



A framework for unsupervised learning and predictive maintenance in Industry 4.0

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References

- [1] C. Chen, N. Lu, B. Jiang, and C. Wang, "A Risk-Averse Remaining Useful Life Estimation for Predictive Maintenance," IEEE CAA J Autom Sin, vol. 8, no. 2, pp. 412–422, 2021, doi: 10.1109/JAS.2021.1003835.
- [2] M. Jasulewicz-Kaczmarek, K. Antosz, P. Żywica, D. Mazurkiewicz, B. Sun, and Y. Ren "Framework of machine criticality assessment with criteria interactions," Eksplot Niezawodn - Maint Reliab, vol. 23, pp. 207–220, 2021, doi: 10.17531/ein.2021.2.1.
- [3] C. K. M. Lee, Y. Cao, and K. H. Ng, "Big Data Analytics for Predictive Maintenance Strategies," in Supply Chain Management in the Big Data Era, H. K. Chan, N. Subramanian, and M. D-A. Abdulrahman, Eds. New York, NY, USA: IGI Global, 2017, pp. 50–74, doi: 10.4018/978-1-5225-0956-1.
- [4] A. K. S. Jardine, D. Lin, and D. Banjevic. "A review on machinery diagnostics and prognostics implementing condition-based maintenance," Mech Syst Signal Process, vol. 20, no. 7, pp. 1483–1510, 2006, doi: 10.1016/j.ymssp.2005.09.012.
- [5] V. L. Trevathan, A Guide to the Automation Body of Knowledge. Research Triangle Park, NC, USA: ISA—The Instrumentation, Systems, and Automation Society, 2006.
- [6] J.-R. Ruiz-Sarmiento, J. Monroy, F.-A. Moreno, C. Galindo, J.-M. Bonelo, and J. Gonzalez-Jimenez, "A predictive model for the maintenance of industrial machinery in the context of industry 4.0," Engineering Applications of Artificial Intelligence, vol. 87, p. 103289, 2020, doi: 10.1016/j.engappai.2019.103289.
- [7] E. Gundogar, A. Yilmaz, and B. Erkayman, "A solution approach to a synchronisation problem in a JIT production system," Prod Plan Control, vol. 25, pp. 990–998, 2014, doi: 10.1080/09537287.2013.794984.
- [8] B. Ji, H. Park, K. Jung, S. H. Bang, M. Lee, J. Kim, and H. Cho, "A Component Selection Method for Prioritized Predictive Maintenance," in Advances in Production Management Systems (APMS 2017), The Path to Intelligent, Collaborative and Sustainable Manufacturing, IFIP Advances in Information and Communication Technology, vol 513, H. Lödding, R. Riedel, K. D. Thoben, G. von Cieminski, and D. Kiritidis, Eds. 2017, pp. 433–440, doi: 10.1007/978-3-319-66923-6_51.
- [9] A. Busse, J. Metternich, and E. Abele, "Evaluating the Benefits of Predictive Maintenance in Production: A Holistic Approach for Cost-Benefit-Analysis," in Advances in Production Research. WGP 2018, R. Schmitt, and G. Schuh, Eds. 2019, pp. 690–704, doi: 10.1007/978-3-03451-1_67.
- [10] U. Moorthy, and U. D. Gandhi, "A Survey of Big Data Analytics Using Machine Learning Algorithms," in HCI Challenges and Privacy Preservation in Big Data Security, D. Lopez, and M. A. Saleem Durai, Eds. New York, NY, USA: IGI Global, 2017, pp. 95–123, doi: 10.4018/978-1-5225-2863-0.ch005.
- [11] G. Kabir, S. Tesfamariam, J. Loeppky, and R. Sadiq, "Predicting water main failures: A Bayesian model updating approach," Knowl-Based Syst, vol. 110, pp. 144–156, 2016, doi: 10.1016/j.knosys.2016.07.024.
- [12] J-H. Shin, and H-B. Jun, "On condition-based maintenance policy," J Comput Des Eng, vol. 2, pp. 119–127, 2015, doi: 10.1016/j.jcde.2014.12.006.
- [13] H.-Y. Wang, and C.-H. Hung, "Complex Industrial Machinery Health Diagnosis Challenges and Strategies," in Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 557, D.-J. Deng and J.-C. Chen, Eds. 2024, pp. 130–140, doi: 10.1007/978-3-031-55976-1_13.

- [14] H. Wang, W. Zhang, D. Yang, and Y. Xiang, "Deep-Learning-Enabled Predictive Maintenance in Industrial Internet of Things: Methods, Applications, and Challenges," *IEEE Systems Journal*, vol. 17, no. 2, pp. 2602-2615, 2023, doi: 10.1109/JSYST.2022.3193200.
- [15] P. Nunes, J. Santos, and E. Rocha, "Challenges in predictive maintenance - A review," *CIRP Journal of Manufacturing Science and Technology*, vol. 40, pp. 53-67, 2023, doi: 10.1016/j.cirpj.2022.11.004.
- [16] H. Hviid Hansen, M. Kulahci, and B. Friis Nielsen, "A primer on predictive maintenance: Potential benefits and practical challenges," *Quality Engineering*, vol. 36, no. 3, pp. 638-649, 2024, doi: 10.1080/08982112.2024.2331140.
- [17] N. H. A. Wahab, K. Hasikin, K. W. Lai, K. Xia, L. Bei, K. Huang, and X. Wu, "Systematic review of predictive maintenance and digital twin technologies challenges, opportunities, and best practices," *PeerJ Comput Sci*, vol. 10, p. e1943, 2024, doi: 10.7717/peerj.cs.1943.
- [18] M. Alabadi, A. Habbal, and M. Guizani, "An Innovative Decentralized and Distributed Deep Learning Framework for Predictive Maintenance in the Industrial Internet of Things," *IEEE Internet of Things Journal*, vol. 11, no. 11, pp. 20271-20286, 2024, doi: 10.1109/JIOT.2024.3372375.
- [19] R. Kumar, M. Mishra, S. Suman, and P. Singh Bali, "Predictive Maintenance in Industrial Systems Using Machine Learning," *International Journal of Innovative Science and Research Technology*, vol. 9, no. 3, pp. 1778-1785, 2024, doi: 10.38124/ijisrt/IJISRT24MAR1367.
- [20] P. Poór and J. Basl, "Machinery maintenance model for evaluating and increasing maintenance, repairs and operations within Industry 4.0 concept," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 947, no. 1, p. 012004, 2020, doi: 10.1088/1757-899X/947/1/012004.
- [21] J-Y. Chen, Y-L. Lin, and B-Y. Lee, "Development of the Adaptive System for Tool Management," *Tehnicki Vjesnik*, vol. 30, no. 2, pp. 648-654, 2023, doi: 10.17559/TV-20220702054333.
- [22] E. Salawu et al., "Impact of Maintenance on Machine Reliability: A Review," *E3S Web of Conferences*, vol. 430, 2023, doi: 10.1051/e3sconf/202343001226.
- [23] R. J. Rabelo, S. P. Zambiasi, and D. Romero, "Softbots 4.0: Supporting Cyber-Physical Social Systems in Smart Production Management," *Int J Ind Eng Manag*, vol. 14, no. 1, pp. 63 - 93, 2023, doi: 10.24867/IJIEM-2023-1-325.
- [24] N. Amruthnath and T. Gupta, "A research study on unsupervised machine learning algorithms for early fault detection in predictive maintenance," in *2018 5th International Conference on Industrial Engineering and Applications (ICIEA)*. Singapore: IEEE, 2018, pp. 355-361, doi: 10.1109/IEA.2018.8387124.
- [25] J. Lee, E. Lapira, S. Yang, and A. Kao, "Predictive Manufacturing System - Trends of Next-Generation Production Systems," *IFAC Proc*, vol. 46, no. 7, pp. 150-156, 2013, doi: 10.3182/20130522-3-BR-4036.00107.
- [26] H. Li and Q. Zhao, "Maintenance Modeling and Scheduling in Fault Tolerant Control Systems," in *Proceedings from the 6th IFAC Symposium, SAFEPROCESS 2006*, Beijing, China, 2007, pp. 777-782, doi: 10.1016/B978-008044485-7/50131-7.
- [27] M. G. Deighton, "Maintenance Management," in *Facility Integrity Management*, M. G. Deighton, Ed. Boston: Gulf Professional Publishing, 2016, pp. 87-139, doi: 10.1016/B978-0-12-801764-7.00005-X.
- [28] G. Nota, A. Postiglione, and R. Carvello, "Text mining techniques for the management of predictive maintenance," *Procedia Computer Science*, vol. 200, pp. 778-792, 2022, doi: 10.1016/j.procs.2022.01.276.
- [29] R. Langone, C. Alzate, B. De Ketelaere and J. A. K. Suykens, "Kernel spectral clustering for predicting maintenance of industrial machines," *2013 IEEE Symposium on Computational Intelligence and Data Mining (CIDM)*, Singapore, 2013, pp. 39-45, doi: 10.1109/CIDM.2013.6597215.
- [30] J. A. K. Suykens, T. Van Gestel, J. De Brabanter, B. De Moor, and J. Vandewalle, *Least Squares Support Vector Machines*. Singapore: World Scientific Publishing, 2002, doi: 10.1142/5089.
- [31] D. Rafique and L. Velasco, "Machine learning for network automation: overview, architecture, and applications," *J Opt Commun Netw*, vol. 10, no. 10, pp. 126-143, 2018, doi: 10.1364/JOCN.10.00D126.
- [32] N. Amruthnath and T. Gupta, "Fault class prediction in unsupervised learning using model-based clustering approach," in *2018 International Conference on Information and Computer Technologies (ICICT)*, DeKalb, IL, USA: IEEE Xplore, 2018, pp. 5-12, doi: 10.1109/INFOCT.2018.8356831.
- [33] Y. Bao, G. Rui, and S. Zhang, "A Unsupervised Learning System of Aeroengine Predictive Maintenance Based on Cluster Analysis," in *Proceedings of the 2020 International Conference on Aviation Safety and Information Technology*. Weihai City, China: ACM, 2020, pp. 187-191, doi: 10.1145/3434581.3434619.
- [34] F. Farbiz, Y. Miaolong, and Z. Yu, "A Cognitive Analytics based Approach for Machine Health Monitoring, Anomaly Detection, and Predictive Maintenance," in *15th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2020, pp. 1104-1109, doi: 10.1109/ICIEA48937.2020.9248409.
- [35] D. Kim, S. Lee, and D. Kim, "An Applicable Predictive Maintenance Framework for the Absence of Run-to-Failure Data," *Appl Sci*, vol. 11, no. 11, p. 5180, 2021, doi: 10.3390/app11115180.
- [36] P. Dayan, M. Sahani, and G. Deback, "Adaptation and Unsupervised Learning," in *Advances in Neural Information Processing Systems*, S. Becker and S. Thrun and K. Obermayer, Eds. 2022, pp. 237-244.
- [37] T. Wuest, D. Weimer, C. Irgens, and K-D. Thoben, "Machine learning in manufacturing: advantages, challenges, and applications," *Prod Manuf Res*, vol. 4, no. 1, pp. 23-45, 2016, doi: 10.1080/21693277.2016.1192517.
- [38] S. H. Bang, R. Ak, A. Narayanan, Y. T. Lee, and H. Cho, "A survey on knowledge transfer for manufacturing data analytics," *Comput Ind*, vol. 104, pp. 116-130, 2019, doi: 10.1016/j.compind.2018.07.001.
- [39] S. Martin-del-Campo, and K. Al-Kahwati, "Unsupervised Ranking of Outliers in Wind Turbines via Isolation Forest with Dictionary Learning," *PHM Society*, vol. 5, no. 1, p. 9, 2020, doi: 10.36001/phme.2020.v5i1.1164.
- [40] L. Monostori, "AI and machine learning techniques for managing complexity, changes and uncertainties in manufacturing," *Eng Appl Artif Intell*, vol. 16, no. 4, pp. 277-291, 2003, doi: 10.1016/S0952-1976(03)00078-2.
- [41] J. Lenz, T. Wuest, and E. Westkämper, "Holistic approach to machine tool data analytics," *J Manuf Syst*, vol. 48, pp. 180-191, 2018, doi: 10.1016/j.jmansy.2018.03.003.
- [42] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput Netw*, vol. 54, no. 15, pp. 2787-2805, 2010, doi: 10.1016/j.comnet.2010.05.010.
- [43] R. Casado and M. Younas, "Emerging trends and technologies in big data processing," *Concurr Comput Pract Exp*, vol. 27, no. 8, pp. 2078-2091, 2014, doi: 10.1002/cpe.3398.

- [44] J. Moradi, H. Shahinzadeh, H. Nafisi, M. Marzband, and G. B. Gharehpetian, "Attributes of Big Data Analytics for Data-Driven Decision Making in Cyber-Physical Power Systems," in 14th International Conference on Protection and Automation of Power Systems (IPAPS), Tehran, Iran, 2019, pp. 83-92, doi: 10.1109/IPAPS49326.2019.9069391.
- [45] M. H. ur Rehman, V. Chang, A. Batoor, and T. Y. Wah, "Big data reduction framework for value creation in sustainable enterprises," *Int J Inf Manag*, vol. 36, no. 6, pp. 917-928, 2016, doi: 10.1016/j.ijinfomgt.2016.05.013.
- [46] D. Reynolds, "Gaussian Mixture Models," in Encyclopedia of Biometrics, S. Z. Li and A. Jain, Eds. Boston, MA, USA: Springer, 2009, pp. 659-663, doi: 10.1007/978-0-387-73003-5_196.
- [47] J. Liu, D. Cai, and X. He, "Gaussian Mixture Model with Local Consistency," in Proceedings of the AAAI Conference on Artificial Intelligence, Atlanta, GA, USA, 2010, doi: 10.1609/aaai.v24i1.7659.
- [48] Y. Zhao and G. E. Mata, "Leverage Artificial Intelligence to Learn, Optimize, and Win (LAILOW) for the Marine Maintenance and Supply Complex System," in IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM), 2020, pp. 678-684, doi: 10.1109/ASONAM49781.2020.9381319.
- [49] A. Alaoui-Belghiti, S. Chevallier, and E. Monacelli, "Unsupervised Anomaly Detection Using Optimal Transport for Predictive Maintenance," in Artificial Neural Networks and Machine Learning - ICANN 2019: Text and Time Series. ICANN 2019, I. V. Tetko, V. Kůrková, P. Karpov, and F. Theis F, Eds. 2019, pp. 686-697, doi: 10.1007/978-3-030-30490-4_54.
- [50] G. L. Tortorella, F. S. Fogliatto, P. A. Cauchick-Miguel, S. Kurnia, and D. Jurburg, "Integration of Industry 4.0 technologies into Total Productive Maintenance practices," *Int J Prod Econ*, vol. 240, p. 108224, 2021, doi: 10.1016/j.ijpe.2021.108224.
- [51] G. Nota and A. Toro Lazo, "Leveraging the GQM+ Strategy approach and Industry 4.0 technologies for environmental sustainability in manufacturing," *Journal of Smart Environments and Green Computing*, vol. 2, no. 3, pp. 143-162, 2022, doi: 10.20517/jsegc.2022.13.
- [52] Oubrahim, N. Sefiani, and A. Happonen, "The Influence of Digital Transformation and Supply Chain Integration on Overall Sustainable Supply Chain Performance: An Empirical Analysis from Manufacturing Companies in Morocco," *Energies*, vol. 16, no. 2, p. 2, 2023, doi: 10.3390/en16021004.
- [53] C. L. Karmaker, A.B.M. Mainul Bari, Md. Z. Anam, T. Ahmed, S. M. Ali, D. A. de Jesus Pacheco, and Md. A. Moktadir, "Industry 5.0 challenges for post-pandemic supply chain sustainability in an emerging economy," *Int J Prod Econ*, vol. 258, p. 108806, 2023, doi: 10.1016/j.ijpe.2023.108806.
- [54] X. Wu, L. Xiao, Y. Sun, J. Zhang, T. Ma, and L. He, "A survey of human-in-the-loop for machine learning," *Future Generation Computer Systems*, vol. 135, pp. 364-381, 2022, doi: 10.1016/j.future.2022.05.014.
- [55] G. Feniza, V. Loia, and G. Nota, Patterns for Visual Management in Industry 4.0," *Sensors*, vol. 21, no. 19, p. 6440, 2021, doi: 10.3390/s21196440.
- [56] M. Di Gregorio, G. Nota, M. Romano, M. Sebillo, and G. Vitiello, "Designing usable interfaces for the Industry 4.0", in Proceedings of the 2020 International Conference on Advanced Visual Interfaces, AVI '20, New York, NY, USA: Association for Computing Machinery, 2020, pp. 1-9, doi: 10.1145/3399715.3399861.
- [57] Lepenioti, A. Bousdekis, D. Apostolou, and G. Mentzas, "Prescriptive analytics: Literature review and research challenges," *Int J Inf Manag*, vol. 50, pp. 57-70, 2020, doi: 10.1016/j.ijinfomgt.2019.04.003.