Modernising Legacy CNC Lathes for Industry 4.0 and 5.0: A Literature Review and Conceptual Integration Framework

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Abstract Legacy CNC lathes are essential in brownfield plants but are limited by closed controllers, limited semantics, and ISO 6983 G-code. This paper presents a deployable framework: (i) smart retrofitting with edge sensing and gateways; (ii) interoperable connectivity combining MTConnect semantics with OPC UA messaging; (iii) digital twins (DT) integrated with AI for tool condition monitoring (TCM), predictive maintenance (PdM), and remaining useful life estimation; (iv) feature-based programming through STEP-NC; (v) deterministic communications using Time-Sensitive Networking (TSN) with OPC UA Pub/Sub; and (vi) energy-efficient optimisation of cutting parameters. The findings indicate that these components collectively extend machine lifespan, reduce downtime, and enhance energy efficiency while maintaining human-centred operations. Ultimately, a standards-driven retrofit approach allows SMEs to achieve IR 4.0/5.0 goals without complete replacement. Future research should focus on expanding turning datasets for portable DT/AI models, increasing STEP-NC adoption in lathe controllers, and conducting multi-vendor field validation of TSN quality-of-service impacts.

1 Introduction

Brownfield CNC lathes remain common across SME workshop floors. However, proprietary interfaces and legacy G-code restrict data access and integration, hindering PdM, adaptive control, and sustainability reporting. Retrofit-based development offers a practical way to add sensing, analytics, and connectivity without replacing the existing assets [1]. Digital Twin (DT) techniques create a consistent virtual model of machine states [2], and when combined with AI, they have achieved intelligent, real-time tool-life prediction in turning processes [3]. Systematic and applied research further demonstrates DT's role in energy efficiency [4] and confirms its real-time deployment on CNC equipment [5]. To stay competitive, legacy lathes require interoperable communication and modern semantics aligned with the evolution of CNC technology [6–8,11].

2 Research Methodology

A structured review was carried out emphasising deployable retrofits, interoperable protocols, and validated DT/AI use cases. Selection favoured peer-reviewed journals and standards bodies. Core areas included (a) brownfield retrofitting [1], (b) DT consistency and architecture [2,12,13], (c) interoperability via MTConnect and OPC UA [7,8], (d) STEP-NC for feature-based programming [11], (e) TSN for deterministic messaging [14], and (f) energy optimisation in turning [9,10]. The literature search covered peer-reviewed publications and standards released between 2010 and 2025, reflecting the maturation of DT, STEP-NC, OPC UA, and TSN technologies within this period.

3 Retrofitting Brownfield Machines

Non-intrusive edge kits that integrate vibration, motor-current, and acoustic sensing can be attached to legacy lathes to stream operational signals into analytics pipelines. Development based on retrofitting shows SMEs can attain IR4/IR5 connectivity, PdM, and lifecycle extension with modest investment [1]. To maintain DT fidelity during operational changes, model-consistency methods are essential [2]; at the same time, intelligent DTs have demonstrated tool-life forecasts suitable for scheduling and preventing premature changeovers [3].

4 Issues on IR 4.0 Concerning CNC Machines

Interoperability and semantics: Chronic vendor lock-in and sparse tagging restrict data exchange in brownfield environments. Combining MTConnect's semantic model with OPC UA's platform-independent messaging enables structured, vendor-neutral integration [7,8]. Timing and determinism: Mission-critical coordination requires limited latency. TSN with OPC UA Pub/Sub provides deterministic flows suitable for multi-vendor shop floors [14]. Programming semantics and traceability: STEP-NC moves programming from device-specific codes to feature intent, improving interoperability and enabling richer on-machine measurement and adaptive control [11]. Energy and sustainability: Multi-objective optimisation of speed, feed, and depth decreases electrical consumption and CO_2 emissions while maintaining surface quality [9,10]. Security: As IT/OT converge, organisation-wide programmes aligned to ISA/IEC 62443 are necessary to govern segmentation, access, and secure updates [15].

5 Results and Discussion

A compact integration stack for legacy lathes includes a tri-axial accelerometer and motor-current sensors feeding an OPC UA server, which is bridged to MTConnect for semantics [7,8]. The DT hosts physics- and data-driven models that detect anomalies, schedule maintenance, and calculate energy baselines [2–5,12,13]. In pilot scenarios, feature-oriented STEP-NC workflows attach process metadata to the digital thread, enhancing traceability beyond conventional G-code [11]. Deterministic networking via TSN supports motion control and tool-change coordination, provided QoS is validated for each use case [14]. Energy-aware optimisation consistently reports savings at the cell level while maintaining product quality [9,10]. Collectively, these measures extend machine life, reduce unplanned downtime, and enable human-centred, sustainable operations without complete replacement [1,4,5].

6 Conclusion

A standards-led retrofit pathway can unlock Industry 4.0/5.0 capabilities on legacy CNC lathes: act as an open data instrument; develop digital twin models for predictive maintenance and energy analytics; adopt STEP-NC for feature-oriented programming; and ensure deterministic, secure operations using TSN and ISA/IEC 62443. Future research should expand turning datasets for portable digital twin and AI models, promote controller support for STEP-NC, and assess the impact of TSN QoS on machining outcomes [3,11,14].

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Conflict of Interest

The authors declare no conflicts of interest.

Ethics Approval

No humans or animals were used; all procedures adhered to institutional safety standards and ethical guidelines.

Author Contribution (CRediT)

Conceptualisation & Methodology: Prof. Izzat; Investigation: Tang Yow Onn; Writing (Original Draft): Tang Yow Onn; Writing (Review & Editing): Prof. Izzat; Supervision: Prof. Izzat; Funding Acquisition: Prof. Izzat, Tang Yow Onn, Fizzah Haq.

AI-use Disclosure

A generative language model was employed solely to enhance grammar and clarity; all technical content, data interpretation, and conclusions were authored and verified by the co-author(s).

References

[1] T.-A. Tran, T. Ruppert, G. Eigner, J. Abonyi, Retrofitting-based development of brownfield Industry 4.0 and Industry 5.0 solutions, IEEE Access, 10, 64348–64374 (2022). https://doi.org/10.1109/ACCESS.2022.3182491

[2] Y. Wei, T. Hu, T. Zhou, Y. Ye, W. Luo, Consistency retention method for CNC machine tool digital twin model, J. Manuf. Syst., 58, 313–321 (2020). https://doi.org/10.1016/j.jmsy.2020.06.002

[3] J. Dominguez-Caballero, S. Ayvar-Soberanis, D. Curtis, Intelligent real-time tool life prediction for a digital twin framework, J. Intell. Manuf. (2025). https://doi.org/10.1007/s10845-025-02606-4

[4] L. Ba, F. Tangour, I. El Abbassi, R. Absi, Analysis of Digital Twin Applications in Energy Efficiency: A Systematic Review, Sustainability, 17(8), 3560 (2025). https://doi.org/10.3390/su17083560

[5] D. Darabă, F. S. Pop, C. Daraba, Digital Twin Used in Real-Time Monitoring of Operations Performed on CNC Technological Equipment, Appl. Sci., 14(22), 10088 (2024). https://doi.org/10.3390/app142210088

[6] K. Yao, D. Chen, C.-H. Pan, C.-L. Lin, The Development Trends of CNC Machine Tool Technology, Mathematics, 12(13), 1923 (2024). https://doi.org/10.3390/math12131923

[7] R. Fisher, G. Shao, Testing of the MTConnect–OPC UA Companion Specification, Proc. MSEC, 58745, V001T02A039 (2019). https://doi.org/10.1115/MSEC2019-2748

[8] OPC Foundation, OPC Unified Architecture: Interoperability for Industrie 4.0 and the Internet of Things (2024). https://opcfoundation.org/wp-content/uploads/2023/05/OPC-UA-Interoperability-For-Industrie4-and-IoT-EN.pdf

[9] S. Pawanr, K. Gupta, Recent Advances in the Energy Efficiency of Machining Processes for Sustainability, Energies, 17(15), 3659 (2024). https://doi.org/10.3390/en17153659

[10] S. Jia, S. Wang, J. Lv, W. Cai, N. Zhang, Z. Zhang, S. Bai, Multi-Objective Optimization of CNC Turning Process Parameters Considering Transient–Steady State Energy Consumption, Sustainability, 13(24), 13803 (2021). https://doi.org/10.3390/su132413803

[11] M. Hardwick, Y.F. Zhao, F. Proctor, A. Nassehi, X. Xu, S. Venkatesh, D. Odendahl, L. Xu, M. Hedlind, M. Lundgren, L. Maggiano, D. Loffredo, J. Fritz, B. Olsson, J.G. Campos, A. Brail, A roadmap for STEP-NC-enabled interoperable manufacturing, Int. J. Adv. Manuf. Technol., 68, 1023–1041 (2013). https://doi.org/10.1007/s00170-013-4894-0

[12] F. Schnicke, D. Espen, P.O. Antonino, T. Kühn, Architecture Blueprint Enabling Distributed Digital Twins, 7th Conference on the Engineering of Computer Based Systems (2021). https://doi.org/10.1145/3459960.3459978

[13] G. Shao, M. Helu, Framework for a digital twin in manufacturing: Scope and requirements, Manufacturing Letters, 24, 105–107 (2020). https://doi.org/10.1016/j.mfglet.2020.04.004

[14] P. Denzler, T. Frühwirth, D. Scheuchenstuhl, M. Schoeberl, W. Kastner, Timing Analysis of TSN-enabled OPC UA PubSub, Int. Conf. on Factory Communication Systems (2022). https://doi.org/10.1109/WFCS53837.2022.9779177

[15] International Society of Automation (ISA), Update to ISA/IEC 62443 Standards Addresses Organization-Wide Cybersecurity in Industrial and Critical Infrastructure Operations (2025). https://www.isa.org/news-press-releases/2025/january/update-to-isa-iec-62443-standards-addresses-organi