APEM journal

Advances in Production Engineering & Management
Volume 21 | Number 2 | June 2026 | pp 239–253
https://doi.org/10.14743/apem2026.2.571

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

An integrated framework for production lot sizing and predictive maintenance based on Remaining Maintenance Life and Proportional Hazard Models

Zhong, C.W.[a], Lei, L.[a], Zhang, H.[b,*], Lu, M.L.[a,*]

[a]School of Economics and Management, Beijing Institute of Petrochemical Technology, Beijing, P.R. China
[b]Northeast Asian Studies College, Jilin University, Changchun, P.R. China

A B S T R A C T

Equipment reliability is critical to maintaining production efficiency and controlling manufacturing costs. Predictive maintenance (PdM), based on machine condition prediction, can effectively reduce the risk of machine failure; consequently, machine degradation assessment and the prediction of remaining maintenance life (RML) are crucial for maintenance decision-making. Moreover, because equipment condition affects production planning, PdM should be integrated into the traditional economic production quantity (EPQ) model. The main contribution of this study is the introduction of RML as a decision-support metric linking equipment degradation prediction with production lot-sizing decisions, thereby enabling the joint optimization of EPQ and PdM policies. To minimize expected average cost, maintenance decisions are integrated into the production lot-sizing model to determine the optimal production lot size and maintenance policy. This study considers a single-machine production process in which the ARMA method is used to forecast the machine degradation index. Cox's proportional hazard model (PHM) is then employed to estimate machine reliability based on the predicted degradation index. Based on this reliability assessment, remaining maintenance life (RML), rather than the traditional remaining useful life (RUL), is employed to link degradation prediction with the EPQ model and to characterize the machine deterioration process. An integrated EPQ–PdM model is developed to jointly determine the optimal production lot size and maintenance policy while minimizing the expected average cost (EAC) over the production cycle. Finally, a case study of an automotive bumper factory demonstrates the effectiveness of the proposed framework. The results show that the framework reduces EAC by 19.6 % relative to the current production strategy and identifies an optimal maintenance threshold of R_{safe} = 0.4 with six maintenance cycles.

A R T I C L E   I N F O

Keywords:
Economic production quantity (EPQ);
Predictive maintenance;
Proportional hazard model (PHM);
Machine degradation;
Remaining maintenance life (RML);
Production lot sizing;
Reliability assessment;
Maintenance optimization;
Condition-based maintenance (CBM);
Integrated production-maintenance optimization

**Corresponding author:*
zhui24@mails.jlu.edu.cn
(Zhang, H.)
lumilin@bipt.edu.cn
(Lu, M.L.)

Article history:
Received 24 September 2025
Revised 22 June 2026
Accepted 25 June 2026

References

[1] Silver, E.A., Peterson, R. (1985). *Decision systems for inventory management and production planning,* 2nd edition, John Wiley & Sons, New York, USA.
[2] Rosenblatt, M.J., Lee, H.L. (1986). Economic production cycles with imperfect production processes, *IIE Transactions*, Vol. 18, No. 1, 48-55, doi: 10.1080/07408178608975329.
[3] Hariga, M., Ben-Daya, M. (1998). Note: The economic manufacturing lot-sizing problem with imperfect production processes: Bounds and optimal solutions, *Naval Research Logistics (NRL)*, Vol. 45, No. 4, 423-433, doi: 10.1002/(SICI)1520-6750(199806)45:4<423::AID-NAV8>3.0.CO;2-7.

[4] Misra, R.B. (1975). Optimum production lot size model for a system with deteriorating inventory, *International Journal of Production Research*, Vol. 13, No. 5, 495-505, doi: 10.1080/00207547508943019.

[5] Rabiu, S., Majahar Ali, M.K. (2024). An enhanced EPQ model: Incorporating Weibull distribution deterioration, defective items, and dynamic demands for sustainable production optimization, *Ain Shams Engineering Journal*, Vol. 15, No. 7, Article No. 102824, doi: 10.1016/j.asej.2024.102824.

[6] Barlow, R.E., Proschan, F. (1996). *Mathematical theory of reliability,* Society for Industrial and Applied Mathematics, Philadelphia, USA, doi: 10.1137/1.9781611971194.

[7] Lee, H.S., Srinivasan, M.M. (2001). A production/Inventory policy for an unreliable machine, In: Rahim, M.A., Ben-Daya, M. (eds.), *Integrated models in production planning, inventory, quality, and maintenance*, Springer, Boston, USA, 79-94, doi: 10.1007/978-1-4615-1635-4_4.

[8] Nakagawa, T. (1986). Periodic and sequential preventive maintenance policies, *Journal of Applied Probability*, Vol. 23, No. 2, 536-542, doi: 10.2307/3214197.

[9] Pham, H., Wang, H. (1996). Imperfect maintenance, *European Journal of Operational Research*, Vol. 94, No. 3, 425-438, doi: 10.1016/S0377-2217(96)00099-9.

[10] van Dinter, R., Tekinerdogan, B., Catal, C. (2022). Predictive maintenance using digital twins: A systematic literature review, *Information and Software Technology*, Vol. 151, Article No. 107008, doi: 10.1016/j.infsof.2022.107008.

[11] Han, X., Wang, Z., Xie, M., He, Y., Li, Y., Wang, W. (2021). Remaining useful life prediction and predictive maintenance strategies for multi-state manufacturing systems considering functional dependence, *Reliability Engineering & System Safety*, Vol. 210, Article No. 107560, doi: 10.1016/j.ress.2021.107560.

[12] Zhang, L., Wang, X., He, S., Mao, X., Li, B., Liu, H. (2024). Multi-models associated with process information-driven process autonomous digital twin for multi-variety production of intelligent machines, *Science China Technological Sciences*, Vol. 67, No. 12, 3825-3842, doi: 10.1007/s11431-024-2778-0.

[13] Wang, S., Guo, Y., Huang, S., Liu, D., Tang, P., Zhang, L. (2024). A spatial-temporal feature fusion network for order remaining completion time prediction in discrete manufacturing workshop, *International Journal of Production Research*, Vol. 62, No. 10, 3638-3653, doi: 10.1080/00207543.2023.2245487.

[14] Tse, E., Makis, V. (1994). Optimization of the lot size and the time to replacement in a production system subject to random failure, In: *Proceedings of the Third International Conference on Automation Technology*, Taipei, Taiwan, Vol. 4, 163-169.

[15] Bányai, Á. (2023). Impact of agile, condition-based maintenance strategy on cost efficiency of production systems, *Advances in Production Engineering & Management*, Vol. 18, No. 3, 317-326, doi: 10.14743/apem2023.3.475.

[16] 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.

[17] Zivlak, N., Dong, M., Lalic, B., Yun, F.Z., Liu, Q.M. (2026). Condition-based maintenance optimization for multi-component systems in mass production considering customer satisfaction, *Advances in Production Engineering & Management*, Vol. 21, No. 1, 89-100, doi: 10.14743/apem2026.1.563.

[18] Pang, J.L. (2023). Adaptive fault prediction and maintenance in production lines using deep learning, *International Journal of Simulation Modelling*, Vol. 22, No. 4, 734-745, doi: 10.2507/IJSIMM22-4-CO20.

[19] He, D.X. (2024). Fault prediction in high-efficiency petroleum machinery production, *International Journal of Simulation Modelling*, Vol. 23, No. 1, 184-195, doi: 10.2507/IJSIMM23-1-CO5.

[20] Jankovič, D., Šimic, M., Herakovič, N. (2024). A comparative study of machine learning regression models for production systems condition monitoring, *Advances in Production Engineering & Management*, Vol. 19, No. 1, 78-92, doi: 10.14743/apem2024.1.494.

[21] 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.

[22] Shih, Y.C. (2024). Impacts of maintenance policies on fractal layout performance, *International Journal of Simulation Modelling*, Vol. 23, No. 3, 401-411, doi: 10.2507/IJSIMM23-3-688.

[23] Wang, Y., Li, X., Chen, J., Liu, Y. (2022). A condition-based maintenance policy for multi-component systems subject to stochastic and economic dependencies, *Reliability Engineering & System Safety*, Vol. 219, Article No. 108174, doi: 10.1016/j.ress.2021.108174.

[24] Alley, S.L. (2015). *A probabilistic assessment of failure for Air Force building systems,* Master's thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, USA, AFIT-ENV-MS-15-M-196, DTIC Accession No. ADA615418.

[25] Pan, E., Liao, W., Xi, L. (2012). A joint model of production scheduling and predictive maintenance for minimizing job tardiness, *The International Journal of Advanced Manufacturing Technology*, Vol. 60, 1049-1061, doi: 10.1007/s00170-011-3652-4.

[26] Cox, D.R. (1972). Regression models and life-tables, *Journal of the Royal Statistical Society: Series B (Methodological)*, Vol. 34, No. 2, 187-202, doi: 10.1111/j.2517-6161.1972.tb00899.x.

[27] Kumar, D., Klefsjö, B. (1994). Proportional hazards model: A review, *Reliability Engineering & System Safety*, Vol. 44, No. 2, 177-188, doi: 10.1016/0951-8320(94)90010-8.

[28] Makis, V., Jardine, A.K.S. (1992). Optimal replacement in the proportional hazards model, *INFOR: Information Systems and Operational Research*, Vol. 30, No. 1, 172-183, doi: 10.1080/03155986.1992.11732183.

[29] Ghasemi, A., Yacout, S., Ouali, M.S. (2007). Optimal condition based maintenance with imperfect information and the proportional hazards model, *International Journal of Production Research*, Vol. 45, No. 4, 989-1012, doi: 10.1080/00207540600596882.

[30] Cansu, T., Bas, E., Egrioglu, E., Akkan, T. (2024). Intuitionistic fuzzy time series forecasting method based on dendrite neuron model and exponential smoothing, *Granular Computing*, Vol. 9, Article No. 49, doi: 10.1007/s41066-024-00474-6.

[31] Hesamian, G., Johannssen, A., Chukhrova, N. (2024). A neural network-based ARMA model for fuzzy time series data, *Computational and Applied Mathematics*, Vol. 43, Article No. 445, doi: 10.1007/s40314-024-02950-w.

[32] Weiss, C.H., Zhu, F., Hoshiyar, A. (2022). Softplus INGARCH models, *Statistica Sinica*, Vol. 32, No. 2, 1099-1120, doi: 10.5705/ss.202020.0353.

[33] Box, G.E.P., Jenkins, G.M., Reinsel, G.C., Ljung, G.M. (2015). *Time series analysis: Forecasting and control,* 5th edition, Hoboken, New Jersey, USA.

[34] Ripatti, S., Palmgren, J. (2000). Estimation of multivariate frailty models using penalized partial likelihood, *Biometrics*, Vol. 56, No. 4, 1016-1022, doi: 10.1111/j.0006-341X.2000.01016.x.

[35] Ducrocq, V., Casella, G. (1996). A Bayesian analysis of mixed survival models, *Genetics Selection Evolution*, Vol. 28, No. 6, 505-529, doi: 10.1186/1297-9686-28-6-505.

[36] Cortiñas Abrahantes, J., Burzykowski, T. (2005). A version of the EM algorithm for proportional hazard model with random effects, *Biometrical Journal*, Vol. 47, No. 6, 847-862, doi: 10.1002/bimj.200410141.

[37] Malik, M.A.K. (1979). Reliable preventive maintenance scheduling, *AIIE Transactions*, Vol. 11, No. 3, 221-228, doi: 10.1080/05695557908974463.