

Advanced Industrial Technologies for Future Research Applications

Dimitrios Tzetzis

Professor, International Hellenic University, Greece

Abstract

Rapid technological advancement is reshaping industrial systems by introducing intelligent automation, advanced manufacturing, digital twins, industrial Internet of Things, artificial intelligence, robotics, additive manufacturing, advanced materials, and data-driven decision-making. These technologies provide new opportunities for improving productivity, flexibility, quality, resource efficiency, and industrial resilience while creating emerging directions for engineering research. This study examines advanced industrial technologies and their potential applications in future research through a qualitative descriptive and conceptual research design based on secondary academic literature.

The study focuses on intelligent manufacturing, autonomous robotics, additive manufacturing, digital twins, industrial artificial intelligence, advanced sensing, cyber-physical systems, and sustainable production technologies. The analysis indicates that the integration of these technologies can support adaptive manufacturing, predictive process management, customized production, real-time monitoring, and resource-efficient industrial operations. However, implementation is constrained by technological complexity, high investment requirements, interoperability limitations, cybersecurity risks, data quality, ethical concerns, and workforce capability gaps.

The study emphasizes that future industrial research should move beyond isolated technological adoption toward integrated systems that combine engineering knowledge, artificial intelligence, automation, simulation, and sustainability. Developing interoperable and human-centered industrial platforms can create opportunities for more flexible and resilient production systems. Future research should particularly investigate hybrid intelligence, autonomous industrial decision-making, trustworthy artificial intelligence, sustainable digital manufacturing, and adaptive cyber-physical production systems.

Keywords: Advanced Industrial Technologies, Future Research, Smart Manufacturing, Artificial Intelligence, Robotics, Digital Twins, Additive Manufacturing, Cyber-Physical Systems, Industrial Innovation, Sustainable Manufacturing.

1. Introduction

Industrial technologies are undergoing substantial transformation as manufacturing organizations increasingly integrate digitalization, automation, artificial intelligence, advanced robotics, additive manufacturing, and interconnected production systems. Conventional production environments generally

depend on predetermined operating conditions and sequential workflows, whereas advanced industrial systems increasingly incorporate real-time data and adaptive decision-making. This transformation is creating new opportunities for improving production efficiency, product quality, operational flexibility, and resource utilization. It also creates an expanding research landscape in which engineering and technological disciplines must address increasingly interconnected industrial systems.

Artificial intelligence has become an important component of advanced industrial technology because it can support prediction, classification, optimization, anomaly detection, and automated decision-making. Machine-learning models can identify patterns within large industrial datasets and support applications such as predictive maintenance, quality assessment, production scheduling, and process optimization. However, industrial environments differ significantly from conventional digital applications because decisions may influence physical equipment and safety-critical operations. Future research therefore needs to investigate reliable, explainable, robust, and engineering-compatible forms of industrial artificial intelligence.

Digital twins and cyber-physical systems provide additional opportunities to connect physical production systems with computational models. Digital twins can represent machines, production lines, and industrial processes while receiving continuously updated information from physical systems. This capability can support simulation, prediction, optimization, and condition monitoring. Cyber-physical architectures similarly facilitate communication between physical equipment, sensors, software, and control systems.

Their development creates important research opportunities related to real-time synchronization, model accuracy, interoperability, distributed intelligence, and adaptive industrial control. Advanced manufacturing technologies are also changing the structure of industrial production. Additive manufacturing enables the production of complex geometries and customized components, while advanced robotics can perform repetitive, precise, and increasingly adaptive tasks.

Industrial Internet of Things systems provide extensive sensing and connectivity capabilities, allowing organizations to monitor production processes in real time. These technologies can collectively support more flexible manufacturing environments in which production systems respond rapidly to changes in demand, materials, machine conditions, and product requirements.

Against this background, this study examines advanced industrial technologies and their potential applications in future research. The study considers intelligent manufacturing, industrial artificial intelligence, robotics, additive manufacturing, digital twins, cyber-physical systems, advanced sensing, and sustainable digital production.

It seeks to identify the technological capabilities, research opportunities, and implementation challenges associated with these developments. The study further argues that future industrial research should emphasize technological integration, human-machine collaboration, sustainability, interoperability, cybersecurity, and adaptive intelligence rather than examining advanced technologies as isolated innovations.

2. Objectives of the Study

The primary objective of this study is to examine advanced industrial technologies and their potential applications in future research by analyzing developments in artificial intelligence, robotics, digital twins, additive manufacturing, industrial Internet of Things, cyber-physical systems, and intelligent automation. The study seeks to identify how technological integration can contribute to productivity, adaptability, sustainability, resilience, and innovation within future industrial environments.

2.1 Examination of Emerging Industrial Technologies

The first objective is to examine emerging technologies that are transforming industrial production and engineering systems. The study focuses on artificial intelligence, autonomous robotics, additive manufacturing, digital twins, advanced sensing, and cyber-physical systems. It seeks to understand their primary capabilities, industrial applications, and potential contributions to future production environments. Examining these technologies collectively can provide a broader understanding of how digital and physical capabilities may converge to create increasingly intelligent and adaptive industrial systems.

2.2 Identification of Future Research Applications

The second objective is to identify research areas where advanced industrial technologies can generate new engineering and technological applications. Potential areas include autonomous production, predictive maintenance, intelligent quality control, adaptive manufacturing, process optimization, human-machine collaboration, and sustainable production. The objective is to identify opportunities for future investigation and technological development while recognizing the need for interdisciplinary approaches that combine industrial engineering, computing, automation, materials science, and sustainability research.

2.3 Assessment of Implementation Requirements

The third objective is to assess major requirements affecting the successful implementation of advanced industrial technologies. These include data availability, computational infrastructure, interoperability, cybersecurity, workforce skills, technological investment, and system reliability. The objective is to understand the conditions necessary for translating emerging technological capabilities into practical industrial applications. Identifying these requirements can help researchers and industrial organizations develop more reliable, scalable, secure, and economically feasible technology-integration strategies.

3. Review of Literature

3.1 Industry 4.0 and Intelligent Manufacturing

Industry 4.0 research has established a foundation for understanding the integration of digital technologies into manufacturing. Lasi et al. (2014) described Industry 4.0 as a transformation involving interconnected and intelligent production systems. Lee, Bagheri, and Kao (2015) further emphasized cyber-physical architectures for integrating computational intelligence with manufacturing processes.

These studies demonstrate that connectivity, automation, data exchange, and intelligent decision-making are central to advanced industrial development. Future research increasingly focuses on how these capabilities can be integrated into scalable and adaptive production systems.

Frank, Dalenogare, and Ayala (2019) examined Industry 4.0 technologies and identified different patterns of technological implementation in manufacturing organizations. Their findings demonstrate that technologies such as the Internet of Things, cloud computing, analytics, and advanced manufacturing can contribute differently depending on organizational requirements.

This suggests that future industrial research should consider technology combinations rather than isolated technological adoption. Integrated architectures can potentially improve information flow, production flexibility, predictive capabilities, and operational responsiveness across complex manufacturing environments.

3.2 Artificial Intelligence, Robotics, and Autonomous Systems

Artificial intelligence has become increasingly important for industrial applications involving prediction, optimization, quality control, and autonomous decision-making. Tao et al. (2018) highlighted the significance of data-driven smart manufacturing and the increasing role of industrial data in intelligent decision-making. Machine learning can support predictive maintenance, anomaly detection, production optimization, and process monitoring. However, industrial deployment requires attention to data quality, interpretability, robustness, and physical constraints.

These requirements create important future research opportunities in trustworthy and engineering-informed artificial intelligence. Robotics research has similarly expanded from conventional programmable automation toward collaborative and increasingly autonomous systems. Koren et al. (2018) discussed the role of adaptable manufacturing systems in responding to product and production variability. Collaborative robots can work alongside human operators and support flexible production activities.

Future research can investigate adaptive robot learning, safe human-robot interaction, multi-robot coordination, autonomous task allocation, and integration with intelligent production-management platforms. Such research can contribute to industrial systems that combine automation with human expertise rather than treating automation as a replacement for workers.

3.3 Digital Twins and Additive Manufacturing

Digital twins have emerged as an important technology for connecting physical industrial assets with digital models. Kritzinger et al. (2018) reviewed digital twin concepts in manufacturing and emphasized their potential for monitoring, simulation, and system management. Digital twins can support predictive maintenance, production optimization, virtual commissioning, and process analysis. Future research needs to improve synchronization between physical and virtual systems, establish reliable data architectures, and develop scalable models capable of representing increasingly complex industrial environments.

Additive manufacturing has introduced alternative approaches to component production, particularly for customized and geometrically complex products. Gibson, Rosen, and Stucker (2015) described additive manufacturing as a production approach involving layer-by-layer material deposition.

The technology can reduce certain manufacturing constraints and enable complex designs. Future research can investigate intelligent process control, material development, defect prediction, automated quality assessment, and integration with digital design systems. Combining additive manufacturing with artificial intelligence and digital twins could create new opportunities for adaptive production and real-time process optimization.

4. Research Methodology

4.1 Research Design

This study adopted a qualitative descriptive and conceptual research design to examine advanced industrial technologies and their future research applications. The study was based on secondary academic literature covering Industry 4.0, intelligent manufacturing, artificial intelligence, robotics, digital twins, additive manufacturing, industrial Internet of Things, cyber-physical systems, and sustainable production. The design was selected because the research aims to synthesize existing knowledge and identify emerging research directions rather than experimentally evaluate a specific technology.

The conceptual structure was organized around technological intelligence, industrial connectivity, advanced manufacturing, autonomous systems, digital representation, and sustainability. These dimensions were examined in relation to their potential industrial applications and future research opportunities. The methodology emphasized relationships between technologies rather than considering each technology independently. This approach supports a broader understanding of how technological convergence may shape future industrial systems.

4.2 Data Collection

Secondary data were collected from peer-reviewed journal articles, scholarly books, engineering publications, and established academic research addressing advanced industrial technologies. Literature concerning Industry 4.0, industrial artificial intelligence, robotics, digital twins, additive manufacturing, industrial Internet of Things, and cyber-physical production systems was reviewed. Sources were selected according to their relevance to the study objectives and their contribution to understanding technological development and industrial applications.

The literature was categorized according to technological capability and prospective application. Information concerning intelligent prediction, automation, connectivity, simulation, autonomous operation, manufacturing flexibility, sustainability, and human-machine collaboration was examined. Particular attention was given to research identifying technological limitations and emerging opportunities. This categorization provided a structured foundation for evaluating the potential contribution of advanced industrial technologies to future research and industrial innovation.

4.3 Data Analysis

The collected literature was analyzed using thematic analysis. Major themes included intelligent manufacturing, artificial intelligence, autonomous robotics, digital twins, additive manufacturing, industrial connectivity, and sustainable industrial technologies.

Each theme was examined according to its technological function, potential industrial application, and research relevance. The analysis emphasized recurring concepts that indicate emerging directions for industrial technology research.

Comparative synthesis was then applied to identify complementary relationships among technologies. Artificial intelligence was examined for predictive and decision-making capabilities, digital twins for simulation and representation, robotics for physical automation, and additive manufacturing for production flexibility. Industrial Internet of Things technologies were considered as connectivity mechanisms supporting data collection and communication. These findings were synthesized into comparative tables presenting major technological capabilities and future research opportunities.

5. Analysis

5.1 Advanced Industrial Technologies and Their Capabilities

Advanced industrial technologies perform different but complementary functions within modern production environments. Their combined implementation can support intelligent monitoring, autonomous operation, adaptive production, predictive decision-making, and digital process management.

Table 1: Major Advanced Industrial Technologies and Their Applications

Technology	Primary Capability	Industrial Application	Future Potential
Artificial Intelligence	Prediction and decision-making	Process optimization	Autonomous industrial intelligence
Industrial IoT	Connectivity and sensing	Real-time monitoring	Distributed intelligent systems
Digital Twins	Digital representation	Simulation and prediction	Autonomous virtual optimization
Advanced Robotics	Physical automation	Flexible production	Adaptive autonomous manufacturing
Additive Manufacturing	Customized production	Complex component manufacturing	Intelligent adaptive production

The table indicates that advanced industrial technologies contribute through different technological mechanisms. Artificial intelligence supports prediction and decision-making, while Industrial IoT and advanced sensors provide the information required for intelligent analysis. Digital twins connect physical systems with virtual representations, and robotics provides physical automation.

Additive manufacturing introduces production flexibility, while cyber-physical systems integrate computational and physical components. Their combined application can provide greater capabilities than isolated deployment.

5.2 Future Research Applications

The convergence of advanced industrial technologies creates several important research opportunities. Future research can investigate how intelligent technologies can become increasingly adaptive, autonomous, sustainable, secure, and human-centered.

Table 2: Future Research Applications of Advanced Industrial Technologies

Research Area	Relevant Technologies	Expected Research Contribution
Autonomous Manufacturing	AI, Robotics, CPS	Adaptive production decision-making
Predictive Maintenance	AI, IoT, Digital Twins	Failure prediction and downtime reduction
Intelligent Quality Control	AI, Sensors, Vision Systems	Automated defect identification
Adaptive Production	AI, Robotics, IoT	Response to changing production conditions
Digital Process Optimization	Digital Twins, AI	Virtual testing and optimization
Sustainable Manufacturing	AI, IoT, Analytics	Energy and resource optimization
Human-Machine Collaboration	Robotics, AI	Improved collaborative production
Secure Industrial Intelligence	CPS, IoT, Cybersecurity	Reliable connected manufacturing

The table demonstrates that future research opportunities are increasingly interdisciplinary. Predictive maintenance combines data collection, machine learning, and digital representations, while autonomous manufacturing requires artificial intelligence, robotics, and cyber-physical integration. Sustainable

manufacturing can use industrial data and optimization algorithms to reduce resource consumption. Human-machine collaboration represents another important area because future industrial systems are likely to combine automated capabilities with human expertise. Secure industrial intelligence is also essential as increased connectivity expands the potential exposure of production systems to cyber risks.

6. Discussion

Advanced industrial technologies are increasingly converging into interconnected technological ecosystems rather than functioning as independent tools. Artificial intelligence can interpret data generated by industrial sensors, digital twins can represent the behavior of physical systems, and robotics can implement decisions in production environments. This convergence can create adaptive production systems capable of responding to changes in machine condition, production demand, and process requirements. However, technological integration also increases system complexity. Future industrial research should therefore focus on architectures that ensure reliable communication, coordinated decision-making, and robust operation across heterogeneous technologies.

Artificial intelligence and autonomous systems represent particularly significant areas for future industrial research. Predictive models can support maintenance and quality management, while intelligent optimization can identify improved production conditions. Robotics can extend these capabilities into physical operations by performing tasks based on changing production requirements. Nevertheless, industrial autonomy requires careful consideration of safety, explainability, accountability, and human oversight. Future research should therefore investigate human-centered autonomy in which intelligent systems provide adaptive capabilities while allowing engineers and operators to retain appropriate control over critical industrial decisions.

Sustainability should become an integrated objective of future industrial technology development. Advanced technologies can improve energy management, reduce material waste, optimize production schedules, and support predictive maintenance. Digital twins can help evaluate alternative production strategies before physical implementation, while artificial intelligence can identify resource-intensive operating patterns. However, digital transformation itself requires hardware, computing resources, communication infrastructure, and energy. Future research should therefore assess the lifecycle environmental impacts of industrial digitalization and develop technologies that provide measurable sustainability benefits rather than simply increasing technological complexity.

7. Challenges

7.1 Technological Complexity

Advanced industrial systems involve numerous interconnected technologies, including sensors, communication networks, artificial intelligence, robotics, cloud platforms, and digital twins. Integrating these components can create substantial engineering complexity. A failure in one component may affect multiple connected processes. Organizations therefore require robust architectures, standardized interfaces, monitoring mechanisms, and systematic validation procedures to maintain reliable operation.

Technological complexity can also increase maintenance requirements. Intelligent systems require continuous software updates, sensor calibration, model validation, and hardware maintenance.

As technologies become more interconnected, troubleshooting can become more difficult because operational problems may originate from interactions among multiple components.

Future research should therefore develop modular, explainable, and self-monitoring architectures that simplify maintenance while maintaining advanced functionality.

7.2 High Investment and Infrastructure Requirements

Advanced industrial technologies can require significant investment in machinery, sensors, computing infrastructure, communication systems, software, and workforce training. Small and medium-sized organizations may experience particular difficulties adopting complex technologies because of limited financial and technical resources. The economic benefits of technological adoption may also vary according to industry, production scale, and implementation strategy.

Infrastructure limitations can further restrict adoption. Older industrial facilities may lack suitable communication networks, digital interfaces, or data-acquisition capabilities. Retrofitting legacy equipment can require additional investment and technical expertise. Future research should therefore investigate cost-effective modernization strategies, modular technologies, and scalable architectures that allow organizations to gradually transition from conventional production systems toward advanced intelligent environments.

7.3 Interoperability and Data Quality

Different industrial technologies frequently use different data formats, communication protocols, and software architectures. This can make interoperability difficult and prevent seamless information exchange. Lack of interoperability can reduce the benefits of digital twins, Industrial IoT systems, artificial intelligence, and cyber-physical platforms. Standardized communication and data architectures are therefore important for future industrial technology development.

Data quality is equally important because intelligent models depend on accurate and representative information. Industrial datasets may contain missing values, sensor errors, inconsistent measurements, and changes in operating conditions. Poor data can reduce model reliability and produce inappropriate recommendations. Future research should develop robust data-validation mechanisms, adaptive models, and standardized industrial data-management practices.

7.4 Cybersecurity and Workforce Capabilities

Increasing connectivity exposes industrial systems to additional cybersecurity risks. Unauthorized access, data manipulation, malicious software, or disruption of connected equipment can affect production continuity and potentially create physical safety concerns. Cybersecurity should therefore be incorporated into industrial technology design rather than treated as an additional feature after implementation.

Workforce capabilities represent another significant challenge. Advanced industrial systems require professionals who understand engineering, automation, data science, artificial intelligence, and digital technologies. Organizations may face difficulties finding personnel with sufficiently interdisciplinary expertise. Continuous training, interdisciplinary education, and human-machine collaboration can help address these limitations. Future research should investigate workforce models

that allow engineers and intelligent systems to operate effectively within increasingly digital industrial environments.

8. Future Research

Future research should prioritize integrated industrial platforms combining artificial intelligence, digital twins, robotics, Industrial IoT, additive manufacturing, and cyber-physical systems. Research should investigate adaptive architectures capable of learning from changing production conditions while maintaining safety and engineering constraints. Greater attention should also be given to explainable industrial artificial intelligence, autonomous process optimization, collaborative robotics, and real-time digital-twin synchronization.

Further research should examine sustainable digital manufacturing through lifecycle assessment, energy optimization, material efficiency, and circular production. Cybersecurity and interoperability should remain central research priorities as industrial systems become increasingly connected. Research should also explore human-centered industrial autonomy, where engineers and intelligent systems share decision-making responsibilities. These directions can help establish industrial technologies that are not only advanced, but also reliable, scalable, secure, sustainable, and practically deployable.

9. Conclusion

Advanced industrial technologies are creating significant opportunities for transforming future production and engineering systems. Artificial intelligence, robotics, digital twins, additive manufacturing, Industrial IoT, advanced sensing, and cyber-physical systems can collectively support more intelligent and adaptive industrial operations. These technologies provide capabilities for prediction, automation, simulation, monitoring, optimization, and flexible production.

Their greatest value can emerge when they are integrated into coordinated technological architectures rather than implemented as isolated systems. Artificial intelligence can improve industrial prediction and decision-making, while digital twins can provide virtual representations for simulation and optimization. Robotics can extend intelligent decision-making into physical production environments, and additive manufacturing can provide new possibilities for customized and complex component production. Industrial IoT technologies provide the connectivity required to collect and exchange real-time information. The convergence of these technologies therefore creates a foundation for increasingly adaptive industrial ecosystems.

The analysis also demonstrates that future industrial research must address more than technological performance. Cybersecurity, interoperability, data quality, workforce capabilities, economic feasibility, and system reliability are essential to successful implementation. Highly advanced technologies may provide limited value if organizations cannot integrate them with existing infrastructure or maintain them effectively. Future research should therefore emphasize scalable architectures, standardized interfaces, explainable models, and human-centered technological development.

Overall, advanced industrial technologies represent a major research frontier for engineering and industrial innovation. The future direction of industrial technology will likely involve greater autonomy,

connectivity, intelligence, and adaptability. However, technological advancement should remain aligned with sustainability, safety, human expertise, and practical industrial requirements.

Research focusing on trustworthy artificial intelligence, autonomous manufacturing, digital twins, collaborative robotics, sustainable digitalization, and secure cyber-physical systems can contribute to the development of resilient and future-ready industrial environments.

References

1. Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: State of the art and future trends. *International Journal of Production Research*, 56(8), 2941–2962.
2. Kusiak, A. (2018). Smart manufacturing. *International Journal of Production Research*, 56(1–2), 508–517.
3. Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of Industry 4.0: A review. *Engineering*, 3(5), 616–630. <https://doi.org/10.1016/j.eng.2017.05.015>
4. Zheng, P., Wang, H., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., Mubarak, K., Yu, S., & Xu, X. (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. *Frontiers of Mechanical Engineering*, 13, 137–150.
5. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, 6, 1–10.
6. Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18–23.
7. Wang, L., Törngren, M., & Onori, M. (2015). Current status and advancement of cyber-physical systems in manufacturing. *Journal of Manufacturing Systems*, 37, 517–527.
8. Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP*, 17, 9–13.
9. Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital twins and cyber-physical systems toward smart manufacturing and Industry 4.0: Correlation and comparison. *Engineering*, 5(4), 653–661. <https://doi.org/10.1016/j.eng.2019.01.014>
10. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, 15(4), 2405–2415.
11. Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., & Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, 61, 101837.
12. Shao, G., & Helu, M. (2020). Framework for a digital twin in manufacturing. *Manufacturing Letters*, 24, 10–13. <https://doi.org/10.1016/j.mfglet.2020.04.004>
13. da Silva, E. R., Shinohara, A. C., Nielsen, C. P., de Lima, E. P., & Angelis, J. (2020). Operating digital manufacturing in Industry 4.0: The role of advanced manufacturing technologies. *Procedia CIRP*, 93, 174–179. <https://doi.org/10.1016/j.procir.2020.04.063>
14. Haleem, A., & Javaid, M. (2019). Additive manufacturing applications in Industry 4.0: A review. *Journal of Industrial Integration and Management*, 4(4), 1930001. <https://doi.org/10.1142/S2424862219300011>

15. Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Rab, S. (2020). Exploring relationships between Industry 4.0, manufacturing systems, and advanced manufacturing technologies. *Journal of Industrial Integration and Management*.
16. Bhatt, P. M., Malhan, R. K., Shembekar, A. V., Yoon, Y. J., & Gupta, S. K. (2020). Expanding capabilities of additive manufacturing through use of robotics technologies: A survey. *Additive Manufacturing*, 31, 100933. <https://doi.org/10.1016/j.addma.2019.100933>
17. Evjemo, L. D., Gjerstad, T., Grøtli, E. I., & Sziebig, G. (2020). Trends in smart manufacturing: Role of humans and industrial robots in smart factories. *Current Robotics Reports*, 1, 35–41. <https://doi.org/10.1007/s43154-020-00006-5>
18. Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, 31, 127–182.
19. Culot, G., Nassimbeni, G., Orzes, G., & Sartor, M. (2020). Behind the definition of Industry 4.0: Analysis and open questions. *International Journal of Production Economics*, 226, 107617.
20. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*,