Predictive maintenance of gas turbine was discussed
17	Shaheen and Nemeth [22]	Hungary	2022	Literature Survey	Relationship between Industry 4.0 and maintenance was discussed
18	Sharma et al. [7]	India	2022	Literature Survey	The study was focused on condition-based monitoring
19	Tortorella et al. [35]	Australia	2022	Managerial Survey	The focus of study was on the total productive maintenance in Industry 4.0
20	Vives [14]	Spain	2022	Hardware Implementation	Vibration analysis was done on bearing fault identification
21	Yakhni et al. [18]	France	2022	Hardware Implementation	Application of DT was implemented in motor fault diagnosis
22	Fu et al. [20]	China	2022	Conceptual framework	The study was based on DT
23	Cakir et al. [10]	Turkey	2021	Hardware Implementation	Different machine learning algorithms were used for vibration analysis of bearing
24	Florian et al. [48]	Italy	2021	Case Study	Cost oriented analysis was done by using machine learning in predictive maintenance
25	Ghazali and Rahiman [29]	Malaysia	2021	Literature Survey	The study was based on vibration analysis and artificial intelligence
26	Kenett and Bortman [27]	Israel	2021	Literature Survey	The research was based on the DT and machine learning
27	Salunkhe et al. [39]	India	2021	Hardware Implementation	SVM and DAMM algorithms were used for vibration analysis of bearing
28	Theissler et al. [30]	Germany	2021	Literature Survey	The survey was focused on the supervised learning algorithms for predictive maintenance
29	Çinar et al. [23]	Turkey	2020	Literature Survey	Literature survey was based on the machine learning
30	Dalzochio et al. [24]	Brazil	2020	Literature Survey	Different machine learning algorithms were discussed for predictive maintenance
31	Errandonea et al. [25]	Spain	2020	Literature Survey	The survey was focused on application of DT
32	Hinduja et al. [19]	India	2020	Theoretical	The application of DT in different areas were discussed
33	Luo et al. [21]	China	2020	Hardware Implementation	The DT of CNC- milling machine was used for predictive maintenance
34	Magadán et al. [40]	Spain	2020	Case Study	Real time monitoring was done in Industry 4.0
35	Roy et al. [17]	India	2020	Case Study	Implementation of DT in industry was proposed
36	Sarmineto et al. [11]	Spain	2020	Hardware Implementation	The study was based on the predictive maintenance through machine learning
37	Silvestri et al. [26]	Italy	2020	Literature Survey	The survey was based on the Industry 4.0
38	Zonta et al. [4]	Brazil	2020	Literature Survey	The challenges and limitations were discussed in this survey
39	Carvalho et al. [12]	Brazil	2019	Literature Survey	Survey was based on the Machine learning and deep learning
40	Pinheiro et al. [13]	Brazil	2019	Hardware Implementation	SVM algorithm was applied for unbalance fault in the system
41	Zenisek et al. [8]	Austria	2019	Case Study	Regression Algorithm was applied for Industrial Fan
42	Anh et al. [6]	Germany	2018	Theoretical	Predictive maintenance in Industry 4.0 was discussed
43	Al-Najjar et al. [32]	Sweden	2018	Theoretical	The application of condition-based monitoring in Maintenance 4.0 was discussed
44	Sezer et al. [38]	Maxico	2018	Hardware Implementation	Machining accuracy of CNC - turning was checked through the machine learning algorithms
45	Kiangala and Wang [41]	South Africa	2017	Case Study	The method of predictive maintenance in small manufacturing industry was mentioned
46	Li et al. [15]	Norway	2017	Case Study	ANN algorithm was used to find the backlash error

#### IV. DISCUSSION AND CONCLUDING REMARK

In industry 4.0, predictive maintenance was used as a maintenance tool [22, 28, 31]. Maintenance was required to get quality, safety, and productivity [4]. Predictive maintenance plays very important role in sustainable maintenance [28, 31]. It also affects the socio-economic factor of the industry [31, 35]. The future work in predictive maintenance can be considered as label the data which were stored in the cloud as much as possible. Predictive model based on the data will be used to develop machine learning model [40, 42]. Machine Learning algorithms were used for the predictive maintenance [24]. The integration of predictive maintenance and machine learning algorithm reduces the cost. But, according to Price Waterhouse and Coopers and Lybrand (PwC) survey only 11% companies have implemented ML for predictive maintenance. The further study can be done on the combinations of the ML algorithms and different type of data acquisition system to collect the real time data [23]. Machine learning was integrated into the DT model. Today, supervised machine learning algorithms were data labelled [27]. For the predictive maintenance in industry 4.0, one needs to create the DT model. It creates the digital representation of the physical system. The digital model can be simulated into the different environment [34]. Machine learning algorithms were used to generate the DT model. Specifically Supervised learning algorithms can be used for the DT. In supervised learning algorithms, trained data were required. The signature analysis was the tool for the predictive maintenance [49] and it can be used to feed the trained data in machine learning for DT of predictive maintenance.

#### REFERENCES

- [1] Nunes, P., Santos, J., & Rocha, E. (2023). *Challenges in predictive maintenance—A review*. *CIRP Journal of Manufacturing Science and Technology*, 40, 53-67.
- [2] Efeoglu, E., & Tuna, G. (2022). *Machine Learning for Predictive Maintenance: Support Vector Machines and Different Kernel Functions*. *Journal of Machinery Manufacture and Reliability*, 51(5), 447-456.
- [3] Costa, V. L., Eberhardt, B., Chen, J., & Roßmann, J. (2023, March). *Towards Predictive Maintenance: an Edge-based Vibration Monitoring System in Industry 4.0*. In *2023 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS)* (pp. 1430-1437). *IEEE*.
- [4] Zonta, T., Da Costa, C. A., da Rosa Righi, R., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). *Predictive maintenance in the Industry 4.0: A systematic literature review*. *Computers & Industrial Engineering*, 150, 106889
- [5] Ouadah, A., Zemmouchi-Ghomari, L., & Salhi, N. (2022). *Selecting an appropriate supervised machine learning algorithm for predictive maintenance*. *The International Journal of Advanced Manufacturing Technology*, 119(7-8), 4277-4301.
- [6] Anh, D. T., & Skrzypek, K. (2018). *The predictive maintenance concept in the maintenance department of the "Industry 4.0" production enterprise*. *Foundations of Management*, 10(1), 283-292.
- [7] Sharma, J., Mittal, M. L., & Soni, G. (2022). *Condition-based maintenance using machine learning and role of interpretability: a review*. *International Journal of System Assurance Engineering and Management*, 1-16.
- [8] Zenisek, J., Holzinger, F., & Affenzeller, M. (2019). *Machine learning based concept drift detection for predictive maintenance*. *Computers & Industrial Engineering*, 137, 106031.
- [9] Arena, S., Florian, E., Zennaro, I., Orrù, P. F., & Sgarbossa, F. (2022). *A novel decision support system for managing predictive maintenance strategies based on machine learning approaches*. *Safety science*, 146, 105529.
- [10] Cakir, M., Guvenc, M. A., & Mistikoglu, S. (2021). *The experimental application of popular machine learning algorithms on predictive maintenance and the design of IIoT based condition monitoring system*. *Computers & Industrial Engineering*, 151, 106948.
- [11] Ruiz-Sarmiento, J. R., Monroy, J., Moreno, F. A., Galindo, C., Bonelo, J. M., & Gonzalez-Jimenez, J. (2020). *A predictive model for the maintenance of industrial machinery in the context of industry 4.0*. *Engineering Applications of Artificial Intelligence*, 87, 103289.
- [12] Carvalho, T. P., Soares, F. A., Vita, R., Francisco, R. D. P., Basto, J. P., & Alcalá, S. G. (2019). *A systematic literature review of machine learning methods applied to predictive maintenance*. *Computers & Industrial Engineering*, 137, 106024.
- [13] Pinheiro, A. A., Brandao, I. M., & Da Costa, C. (2019). *Vibration analysis in turbomachines using machine learning techniques*. *European Journal of Engineering and Technology Research*, 4(2), 12-16.
- [14] Vives, J. (2022). *Vibration Analysis for Fault Detection of Wind Turbine: New Methodology of Supervised Machine Learning Techniques*. *INTERNATIONAL JOURNAL OF ACOUSTICS AND VIBRATION*, 27(2), 100-105.
- [15] Li, Z., Wang, Y., & Wang, K. S. (2017). *Intelligent predictive maintenance for fault diagnosis and prognosis in machine centers: Industry 4.0 scenario*. *Advances in*

- Manufacturing*, 5, 377-387.
- [16] Es-sakali, N., Cherkaoui, M., Mghazli, M. O., & Naimi, Z. (2022). Review of predictive maintenance algorithms applied to HVAC systems. *Energy Reports*, 8, 1003-1012.
- [17] Roy, R. B., Mishra, D., Pal, S. K., Chakravarty, T., Panda, S., Chandra, M. G., ... & Misra, S. (2020). Digital twin: current scenario and a case study on a manufacturing process. *The International Journal of Advanced Manufacturing Technology*, 107, 3691-3714.
- [18] Yakhni, M. F., Hosni, H., Cauet, S., Sakout, A., Etien, E., Rambault, L., ... & El-Gohary, M. (2022). Design of a Digital Twin for an Industrial Vacuum Process: A Predictive Maintenance Approach. *Machines*, 10(8), 686.
- [19] Hinduja, H., Kekkar, S., Chourasia, S., & Chakrapani, H. B. (2020). Industry 4.0: digital twin and its industrial applications. *Int. J. Sci. Eng. Technol*, 8(4).
- [20] Fu, Y., Zhu, G., Zhu, M., & Xuan, F. (2022). Digital twin for integration of design-manufacturing-maintenance: an overview. *Chinese Journal of Mechanical Engineering*, 35(1), 80.
- [21] Luo, W., Hu, T., Ye, Y., Zhang, C., & Wei, Y. (2020). A hybrid predictive maintenance approach for CNC machine tool driven by Digital Twin. *Robotics and Computer-Integrated Manufacturing*, 65, 101974.
- [22] Shaheen, B. W., & Németh, I. (2022). Integration of Maintenance Management System Functions with Industry 4.0 Technologies and Features—A Review. *Processes*, 10(11), 2173.
- [23] Çınar, Z. M., Abdussalam Nuhu, A., Zeeshan, Q., Korhan, O., Asmael, M., & Safaei, B. (2020). Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0. *Sustainability*, 12(19), 8211.
- [24] Dalzochio, J., Kunst, R., Pignaton, E., Binotto, A., Sanyal, S., Favilla, J., & Barbosa, J. (2020). Machine learning and reasoning for predictive maintenance in Industry 4.0: Current status and challenges. *Computers in Industry*, 123, 103298.
- [25] Errandonea, I., Beltrán, S., & Arrizabalaga, S. (2020). Digital Twin for maintenance: A literature review. *Computers in Industry*, 123, 103316.
- [26] Silvestri, L., Forcina, A., Introna, V., Santolamazza, A., & Cesarotti, V. (2020). Maintenance transformation through Industry 4.0 technologies: A systematic literature review. *Computers in Industry*, 123, 103335.
- [27] Kenett, R. S., & Bortman, J. (2022). The digital twin in Industry 4.0: A wide-angle perspective. *Quality and Reliability Engineering International*, 38(3), 1357-1366.
- [28] Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On predictive maintenance in industry 4.0: Overview, models, and challenges. *Applied Sciences*, 12(16), 8081.
- [29] Mohd Ghazali, M. H., & Rahiman, W. (2021). Vibration analysis for machine monitoring and diagnosis: a systematic review. *Shock and Vibration*, 2021, 1-25.
- [30] Theissler, A., Pérez-Velázquez, J., Kettelgerdes, M., & Elger, G. (2021). Predictive maintenance enabled by machine learning: Use cases and challenges in the automotive industry. *Reliability engineering & system safety*, 215, 107864.
- [31] Jasiulewicz-Kaczmarek, M., Legutko, S., Khaire, S., & Kluk, P. (2020). Maintenance 4.0 technologies—new opportunities for sustainability driven maintenance. *Management and production engineering review*, 11.
- [32] Al-Najjar, B., Algabroun, H., & Jonsson, M. (2018). Maintenance 4.0 to fulfil the demands of Industry 4.0 and Factory of the Future. *International Journal of Engineering Research and Applications*, 8(11), 20-31.
- [33] Cao, Q., Zanni-Merk, C., Samet, A., Reich, C., De Beuvron, F. D. B., Beckmann, A., & Giannetti, C. (2022). KSPMI: a knowledge-based system for predictive maintenance in industry 4.0. *Robotics and Computer-Integrated Manufacturing*, 74, 102281.
- [34] Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE access*, 8, 108952-108971.
- [35] Tortorella, G., Fogliatto, F. S., Gao, S., & Chan, T. K. (2022). Contributions of Industry 4.0 to supply chain resilience. *The international journal of logistics management*, 33(2), 547-566.
- [36] Abidi, M. H., Mohammed, M. K., & Alkhalefah, H. (2022). Predictive maintenance planning for industry 4.0 using machine learning for sustainable manufacturing. *Sustainability*, 14(6), 3387.
- [37] Łuczak, D. (2023). Mechanical vibrations analysis in direct drive using CWT with complex Morlet wavelet. *Power Electronics and Drives*, 8(1), 65-73.
- [38] Sezer, E., Romero, D., Guedea, F., Macchi, M., & Emmanouilidis, C. (2018, June). An industry 4.0-enabled low cost predictive maintenance approach for smes. In *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1-8). IEEE.
- [39] Salunkhe, V. G., & Desavale, R. G. (2021). An Intelligent

- Prediction for Detecting Bearing Vibration Characteristics Using a Machine Learning Model. Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems, 4(3).*
- [40] Magadán, L., Suárez, F. J., Granda, J. C., & García, D. F. (2020). Low-cost real-time monitoring of electric motors for the Industry 4.0. *Procedia Manufacturing, 42*, 393-398.
- [41] Kiangala, K. S., & Wang, Z. (2018). Initiating predictive maintenance for a conveyor motor in a bottling plant using industry 4.0 concepts. *The International Journal of Advanced Manufacturing Technology, 97*, 3251-3271.
- [42] Muñoz, R., Nuño, F., Díaz, J., González, M., J Prieto, M., & Menéndez, Ó. (2023). Real-time monitoring solution with vibration analysis for industry 4.0 ventilation systems. *The Journal of Supercomputing, 79(6)*, 6203-6227.
- [43] Liang, Z., Wang, S., Peng, Y., Mao, X., Yuan, X., Yang, A., & Yin, L. (2022). The process correlation interaction construction of Digital Twin for dynamic characteristics of machine tool structures with multi-dimensional variables. *Journal of Manufacturing Systems, 63*, 78-94.
- [44] Abbate, R., Caterino, M., Fera, M., & Caputo, F. (2022). Maintenance digital twin using vibration data. *Procedia Computer Science, 200*, 546-555.
- [45] Dos Santos, J. F., Tshombe, B. K., Santos, L. H., Araújo, R. C., Manito, A. R., Fonseca, W. S., & Silva, M. O. (2022). Digital Twin-Based Monitoring System of Induction Motors Using IoT Sensors and Thermo-Magnetic Finite Element Analysis. *IEEE Access, 11*, 1682-1693.
- [46] Khaire, P., & Phalle, V. M. (2022). CONDITION MONITORING OF BALL BEARING HAVING DEFECT AT INNER RACE USING VIBRATION ANALYSIS AND MACHINE LEARNING.
- [47] Mugnaini, V., Fragonara, L. Z., & Civera, M. (2022). A machine learning approach for automatic operational modal analysis. *Mechanical Systems and Signal Processing, 170*, 108813.
- [48] Florian, E., Sgarbossa, F., & Zennaro, I. (2021). Machine learning-based predictive maintenance: A cost-oriented model for implementation. *International Journal of Production Economics, 236*, 108114.
- [49] Nagrani, S., Pathan, S. S., & Bhoraniya, I. H. (2012). Misalignment fault diagnosis in rotating machinery through the signal processing technique-signature analysis. *International*