

Applications of Artificial Intelligence in Industry 4.0/5.0: Innovations, Challenges, and Future Directions

Filipe Pereira ^{1,2,3,4,*} , Carlos Felgueiras ² , Vítor Carvalho ^{5,6}  and Pedro M. B. Torres ^{7,8} 

- ¹ Faculdade de Engenharia, Universidade do Porto (FEUP), Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
² Instituto Superior de Engenharia do Porto (ISEP), Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal; mcf@isep.ipp.pt
³ Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
⁴ Research Center in Digitalization and Intelligent Robotics (CeDRI), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
⁵ 2Ai—Applied Artificial Intelligence Laboratory, School of Technology, Polytechnic University of Cávado and Ave (IPCA), Campus of IPCA, Vila Frescaíña S. Martinho, 4750-810 Barcelos, Portugal; vcarvalho@ipca.pt
⁶ Algoritmi R&D Centre, Minho University, 4710-057 Braga, Portugal
⁷ Research Center for Systems and Technologies (SYSTEC-DIGI2), ARISE & ECE Department, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal; pedrotorres@ipcb.pt
⁸ Polytechnic Institute of Castelo Branco, Av. Pedro Álvares Cabral No 12, 6000-084 Castelo Branco, Portugal
* Correspondence: filipepereira@fe.up.pt

1. Introduction

Artificial Intelligence (AI) has become a fundamental enabling technology in the transformation of modern industrial systems. Within the Industry 4.0 paradigm, the integration of cyber–physical systems (CPS), industrial internet of things (IIoT), cloud and edge computing, and advanced automation technologies has enabled the development of intelligent manufacturing environments capable of real-time monitoring, predictive maintenance, and data-driven decision-making [1–5]. These technologies support improved operational efficiency, flexibility, and quality control across industrial processes.

More recently, the concept of Industry 5.0 has emerged as an evolution of Industry 4.0, emphasizing human-centricity, sustainability, and resilience in industrial ecosystems. Unlike previous paradigms focused primarily on automation and productivity, Industry 5.0 promotes collaboration between humans and intelligent machines, integrating technological innovation with social and environmental objectives [6–8]. In this context, intelligent automation, collaborative robotics, and human–machine interaction are key components of next-generation industrial systems.

Artificial Intelligence plays a central role in enabling this transition. Advances in machine learning, deep learning, and reinforcement learning have significantly expanded the capabilities of industrial systems, enabling predictive modelling, intelligent control, and adaptive optimization in complex production environments [9–11]. In addition, the integration of AI with CPS architectures and industrial communication frameworks enables real-time data processing and distributed decision-making in smart factories.

Recent research has emphasized the integration of AI with industrial automation and digital transformation frameworks, highlighting the critical role of interoperability, real-time analytics, and system-level integration in enabling scalable and resilient smart manufacturing systems [12]. Furthermore, advances in distributed architectures, including edge computing and blockchain technologies, have been proposed to enhance security, scalability, and resilience in Industry 5.0 environments [13].



Received: 11 July 2026

Accepted: 25 July 2026

Published: 30 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

The integration of AI with computer vision and collaborative robotics has also gained significant attention, enabling intelligent inspection systems and real-time industrial applications. These approaches demonstrate the potential of deep learning techniques to improve quality control, automation, and human–machine collaboration in industrial settings [14].

Despite these advances, several challenges remain, including scalability, explainability, interoperability, and the integration of AI with legacy industrial infrastructures. Addressing these challenges requires interdisciplinary research combining Artificial Intelligence, industrial engineering, and manufacturing systems [15].

In this context, this Special Issue, titled “Applications of Artificial Intelligence in Industry 4.0/5.0: Innovations, Challenges, and Future Directions”, provides a comprehensive overview of recent advances in AI-driven industrial technologies, covering predictive modelling, intelligent automation, computer vision, reinforcement learning, and systematic analyses of AI methodologies in industrial environments.

2. Overview of Published Articles

The first article (Contribution 1) presents an AI-driven approach to manufacturing digitalization through real-time predictive models, enabling proactive decision-making and improved operational efficiency.

The second article (Contribution 2) proposes a neural-network-based framework for estimating wind power density, demonstrating how AI can support sustainable energy planning and industrial decision-making.

The third article (Contribution 3) investigates reinforcement learning for optimizing an automated substrate irrigation system, illustrating the application of adaptive control strategies in industrial environments.

The fourth article (Contribution 4) provides a systematic review of biases in AI-supported Industry 4.0 research, proposing mitigation strategies to improve transparency and reliability.

The fifth article (Contribution 5) explores computer vision techniques for automated construction waste sorting, demonstrating the potential of AI-driven perception systems in industrial recycling processes.

The sixth article (Contribution 6) presents an automated wastewater treatment system combining PLC-based control with LSTM neural networks for process optimization.

The seventh article (Contribution 7) proposes a framework for integrating Robotic Process Automation with Artificial Intelligence in Industry 5.0 environments, highlighting the role of intelligent automation in human-centric industrial systems.

The eighth article (Contribution 8) analyzes the transition from Industry 4.0 to Industry 5.0 through bibliometric methods, identifying key research trends and thematic developments.

The ninth article (Contribution 9) presents a systematic review of machine learning methods applied to process optimization in laser welding, contributing to advanced manufacturing research.

The tenth article (Contribution 10) provides a systematic review of reinforcement learning in process industries, proposing a taxonomy of applications and future research directions.

Taken together, these contributions demonstrate that AI is being successfully applied across multiple industrial domains, ranging from manufacturing and energy systems to process industries, computer vision, automation, and decision support, illustrating both the technological maturity and multidisciplinary nature of AI-driven Industry 5.0.

3. Conclusions

The contributions presented in this Special Issue demonstrate the growing impact of Artificial Intelligence in industrial systems. The articles cover a wide range of applications, including predictive modelling, reinforcement learning, computer vision, intelligent automation, and systematic analyses of AI methodologies.

These studies highlight the transformation of industrial environments into intelligent, adaptive, and data-driven ecosystems. At the same time, the transition toward Industry 5.0 emphasizes the importance of human-centric design, sustainability, and resilience.

Future research should focus on improving the scalability and robustness of AI models, enhancing explainability and transparency, and strengthening the integration between Artificial Intelligence, cyber-physical systems, and human operators.

These findings reinforce the role of Artificial Intelligence as a cornerstone technology in the transition toward Industry 5.0, enabling the development of sustainable, resilient, and human-centric industrial systems.

Overall, the papers gathered in this Special Issue confirm that Artificial Intelligence is no longer a peripheral technological addition but rather a strategic enabler of next-generation industrial systems. Beyond efficiency and automation, the contributions also highlight the increasing importance of sustainability, resilience, interoperability, and human-centricity as defining principles of Industry 5.0.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Horr, A.M.; Milicic, S.; Blacher, D. AI-Driven Innovation in Manufacturing Digitalization: Real-Time Predictive Models. *Appl. Sci.* **2025**, *15*, 13225. <https://doi.org/10.3390/app152413225>.
2. Molina-Almaraz, M.; Solís-Sánchez, L.O.; Bañuelos-García, L.E.; Castañeda-Miranda, C.L.; Guerrero-Osuna, H.A.; García-Sánchez, E. Efficient Neural Modeling of Wind Power Density for National-Scale Energy Planning: Toward Sustainable AI Applications in Industry 5.0. *Appl. Sci.* **2025**, *15*, 13000. <https://doi.org/10.3390/app152413000>.
3. Kavaliauskas, Ž.; Blažiūnas, G.; Šajev, I. Optimization of an Automated Substrate Irrigation System Using the SAC Reinforcement Learning Agent. *Appl. Sci.* **2025**, *15*, 12715. <https://doi.org/10.3390/app152312715>.
4. Arévalo-Royo, J.; Flor-Montalvo, F.-J.; Latorre-Biel, J.-I.; Jiménez-Macías, E.; Martínez-Cámara, E.; Blanco-Fernández, J. Biases in AI-Supported Industry 4.0 Research: A Systematic Review, Taxonomy, and Mitigation Strategies. *Appl. Sci.* **2025**, *15*, 10913. <https://doi.org/10.3390/app152010913>.
5. Liu, X.; Farshadfar, Z.; Khajavi, S.H. Computer Vision-Enabled Construction Waste Sorting: A Sensitivity Analysis. *Appl. Sci.* **2025**, *15*, 10550. <https://doi.org/10.3390/app151910550>.
6. Kavaliauskas, Ž.; Blažiūnas, G.; Šajev, I.; Iljinas, A.; Gimžauskaitė, D. Development and Optimization of an Automated Industrial Wastewater Treatment System Using PLC and LSTM Neural Network. *Appl. Sci.* **2025**, *15*, 8990. <https://doi.org/10.3390/app15168990>.
7. Patrício, L.; Varela, L.; Silveira, Z.; Felgueiras, C.; Pereira, F. A Framework for Integrating Robotic Process Automation with Artificial Intelligence Applied to Industry 5.0. *Appl. Sci.* **2025**, *15*, 7402. <https://doi.org/10.3390/app15137402>.
8. Rosário, A.T.; Raimundo, R.J.G. AI, Optimization, and Human Values: Mapping the Intellectual Landscape of Industry 4.0 to 5.0. *Appl. Sci.* **2025**, *15*, 7264. <https://doi.org/10.3390/app15137264>.
9. Paz Ramos, M.A.; Busboom, A. Systematic Review of Reinforcement Learning in Process Industries: A Contextual and Taxonomic Approach. *Appl. Sci.* **2025**, *15*, 12904. <https://doi.org/10.3390/app152412904>.
10. Voets, J.; Tercan, H.; Meisen, T.; Esen, C. A Systematic Review and Taxonomy of Machine Learning Methods for Process Optimization and Control in Laser Welding. *Appl. Sci.* **2026**, *16*, 1568. <https://doi.org/10.3390/app16031568>.

References

1. Kagermann, H.; Wahlster, W.; Helbig, J. *Recommendations for Implementing the Strategic Initiative Industrie 4.0: Final Report of the Industrie 4.0 Working Group*; Acatech: Munich, Germany, 2013.
2. Lee, J.; Bagheri, B.; Kao, H.A. A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manuf. Lett.* **2015**, *3*, 18–23. [[CrossRef](#)]
3. Qin, J.; Liu, Y.; Grosvenor, R. A categorical framework of manufacturing for Industry 4.0 and beyond. *Procedia CIRP* **2016**, *52*, 173–178. [[CrossRef](#)]
4. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. [[CrossRef](#)]
5. Nahavandi, S. Industry 5.0—A human-centric solution. *Sustainability* **2019**, *11*, 4371. [[CrossRef](#)]
6. Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; European Commission: Brussels, Belgium, 2021.
7. Leng, J.; Sha, W.; Wang, B.; Zheng, P.; Zhuang, C.; Liu, Q.; Wuest, T.; Mourtzis, D.; Wang, L. Industry 5.0: Prospect and retrospect. *J. Manuf. Syst.* **2022**, *65*, 279–295. [[CrossRef](#)]
8. Russell, S.; Norvig, P. *Artificial Intelligence: A Modern Approach*, 4th ed.; Pearson: Hoboken, NJ, USA, 2021.
9. Pereira, M.Â.; Vieira, G.; Varela, L.; Putnik, G.; Cruz-Cunha, M.; Santos, A.; Dieguez, T.; Pereira, F.; Leal, N.; Machado, J. Manufacturing Management Processes Integration Framework. *Appl. Sci.* **2025**, *15*, 9165. [[CrossRef](#)]
10. Oliveira, M.; Chauhan, S.; Pereira, F.; Felgueiras, C.; Carvalho, D. Blockchain Protocols and Edge Computing Targeting Industry 5.0 Needs. *Sensors* **2023**, *23*, 9174. [[CrossRef](#)]
11. Terras, N.; Pereira, F.; Ramos Silva, A.; Santos, A.A.; Lopes, A.M.; Silva, A.F.d.; Cartal, L.A.; Apostolescu, T.C.; Badea, F.; Machado, J. Integration of Deep Learning Vision Systems in Collaborative Robotics for Real-Time Applications. *Appl. Sci.* **2025**, *15*, 1336. [[CrossRef](#)]
12. Jourabchi Amirkhizi, P.; Pedrammehr, S.; Pakzad, S.; Shahhoseini, A. Generative Artificial Intelligence in Adaptive Social Manufacturing: A Pathway to Achieving Industry 5.0 Sustainability Goals. *Processes* **2025**, *13*, 1174. [[CrossRef](#)]
13. Kovič, K.; Tominc, P.; Prester, J.; Palčič, I. Artificial Intelligence Software Adoption in Manufacturing Companies. *Appl. Sci.* **2024**, *14*, 6959. [[CrossRef](#)]
14. Ahmmed, M.S.; Isanaka, S.P.; Liou, F. Promoting Synergies to Improve Manufacturing Efficiency in Industrial Material Processing: A Systematic Review of Industry 4.0 and AI. *Machines* **2024**, *12*, 681. [[CrossRef](#)]
15. Martini, B.; Bellisario, D.; Coletti, P. Human-Centered and Sustainable Artificial Intelligence in Industry 5.0: Challenges and Perspectives. *Sustainability* **2024**, *16*, 5448. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.