14th Annual International Conference on Industrial Engineering and Operations Management Dubai United Arab Emirates (UAE), February 12-14, 2024

Publisher: IEOM Society International, USA DOI: 10.46254/AN14.20240489
Published: February 12, 2024

A Review of Digital Twins in Manufacturing for Improving Sustainability and Process Optimizing

Onu Peter and Charles Mbohwa
Department of Quality and Operations Management
Faculty of Engineering and the Built Environment, University of Johannesburg, P. O. Box 524, Johannesburg, South Africa
onup@uj.ac.za

Abstract

Digital twins are models that emulate the operations, conduct, and execution of physical products, systems, or processes dynamically in or close to real-time. Their efficacy depends on data from various sources, such as sensors and simulations. Digital twins offer several advantages, including predictive maintenance, minimizing downtime, enhancing the lifespan of machinery, and optimizing production processes. This optimization promotes sustainability in manufacturing by curbing energy consumption, improving material efficiency, and reducing environmental waste. Despite these benefits, digital twin technology has not yet reached its full potential in manufacturing. Therefore, this study highlights how proactive maintenance and process optimization can enhance sustainability outcomes. It also emphasizes the importance of efficiently utilizing robust data analytics, data governance, and modelling techniques. To provide a thorough understanding of this ground-breaking technology, the study undertakes a systematic literature review on the associated implications of using digital twins. The review examines potential opportunities, challenges, and ethical considerations that can enhance the efficacy and sustainability of manufacturing processes.

Keywords
Digital twin, Manufacturing, Sustainability, Process optimization, Opportunities and challenges

1. Introduction
1.1 Background
The dynamic landscape of the manufacturing industry is witnessing a profound transformation, propelled by rapid advancements in digital technologies. Among the innovative approaches garnering significant attention, the concept of digital twins is a promising solution (Onu & Mbohwa, 2021). Digital twins, dynamic virtual replicas of physical products, systems, or processes, can simulate, monitor, and optimize real-time or near-real-time behaviors (Lee et al., 2022; Zhou et al., 2020). Simultaneously, the pressing concern for sustainability has permeated various sectors, encompassing transportation, energy, aerospace, and manufacturing (Lee et al., 2022; Onu & Mbohwa, 2021). The urgency to curtail environmental impact, minimize energy consumption, optimize material efficiency, and mitigate waste generation has never been more pronounced. Digital twins emerge as a beacon of hope in this context, facilitating proactive maintenance and process optimization to bolster sustainability efforts (Rojek et al., 2021; Tao et al., 2018). Although the notion of digital twin technology was coined by Professor Michael Grieves at the University of Michigan in 2002, its true potential was unlocked with the advent of Internet of Things (IoT) technology, rendering it more cost-effective and accessible across diverse industries (Kuehn, 2018; Peter et al., 2023). As a result, businesses worldwide are exploring the manifold applications of digital twins, seeking to enhance operational quality and effectiveness (Tao et al., 2018).

In the context of manufacturing, we witness inspiring examples of digital twin technology. Unilever PLC, a global consumer goods giant, harnesses digital twins to streamline production processes, optimizing efficiency and flexibility (Alabi & Telukdarie, 2021). Chevron, a leading energy company, employs digital twins to gain real-time insights into equipment and physical assets, reducing maintenance issues and optimizing production output (Feder, 2020). Automotive manufacturers also embrace this technology, leveraging digital twins to fathom the intricate interactions between entire systems, not merely individual devices, thereby unlocking new frontiers of smart manufacturing. Beyond the production floor, digital twins play a vital role in the supply chain and logistics/distribution (E.g. Amazon and Walmart), where they track and analyze key performance indicators, such as packaging, to improve overall efficiency (Rosenbloom, 2016).

1.2 Research Aim and Objective

The primary aim of this paper is to explore how digital twins, synergized with advanced data analytics systems, can empower sustainability within the realm of manufacturing processes. Aligned with this objective, we have formulated several incisive research questions, shedding light on the contributions of digital twins to sustainability enhancement, the pivotal challenges and opportunities in their seamless integration, and the ethical implications and guidelines for responsible implementation. By addressing these research questions, our study endeavors to enrich the existing knowledge base and offer actionable insights for industry practitioners and policymakers alike, seeking to harness the power of digital twin technology responsibly and effectively.

RQ1: How can digital twins contribute to improving sustainability in manufacturing processes?
RQ2: What are the key challenges and opportunities associated with implementing digital twins in manufacturing?
RQ3: What are the ethical implications and guidelines for the responsible utilization of digital twins in manufacturing?

2. Research Approach

To explore the role of digital twins in improving sustainability in manufacturing processes, a systematic literature review (SLR) was conducted. The SLR's structure was formulated based on previous studies (Ikumapayi, Akinlabi, & Onu, 2020; Onu et al., 2023b). This review aimed to identify key challenges and opportunities related to implementing digital twins and gather information on ethical considerations and guidelines for their responsible utilization. Overall, the study sought to answer research questions related to the use of digital twins in manufacturing.

2.1 Search Strategy

To improve the likelihood of finding relevant research papers, a search string with Boolean operators was utilized: ("Digital Twins" OR "Digital Twin" OR "Digital Simulation" OR "Simulation Model") AND ("Manufacturing Processes" OR "Production Processes" OR "Industrial Processes") AND ("Sustainability" OR "Sustainable Practices" OR "Environmental Impact" OR "Eco-friendly") AND ("Optimization" OR "Efficiency" OR "Resource Management" OR "Process Improvement"). The search was conducted on four scientific journal databases - IEEE Xplore, ScienceDirect, ACM Digital Library, and Google Scholar - to gather as much relevant information as possible.

2.2 Paper Selection and Analysis

The study employed inclusion and exclusion criteria to identify important research papers for further analysis, as illustrated in Figure 1. A specific search string was used to obtain papers on ScienceDirect, Scopus, and Web of Science, which were then scanned to remove duplicates and analyzed for relevance. Many articles were discarded as they were unrelated to the topic. The remaining papers were categorized, and only a few were excluded at a later stage.

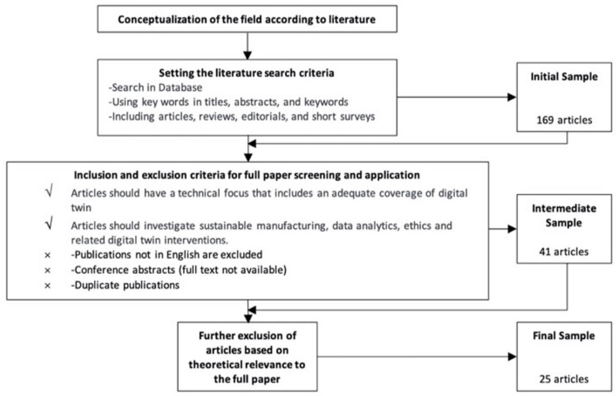

Figure 1. Paper selection flow diagram

The key papers were subjected to qualitative analysis and categorization based on their content, with further discussion in section 4. These literature (Qi et al., 2018b; Rojek et al., 2021b; Tao et al., 2018b; Zhou et al., 2020b) were utilized to support the potential of digital twins in improving sustainability in manufacturing. Furthermore, the analysis provided valuable insights into emerging ethical considerations.

3. Result

Given the emerging nature of digital twins as a technological innovation in the manufacturing sector, the search was restricted to the years between 2014 and 2023. A search of the Scopus and Web of Science databases yielded 169 papers, of which 128 were screened based on their relevance to DT for Improving Sustainability by Simulating and Optimizing Manufacturing Processes (Figure 1). The final sample of 41 articles was further narrowed down to a focus on 25 selected studies for the systematic review. Notably, the majority (64%) of the papers identified were published after 2020, indicating a growing interest in this area of research, particularly since 2019 (Figure 2). Among the final sample of articles, 3 were book chapters, 4 were conference papers, and 18 were journal articles. An in-depth analysis of the findings highlights the growing recognition of this technology as a critical driving force for smart manufacturing, as discussed in detail in the following section.

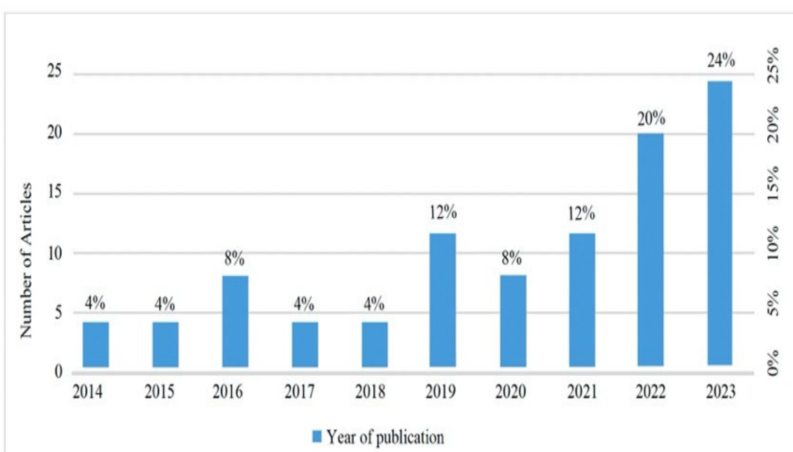

Figure 2. Distribution of article – year

4. Discussions of Findings

4.1 Sustainable Manufacturing and the implication of Digital twin

The manufacturing industry faces various sustainability challenges that require proactive measures to implement effective strategies and leverage digital twin technology to address them. One of the primary sustainability challenges is the reliance on energy-intensive traditional manufacturing processes, resulting in significant carbon emissions and increased reliance on non-renewable energy sources (He & Bai, 2021).

Another challenge is improving material efficiency, for which the manufacturing industries need to explore recycling and circular economy practices to ensure sustainable production and responsible resource management (Tao & Zhang, 2017). Through real-time or near-real-time simulations, digital twins can enable manufacturers to identify inefficient processes and optimize them to reduce energy consumption (Xiang et al., 2019).

Through data-driven analysis, manufacturers can pinpoint energy-intensive areas and implement targeted improvements such as optimizing equipment usage, adjusting production schedules, or identifying energy-saving opportunities (Qi et al., 2018). Additionally, by virtually testing different designs, materials, and production parameters, manufacturers can identify the most efficient and sustainable configurations, further optimizing material usage throughout the product lifecycle (Ma et al., 2022).

Furthermore, digital twins support waste management efforts by enabling manufacturers to monitor and analyze waste generation and disposal data (Bankhead et al., 2018; Chen & Huang, 2020). Consequently, by integrating data from various sources, including sensors and production systems, digital twins can provide a comprehensive view of waste generation points and patterns. This information can be used to implement effective waste reduction strategies and optimize recycling processes, ensuring compliance with environmental regulations.

4.2 Enabling Proactive Maintenance and Process Optimization

Digital twins play a crucial role in enabling proactive maintenance and optimizing manufacturing processes by providing advanced capabilities for monitoring, analyzing, and simulating the behavior of physical assets. Such capabilities facilitate predictive maintenance strategies and drive process improvements (Hosamo et al., 2022). Unlike traditional maintenance approaches, which often rely on scheduled or reactive maintenance that can lead to unnecessary downtime or costly repairs, digital twins integrate data from sensors embedded in physical assets to detect anomalies and deviations from normal operating parameters, thus enabling gainful operational performance.

Researchers are exploring advanced analytics algorithms to predict maintenance needs so manufacturers can schedule maintenance activities precisely when needed, reducing unplanned downtime and maximizing equipment availability (Feder, 2020; Hehn & Mendez, 2022; Huang et al., 2020). Furthermore, manufacturers can simulate the impact of these changes on performance metrics, energy consumption, material efficiency, and other key indicators through the virtual capabilities and integration of digital twins. Digital twins have the potential to enable manufacturers to identify inefficiencies, bottlenecks, or suboptimal configurations within their processes and make data-driven decisions to optimize workflows, improve resource allocation, and enhance overall process efficiency (Lu et al., 2021; Soori et al., 2023). Such optimization ultimately contributes to reduced energy consumption, increased production output, minimized waste generation, and improved sustainability outcomes (He & Bai, 2021; Tao et al., 2018).

Several case studies illustrate the successful implementation of digital twins in proactive maintenance and process optimization. For example, in one study (Khoury & Figueiredo, 2020), a manufacturing company specializing in oil and gas products utilized digital twins to monitor the health and performance of their equipment "The Digital Twin of Oil and Gas Pipeline System". By integrating sensor data and advanced analytics, the digital twin system detected early indications of component wear, enabling the company to target its maintenance activities more effectively. This approach resulted in a significant decrease in equipment downtime and maintenance costs. In another study (Lee et al., 2022), a semiconductor manufacturing facility employed digital twins to optimize its production line. By simulating different process configurations, the digital twin system identified the most energy-efficient operating parameters and optimized the allocation of manufacturing resources. As a result, significant energy savings were achieved, and overall process performance improved. These case studies demonstrate the transformative impact of digital twins on proactive maintenance and process optimization, enabling informed decision-making, enhanced equipment reliability, minimized downtime, and sustainable process improvements.

4.3 Data Analytics, Modeling Techniques, and Data Governance

Establishing effective data governance ensures the integrity, quality, security, and accessibility of data throughout its lifecycle to enable its use for making data-driven decisions and improving the sustainability and efficiency of manufacturing operations and products. Data governance involves establishing clear data ownership, defining data standards and protocols, ensuring data privacy and security, and implementing data integration and interoperability frameworks. Advanced analytics methods such as machine learning, statistical analysis, and data mining can identify trends, anomalies, and optimization opportunities beneficial for manufacturers (Ivanov & Dolgui, 2021; Wang et al., 2021). Additionally, modeling techniques are crucial to enhance the accuracy and realism of digital twin simulations. Models within digital twins replicate physical systems, and the reliability and effectiveness of the digital twin system depend on their accuracy. The choice of modeling technique varies depending on the simulated system's complexity and characteristics. Techniques such as physics-based modeling, system dynamics modeling, and agent-based modeling capture the dynamics and interactions within manufacturing processes (Tao et al., 2022). Robust data governance practices, analytics, and modeling techniques are essential to successful digital twin implementations. According to the literature (Zhou et al., 2020) manufacturers can fully harness digital twins' potential for simulating and improving manufacturing processes by ensuring data quality and security, applying advanced analytics to extract insights, and refining models for accurate simulations.

4.4 Potential, Opportunities, and Challenges

Integrating digital twins with emerging technologies such as the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) is a significant opportunity for the technology to thrive (Hehn & Mendez, 2022). This integration opens avenues for dynamic optimization, adaptive control, and intelligent manufacturing systems (Ikumapayi, Akinlabi, Onu, et al., 2020). Manufacturers can optimize production parameters, identify bottlenecks, and predict maintenance needs, ultimately improving productivity, efficiency, and sustainability (Onu et al., 2023a).

Digital twin technology also faces specific challenges and limitations in manufacturing. One of the primary challenges is the complexity of data integration and interoperability (Attaran & Celik, 2023). Manufacturing environments often comprise a variety of systems, equipment, and software platforms, leading to heterogeneous data sources. Establishing seamless integration and interoperability among these diverse sources can be challenging and requires standardized protocols and interfaces. Another challenge is the requirement for robust and reliable connectivity and data infrastructure. Digital twins heavily rely on continuous data exchange between physical assets, sensors, and the digital realm. Ensuring high-speed, reliable, and secure connectivity across the manufacturing environment is essential to support real-time or near-real-time data synchronization and analysis (Botín-Sanabria et al., 2022).

Moreover, the cost of implementing digital twin systems can be a limitation for some manufacturers, especially smaller enterprises. Deploying sensors, data storage, computing resources, and analytics capabilities may require substantial investments. Therefore, cost-effective solutions, scalable architectures, and business models that cater to manufacturing contexts must be developed.

4.5 Implication of Digital Twin Utilization

Integrating digital twins in manufacturing presents ethical considerations that necessitate responsible and ethical adoption of this transformative technology (Braun, 2022). These ethical implications are critical for fostering a sustainable and trustworthy implementation of digital twin systems in manufacturing operations.

- Data Privacy and Security
  Digital twins rely on extensive data collection, including sensor data, production records, and potentially personal information. To safeguard individuals' privacy and prevent unauthorized access/misuse of sensitive data, robust data protection measures, such as encryption and access controls, must be established by manufacturers.
- Bias and Fairness
  The potential for algorithmic bias and discrimination requires careful attention. Digital twins employ data analytics and machine learning algorithms for predictions and process optimization. Ensuring the representativeness and impartiality of training data is essential, and continuous monitoring and assessment of algorithms are needed to identify and address any biases.
- Transparency and Explainability

Transparency and explainability are vital aspects of building trust in digital twin systems. As the technology becomes more complex and autonomous, clear explanations of decision-making processes and recommendations are crucial. Manufacturers must strive to make the inner workings of digital twins understandable and accessible to stakeholders, fostering informed decision-making and trust.

- Intellectual Property Rights
  Responsible utilization of digital twin technology also requires compliance with relevant legal and regulatory considerations. Awareness of laws governing data privacy, intellectual property rights, and cybersecurity is essential to protect rights, respect intellectual property, and maintain the integrity and security of digital twin systems.

Beyond technical aspects, ethical considerations extend to social and environmental impacts. Manufacturers must assess the broader implications of digital twin implementations on employees, communities, and the environment (Job Displacement and Worker Well-being). Addressing potential job displacement, promoting social equity, and considering environmental sustainability (Environmental Impact) are key aspects of responsible adoption (Shengli, 2021).

5. Conclusions

In summary, this study has explored the potential of digital twins in improving sustainability within manufacturing processes with inference to the other nascent concepts covered in literature (Onu, Mbohwa, et al., 2024b, 2024a; Onu, Pradhan, et al., 2024a, 2024c, 2024b). Several key findings and contributions have been identified through an analysis of the concept, applications, and challenges.

Digital twins offer significant advantages for sustainability in manufacturing. They enable proactive maintenance strategies, optimizing equipment performance and reducing downtime. By leveraging real-time data and advanced analytics, manufacturers can identify inefficiencies, minimize energy consumption, maximize material efficiency, and mitigate environmental waste. Digital twins provide a holistic view of the manufacturing ecosystem, facilitating data-driven decision-making and fostering continuous process improvements.

The importance of robust data governance practices, data analytics, and modeling techniques has been emphasized. Robust data governance ensures data integrity, security, and privacy, while data analytics techniques extract valuable insights for process optimization. Modeling techniques enhance the accuracy and realism of digital twin simulations, enabling manufacturers to make more informed decisions.

Digital twins also raise ethical considerations like privacy, data security, algorithmic bias, and transparency. Responsible and ethical utilization of digital twin technology requires compliance with relevant laws and regulations, addressing biases, and ensuring transparency and explainability.

There are several future directions and recommendations for further research in digital twin utilization. First, there is a need for standardized frameworks and protocols to enable seamless data integration and interoperability across diverse manufacturing systems.

Furthermore, research can explore the integration of digital twins with emerging technologies such as the Internet of Things, cloud computing, and artificial intelligence to unlock new opportunities for dynamic optimization and intelligent manufacturing systems.

In conclusion, digital twins have the potential to revolutionize manufacturing processes by driving sustainability, enhancing efficiency, and enabling data-driven decision-making. Expanding the applications of digital twins to encompass supply chains and interconnect stakeholders presents avenues for enhancing sustainability and efficiency on a larger scale. Future research should focus on developing scalable architectures and cost-effective solutions to make digital twins accessible to various manufacturers, including smaller enterprises.

References

Alabi, M., & Telukdarie, A., BLOCKCHAIN TECHNOLOGY AND DIGITAL SUPPLY CHAINS: TOWARDS REVOLUTIONIZING THE INDUSTRY OF THE FUTURE. *2021 ASEM Virtual International Annual Conference "Engineering Management and The New Normal."* 2021

Attaran, M., & Celik, B. G., Digital Twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, 2023, https://doi.org/10.1016/j.dajour.2023.100165

Bankhead, M., Fritsch, K., MacDonald-Taylor, J., Trivedi, D., Ecclestone, G., & O'Brien, W. J., Digital twin of nuclear waste management facilities. *8Th International Workshop on Reliable Engineering Computing, "Computing with Confidence."* 2018

Botín-Sanabria, D. M., Mihaita, S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. de J., Digital Twin Technology Challenges and Applications: A Comprehensive Review. In *Remote Sensing*, 2022, https://doi.org/10.3390/rs14061335

Braun, M., Ethics of digital twins: four challenges. *Journal of Medical Ethics*, 2022, https://doi.org/10.1136/medethics-2021-107675

Chen, Z., & Huang, L., Digital Twin in Circular Economy: Remanufacturing in Construction. *IOP Conference Series: Earth and Environmental Science*, 2020, https://doi.org/10.1088/1755-1315/588/3/032014

Feder, J., Upstream Digitalization Is Proving Itself in the Real World. *Journal of Petroleum Technology*, 2020, https://doi.org/10.2118/0420-0026-jpt

He, B., & Bai, K. J., Digital twin-based sustainable intelligent manufacturing: a review. *Advances in Manufacturing*, 2021, https://doi.org/10.1007/s40436-020-00302-5

Hehn, J., & Mendez, D. *Combining Design Thinking and Software Requirements Engineering to Create Human-Centered Software-Intensive Systems*, 2022, https://doi.org/10.1007/978-3-030-90594-1_2

Hosamo, H. H., Svennevig, P. R., Svidt, K., Han, D., & Nielsen, H. K., A Digital Twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. *Energy and Buildings*, 2022, https://doi.org/10.1016/j.enbuild.2022.111988

Huang, J., Gheorghe, A., Handley, H., Pazos, P., Pinto, A., Kovacic, S., Collins, A., Keating, C., Sousa-Poza, A., Rabadi, G., Unal, R., Cotter, T., Landaeta, R., & Daniels, C., Towards digital engineering: The advent of digital systems engineering. *International Journal of System of Systems Engineering*, 2020, https://doi.org/10.1504/ijsse.2020.109737

Ikumapayi, O. M., Akinlabi, E. T., & Onu, P., Emerging trend in forging operation. *Lecture Notes in Mechanical Engineering*, 2020, https://doi.org/10.1007/978-981-15-5753-8_15

Ikumapayi, O. M., Akinlabi, E. T., Onu, P., & Abolusoro, O. P., Rolling operation in metal forming: Process and principles – A brief study. *Materials Today: Proceedings*, 2020, https://doi.org/10.1016/j.matpr.2020.02.343

Ivanov, D., & Dolgui, A., A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning and Control*, 2021, https://doi.org/10.1080/09537287.2020.1768450

Khoury, G., & Figueiredo, M., Improved decision-making, safety and reliability with visual asset performance management. *Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference 2020, ADIP 2020*. https://doi.org/10.2118/203167-ms

Kuehn, W., Digital twins for decision making in complex production and logistic enterprises. *International Journal of Design and Nature and Ecodynamics*, 2018, https://doi.org/10.2495/DNE-V13-N3-260-271

Lee, D., Kim, C. K., Yang, J., Cho, K. Y., Choi, J., Noh, S. Do, & Nam, S. (2022). Digital Twin-Based Analysis and Optimization for Design and Planning of Production Lines. *Machines*. https://doi.org/10.3390/machines10121147

Lu, Y., Liu, Z., & Min, Q., A digital twin-enabled value stream mapping approach for production process reengineering in SMEs. *International Journal of Computer Integrated Manufacturing*, 2021, https://doi.org/10.1080/0951192X.2021.1872099

Ma, S., Ding, W., Liu, Y., Ren, S., & Yang, H., Digital twin and big data-driven sustainable smart manufacturing based on information management systems for energy-intensive industries. *Applied Energy*, 2022, https://doi.org/10.1016/j.apenergy.2022.119986

Onu, P., & Mbohwa, C., Industry 4.0 opportunities in manufacturing SMEs: Sustainability outlook. *Materials Today: Proceedings*, 2021, https://doi.org/10.1016/j.matpr.2020.12.095

Onu, P., Mbohwa, C., & Pradhan, A., *Advancements, Challenges, and Recommendations for Resilient and Decarbonized Future Smart Grids*, 2024a, https://doi.org/10.1109/ICECET58911.2023.10389344

Onu, P., Mbohwa, C., & Pradhan, A., *Machine Learning: A Comprehensive Exploration of Fault Detection and Diagnosis in Smart Grids*, 2024b, https://doi.org/10.1109/ICECET58911.2023.10389596

Onu, P., Pradhan, A., & Mbohwa, C., Potential to use metaverse for future teaching and learning. *Education and Information Technologies*, 2023a, https://doi.org/10.1007/s10639-023-12167-9

Onu, P., Pradhan, A., & Mbohwa, C., The potential of industry 4.0 for renewable energy and materials development – The case of multinational energy companies. *Heliyon*, 2023b, https://doi.org/10.1016/j.heliyon.2023.e20547

Onu, P., Pradhan, A., & Mbohwa, C., *EcoMechatronics : Advancing Sustainable Production Through Mechatronic Systems*, 2024a, https://doi.org/10.1109/ieem58616.2023.10406694

Onu, P., Pradhan, A., & Mbohwa, C., *Industry 4. 0 and Beyond: Enabling Digital Transformation and Sustainable Growth in Industry X.0*, 2024b, https://doi.org/10.1109/ieem58616.2023.10406334

Onu, P., Pradhan, A., & Mbohwa, C., *Sustainable Production Through Competency Development in Smart Manufacturing*, 2024c, https://doi.org/10.1109/ieem58616.2023.10406990

Peter, O., Pradhan, A., & Mbohwa, C., Industrial internet of things (IIoT): opportunities, challenges, and requirements in manufacturing businesses in emerging economies. *Procedia Computer Science*, *217*, 856–865, 2023, https://doi.org/10.1016/j.procs.2022.12.282

Qi, Q., Tao, F., Zuo, Y., & Zhao, D., Digital Twin Service towards Smart Manufacturing. *Procedia CIRP*, 2018, https://doi.org/10.1016/j.procir.2018.03.103

Rojek, I., Mikołajewski, D., & Dostatni, E., Digital twins in product lifecycle for sustainability in manufacturing and maintenance. *Applied Sciences (Switzerland)*, 2021, https://doi.org/10.3390/app11010031

Rosenbloom, M., *Amazon is eating the world, so Walmart just bought a Bezos whisperer*. LinkedIn, 2016

Shengli, W., Is Human Digital Twin possible? *Computer Methods and Programs in Biomedicine Update*, 2021, https://doi.org/10.1016/j.cmpbup.2021.100014

Soori, M., Arezoo, B., & Dastres, R., Digital twin for smart manufacturing, A review. *Sustainable Manufacturing and Service Economics*, 2023, https://doi.org/10.1016/j.smse.2023.100017

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F., Digital twin-driven product design, manufacturing and service with big data. *International Journal of Advanced Manufacturing Technology*, 2018, https://doi.org/10.1007/s00170-017-0233-1

Tao, F., Xiao, B., Qi, Q., Cheng, J., & Ji, P., Digital twin modeling. In *Journal of Manufacturing Systems*, 2022, https://doi.org/10.1016/j.jmsy.2022.06.015

Tao, F., & Zhang, M., Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. *IEEE Access*, 2017, https://doi.org/10.1109/ACCESS.2017.2756069

Wang, T., Li, J., Deng, Y., Wang, C., Snoussi, H., & Tao, F., Digital twin for human-machine interaction with convolutional neural network. *International Journal of Computer Integrated Manufacturing*, 2021, https://doi.org/10.1080/0951192X.2021.1925966

Xiang, F., Zhang, Z., Zuo, Y., & Tao, F., Digital twin driven green material optimal-selection towards sustainable manufacturing. *Procedia CIRP*, 2019, https://doi.org/10.1016/j.procir.2019.04.015

Zhou, G., Zhang, C., Li, Z., Ding, K., & Wang, C., Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing. *International Journal of Production Research*, 2020, https://doi.org/10.1080/00207543.2019.1607978

Biographies

Peter Onu is a professional who is deeply interested in utilizing the Fourth Industrial Revolution to enhance productivity, improve quality assurance and manage risks associated with operations. His primary area of focus is on sustainable digitalization.

Charles Mbohwa is Distinguisehed Professor of Sustainable Engineering and a visiting professor at the University of Johannesburg, South Africa.