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Condition-based maintenance optimization for multi-component systems in mass production considering customer satisfaction

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A B S T R A C T

When multiple orders with different requirements must be fulfilled under limited capacity, order selection and maintenance planning for multi-component systems become strongly interdependent. To address this problem, this study proposes a condition-based maintenance strategy for multi-component systems and a joint optimization model for multi-order batch production that incorporates customer satisfaction. First, the deterioration trend of each component is described using the proportional hazards model, and the health status of each component is represented by virtual age. Different maintenance modes are then determined according to real-time monitoring results and maintenance thresholds after the completion of each production batch. With profit maximization as the objective, the condition-based maintenance strategy is integrated with a capacitated batch production model and a customer satisfaction model to develop a joint optimization framework for maintenance and multi-order production. Finally, the model is solved using simulated annealing and particle swarm optimization. A case study is used to verify the effectiveness of the proposed approach and to demonstrate its practical relevance, and a sensitivity analysis of the key model parameters is also conducted.

A R T I C L E I N F O

Keywords:
Condition-based maintenance;
Multi-component systems;
Batch production;
Maintenance optimization;
Proportional hazards model;
Customer satisfaction;
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Simulated annealing

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References

[1] Rajković, T., Makajić-Nikolić, D., Lečić-Cvetković, D., Aničić, N. (2025). The most commonly used Industry 4.0 technologies in manufacturing: A systematic literature review, *Advances in Production Engineering & Management*, Vol. 20, No. 4, 507-528, doi: 10.14743/apem2025.4.555.

[2] Huang, J., Wang, L., Jiang, Z. (2019). A method combining rules with genetic algorithm for minimizing makespan on a batch processing machine with preventive maintenance, *International Journal of Production Research,* Vol. 58, No. 13, 4086-4102, doi: 10.1080/00207543.2019.1641643.

[3] Tambe, P.P., Kulkarni, M.S. (2022). A reliability based integrated model of maintenance planning with quality control and production decision for improving operational performance, *Reliability Engineering & System Safety,* Vol. 226, Article No. 108681, doi: 10.1016/j.ress.2022.108681.

[4] Hnaien, F., Yalaoui, F., Mhadhbi, A., Nourelfath, M. (2016). A mixed-integer programming model for integrated production and maintenance, *IFAC-PapersOnLine,* Vol. 49, No. 12, 556-561, doi: 10.1016/j.ifacol.2016.07.694.

[5] Fitouhi, M.-C., Nourelfath, M. (2012). Integrating noncyclical preventive maintenance scheduling and production planning for a single machine, *International Journal of Production Economics,* Vol. 136, No. 2, 344-351, doi: 10.1016/j.ijpe.2011.12.021.

[6] Lai, X., Chen, Z., Sarker, B.R. (2020). Optimal production lot sizing for an imperfect manufacturing system with machine breakdown and emergency maintenance policy, *Kybernetes,* Vol. 49, No. 5, 1533-1560, doi: 10.1108/K-12-2018-0687.

[7] Hadian, S.M., Farughi, H., Rasay, H. (2023). Development of a simulation-based optimization approach to integrate the decisions of maintenance planning and safety stock determination in deteriorating manufacturing systems, *Computers & Industrial Engineering,* Vol. 178, Article No. 109132, doi: 10.1016/j.cie.2023.109132.

[8] BouAbid, H., Dhouib, K., Gharbi, A. (2024). Integrated production and maintenance policy for manufacturing systems prone to products' quality degradation, *Advances in Production Engineering & Management*, Vol. 19, No. 4, 512-526, doi: 10.14743/apem2024.4.521.

[9] Selech, J., Matijosius, J., Kilikevicius, A., Marinkovic, D. (2025). Reliability analysis and the costs of corrective maintenance for a component of a fleet of trams, *Tehnički Vjesnik – Technical Gazette*, Vol. 32, No. 1, 205-216, doi: 10.17559/TV-20241121002144.

[10] Duan, C., Li, Z., Liu, F. (2020). Condition-based maintenance for ship pumps subject to competing risks under stochastic maintenance quality, *Ocean Engineering,* Vol. 218, Article No. 108180, doi: 10.1016/j.oceaneng.2020.108180.

[11] Zhang, X., Liao, H., Zeng, J., Shi, G., Zhao, B. (2021). Optimal condition-based opportunistic maintenance and spare parts provisioning for a two-unit system using a state space partitioning approach, *Reliability Engineering & System Safety,* Vol. 209, Article No. 107451, doi: 10.1016/j.ress.2021.107451.

[12] Zheng, R., Zhou, Y., Gu, L., Zhang, Z. (2021). Joint optimization of lot sizing and condition-based maintenance for a production system using the proportional hazards model, *Computers & Industrial Engineering,* Vol. 154, Article No. 107157, doi: 10.1016/j.cie.2021.107157.

[13] Zheng, R., Chen, B., Gu, L. (2020). Condition-based maintenance with dynamic thresholds for a system using the proportional hazards model, *Reliability Engineering & System Safety,* Vol. 204, Article No. 107123, doi: 10.1016/j.ress.2020.107123.

[14] Zheng, M., Ye, H., Wang, D., Pan, E. (2021). Joint optimization of condition-based maintenance and spare parts orders for multi-unit systems with dual sourcing, *Reliability Engineering & System Safety,* Vol. 210, Article No. 107512, doi: 10.1016/j.ress.2021.107512.

[15] Yousefi, N., Coit, D.W., Song, S., Feng, Q. (2019). Optimization of on-condition thresholds for a system of degrading components with competing dependent failure processes, *Reliability Engineering & System Safety,* Vol. 192, Article No. 106547, doi: 10.1016/j.ress.2019.106547.

[16] Uit Het Broek, M.A.J., Teunter, R.H., de Jonge, B., Veldman, J. (2021). Joint condition-based maintenance and load-sharing optimization for two-unit systems with economic dependency, *European Journal of Operational Research,* Vol. 295, No. 3, 1119-1131, doi: 10.1016/j.ejor.2021.03.044.

[17] Wang, J., Qiu, Q., Wang, H., Lin, C. (2021). Optimal condition-based preventive maintenance policy for balanced systems, *Reliability Engineering & System Safety,* Vol. 211, Article No. 107606, doi: 10.1016/j.ress.2021.107606.

[18] Xu, J., Liang, Z., Li, Y.-F., Wang, K. (2021). Generalized condition-based maintenance optimization for multi-component systems considering stochastic dependency and imperfect maintenance, *Reliability Engineering & System Safety,* Vol. 211, Article No. 107592, doi: 10.1016/j.ress.2021.107592.

[19] Shi, Y., Zhu, W., Xiang, Y., Feng, Q. (2020). Condition-based maintenance optimization for multi-component systems subject to a system reliability requirement, *Reliability Engineering & System Safety,* Vol. 202, Article No. 107042, doi: 10.1016/j.ress.2020.107042.

[20] Liu, B., Wang, Y., Yang, H., Segerstedt, A., Zhang, L. (2021). Maintenance service strategy for leased equipment: Integrating lessor-preventive maintenance and lessee-careful protection efforts, *Computers & Industrial Engineering,* Vol. 156, Article No. 107257, doi: 10.1016/j.cie.2021.107257.

[21] Iskandar, B.P., Husniah, H. (2017). Optimal preventive maintenance for a two dimensional lease contract, *Computers & Industrial Engineering,* Vol. 113, 693-703, doi: 10.1016/j.cie.2017.09.028.

[22] Nezami, F.G., Yildirim, M.B. (2013). A sustainability approach for selecting maintenance strategy, *International Journal of Sustainable Engineering,* Vol. 6, No. 4, 332-343, doi: 10.1080/19397038.2013.765928.

[23] Ruan, Y., Wu, G., Luo, X. (2022). Optimal joint design of two-dimensional warranty and preventive maintenance policies for new products considering learning effects, *Computers & Industrial Engineering,* Vol. 166, Article No. 107958, doi: 10.1016/j.cie.2022.107958.

[24] Brenière, L., Doyen, L., Bérenguer, C. (2020). Virtual age models with time-dependent covariates: A framework for simulation, parametric inference and quality of estimation, *Reliability Engineering & System Safety,* Vol. 203, Article No. 107054, doi: 10.1016/j.ress.2020.107054.