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Artículo de Investigación

Digital Twins in Industry 5.0 – a systematic literatura review

Gemelos Digitales en la Industria 5.0 – una Revisión Sistemática de Literatura

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Abstract:
Introduction: Industry 5.0 integrates advanced technologies with human-centric approaches to enhance manufacturing safety, human-robot collaboration, and efficiency. Digital twins, virtual replicas of physical systems, are central to this initiative to improve workplace safety and operational efficiency. **Methodology:** This SLR used a comprehensive search strategy across five digital libraries: IEEE Explore, Scopus, Taylor & Francis Online, ACM Digital Library, and Web of Science. **Results:** The findings highlight digital twins' contributions to worker safety through real-time monitoring, intelligent sensing, and proactive risk management. Human-robot collaboration is achieved through real-time data integration. Digital twins also improve manufacturing efficiency by enabling smarter, adaptive production systems. **Discussion:** Despite their potential, challenges such as data quality, computational complexity, cybersecurity, human factors, and socio-economic impacts need addressing. **Conclusions:** This SLR underscores the role of digital twins in advancing Industry 5.0, promoting safer, more efficient, and human-centric industrial environments.

Keywords: Digital Twins; Industry 5.0; Human-Robot Collaboration; Worker Safety; Manufacturing Efficiency; Artificial Intelligence; Augmented Reality; Human-Centric Systems.

Resumen:
Introducción: La Industria 5.0 integra tecnologías avanzadas con enfoques centrados en el ser humano para mejorar la seguridad en la fabricación, la colaboración humano-robot y la eficiencia. Los gemelos digitales, réplicas virtuales de sistemas físicos, son centrales en esta iniciativa para mejorar la seguridad laboral y la eficiencia operativa. **Metodología:** Esta SLR utilizó una estrategia de búsqueda exhaustiva en cinco bibliotecas digitales: *IEEE Explore*, *Scopus*, *Taylor & Francis Online*, *ACM Digital Library* y *Web of Science*. **Resultados:** Los hallazgos destacan las contribuciones de los gemelos digitales a la seguridad de los trabajadores mediante el monitoreo en tiempo real, la detección inteligente y la gestión proactiva de riesgos. La colaboración humano-robot se logra a través de la integración de datos en tiempo real. Los gemelos digitales también mejoran la eficiencia en la fabricación al permitir sistemas de producción más inteligentes y adaptativos. **Discusión:** A pesar de su potencial, se deben abordar desafíos como la calidad de los datos, la complejidad computacional, la ciberseguridad, los factores humanos y los impactos socioeconómicos. **Conclusiones:** Esta SLR subraya el papel de los gemelos digitales en el avance de la Industria 5.0, promoviendo entornos industriales más seguros, eficientes y centrados en el ser humano.

Palabras clave: Gemelos Digitales; Industria 5.0; Colaboración Humano-Robot; Seguridad de los Trabajadores; Eficiencia en la Fabricación; Inteligencia Artificial; Realidad Aumentada; Sistemas Centrados en el Ser Humano.

1. Introduction

In today's global economy, we often depend on traditional economic models that are progressively being updated or replaced by new approaches powered by artificial intelligence and modern technologies. We are currently at a crossroads between two significant transformations: the Fourth Industrial Revolution, or Industry 4.0, which presents a technological vision for the future economy, and the Fifth Industrial Revolution, or Industry 5.0, which highlights "coopetition" and personalization. This new phase recognizes the increasing value of human capital amidst ongoing technological advancements (Ungureanu, 2020). A report by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in June 2021 emphasized that technological progress, including that which pertains to industrial evolution, should adhere to ethical guidelines and positively impact society (Lewis et al., 2021). Industry 5.0 reflects this ethos by melding technological innovation with a pronounced focus on human welfare, underpinning its approach with human-centricity, sustainability, and resilience to foster more inclusive, sustainable, and efficient industrial practices (Xu et al., 2021).

Central to this initiative are digital twins-virtual replicas of physical systems that amalgamate real-time data with human factors to significantly enhance workplace safety and operational efficiency. This Systematic Literature Review (SLR) evaluates the impact of digital twin technologies within this framework, focusing on their role in human-centric manufacturing and their integration with advanced technologies such as Artificial Intelligence (AI), Augmented Reality (AR), Human-Cyber Physical Systems (HCPS), and the Artificial Intelligence of Things (AIoT).

Worker safety is a key focus within Industry 5.0, where digital twins play a crucial role. For example, Wang et al. (2024) developed a deep learning-enhanced digital twin framework for safer human-robot collaboration, using semi-supervised models to improve detection and classification of interactions. This system detects unsafe conditions and autonomously mitigates potential hazards, showcasing robustness in challenging environments. Integrating cutting-edge technologies, Li et al. (2023) and Grimmeisen et al. (2023) demonstrate how

Augmented Reality (AR), and deep reinforcement learning (DRL) can be synergized with digital twins to foster a safer manufacturing workspace. Yin et al. (2023) highlights the integration of AR with digital twins to provide intuitive visualizations and real-time feedback, allowing operators to interact seamlessly with digital twins. This integration improves task planning, optimization, and execution, significantly enhancing cognitive functions and decision-making capabilities of operators.

Human-robot collaboration has also emerged as a crucial factor in enhancing manufacturing processes within Industry 5.0. Digital twin technologies facilitate seamless interactions between humans and robots by providing real-time data integration, simulation, and optimization capabilities. For instance, Xie et al. (2024) discuss the development of an XR-based human-robot collaboration assembly system grounded in the industrial metaverse. This system integrates Extended Reality (XR), blockchain, and end-edge-cloud collaborative network architecture to enhance real-time physical operations through pre-planning, task optimization, and strategic decision-making, facilitating efficient human-robot interaction.

This review also explores how digital twins, when integrated with AI and IoT technologies, optimize manufacturing processes and responsiveness. The implementation of smart factory concepts showcases the efficiency-enhancing potential of digital twins. Peter et al. (2021) describe a step-by-step guide for creating a smart factory using digital twin technology. By integrating key Industry 4.0 technologies such as IoT, cloud computing, and big data analytics, the smart factory enables real-time communication and data exchange between machinery and systems. This results in optimized production processes, predictive maintenance, and reduced operational costs.

This SLR is the first to explore the intersection of digital twins and Industry 5.0 from a human-centric perspective, making a significant and timely contribution to the field. The emphasis on human-centric approaches aligns with the evolving paradigm of Industry 5.0, which prioritizes human well-being, safety, and collaboration alongside technological advancements. Understanding the human factors in digital twin applications is essential because it directly impacts worker safety, ergonomics, and productivity. By systematically reviewing the literature on this topic, we aim to identify best practices, potential challenges, and gaps in current research, providing a comprehensive foundation for future studies and practical implementations. This SLR highlights the transformative potential of digital twins in creating safer, more efficient, and human-friendly manufacturing environments, thus paving the way for more inclusive and sustainable industrial practices.

This systematic literature review is guided by several key objectives and research questions designed to explore the depth and breadth of digital twin technologies within Industry 5.0. Specifically, this SLR seeks to address the following:

1. What are the impacts of digital twin technologies on worker safety within human-centric manufacturing environments?
2. How do digital twin technologies facilitate human-robot collaboration in Industry 5.0, and what are the outcomes of these interactions?
3. In what ways do digital twins optimize manufacturing processes, and what specific advancements have they introduced in terms of process efficiency and resource management?

By answering these questions, this systematic literature review not only clarifies the current capabilities and contributions of digital twin technologies in Industry 5.0 but also underscores their significance for various stakeholders. Policymakers, industrial managers, and technology developers can utilize these insights to drive more effective and sustainable implementations of digital twins, particularly in enhancing workplace safety and operational efficiencies. Thus, this review serves as a foundational reference that catalyzes further investigation and development within the academic and industrial communities, promoting a more inclusive and sustainable approach to manufacturing in the era of Industry 5.0.

2. Methods

This SLR used a comprehensive search strategy across five digital libraries: *IEEE Explore*, *Scopus*, *Taylor & Francis Online*, *ACM Digital Library*, and *Web of Science*. The search included boolean search strings related to the terms digital twins, Industry 5.0, manufacturing, AI, and human-centric systems, focusing on papers published over the past 4 years. Selected papers were evaluated for their relevance and contribution to understanding digital twins in Industry 5.0.

2.1. Selection Criteria and Search Strategy

The Boolean search strings were designed to capture the intersection of digital twin technology with human safety, human-machine collaboration, and manufacturing efficiency within the context of Industry 5.0:

- S1: "Digital Twin AND Worker Safety AND Industry 5.0"
- S2: "Digital Twin AND Human-Machine Collaboration AND Industry 5.0"
- S3: "Digital Twin AND Manufacturing Efficiency AND Industry 5.0"

The combined query search string (R), where topic search (TS) includes title, abstract, and keywords, is: R = TS=(S1) AND TS=(S2) AND TS=(S3)

2.2. Screening and Data Extraction

Titles, abstracts, and full texts of available papers were systematically screened to select studies that aligned with the research questions of this SLR. The initial screening phase involved removing duplicates across the search databases and then a reading of abstracts to filter out non-relevant articles. This was followed by a thorough reading of the full texts to identify the most relevant studies for in-depth synthesis and analysis.

2.3. Synthesis and Analysis

The goal of this SLR was to integrate findings from the selected articles to identify overarching themes, discern trends, and extract significant insights on the role of digital twins within Industry 5.0. The synthesis focused on digital twins' applications and benefits, as well as their implications for future industrial practices and research, particularly in terms of enhancing human safety, human-machine collaboration, and manufacturing efficiency.

3. Results

The systematic literature review process followed the PRISMA guides with several stages of filtering to identify the most relevant articles for analysis. The inclusion and exclusion criteria applied at each stage are detailed in the flow diagram below as well as the number of resulting articles.

Figure 1.

Flow diagram of SLR search process showing the inclusion and exclusion criteria of each filter and the number of articles it´s applied to

Search Queries (Title, Abstract, Keywords)
S1: "Digital Twin AND Worker Safety AND Industry 5.0"
S2: "Digital Twin AND Human-Machine Collaboration AND Industry 5.0"
S3: "Digital Twin AND Manufacturing AND Industry 5.0"

↓

Database
IEEE Explore
Scopus
Web of Science
Taylor and Francis
ACM Digital Library

↓

Filter 1: Exclude – Duplicates	1820

↓

Filter 2: Exclude Non-Relevant Abstracts	230

↓

Filter 3: Exclude Articles Not Available in Full-Text	125

↓

Filter 4: Full Text Analysis, Include Relevant Articles	95

↓

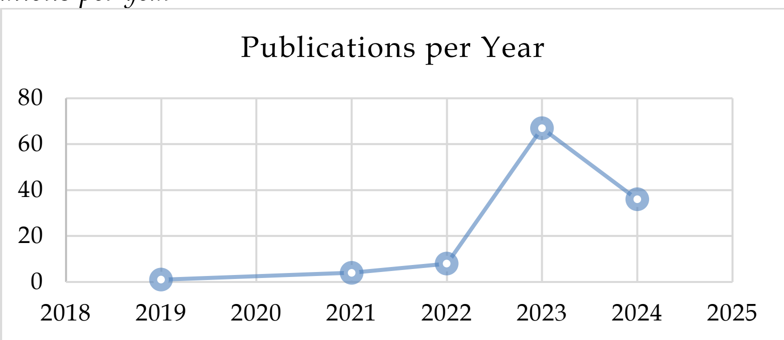
54 Articles for Analysis

Source: Own elaboration.

As seen in Figure 2, the distribution of publications per year demonstrates the growing interest in digital twin technologies and their applications across various industrial domains. The trend highlights significant research activity in recent years, reflecting the evolving nature of Industry 5.0

Figure 2.

Number of Publications per year



Source: Own elaboration.

As seen in Table 1, the studies included in this review cover three major themes: worker safety, human-robot collaboration, and industrial efficiency. The table below categorizes the references according to the subcategory of these themes and the type of study conducted.

Table 1.

Topic and type of study of each study included in this SLR

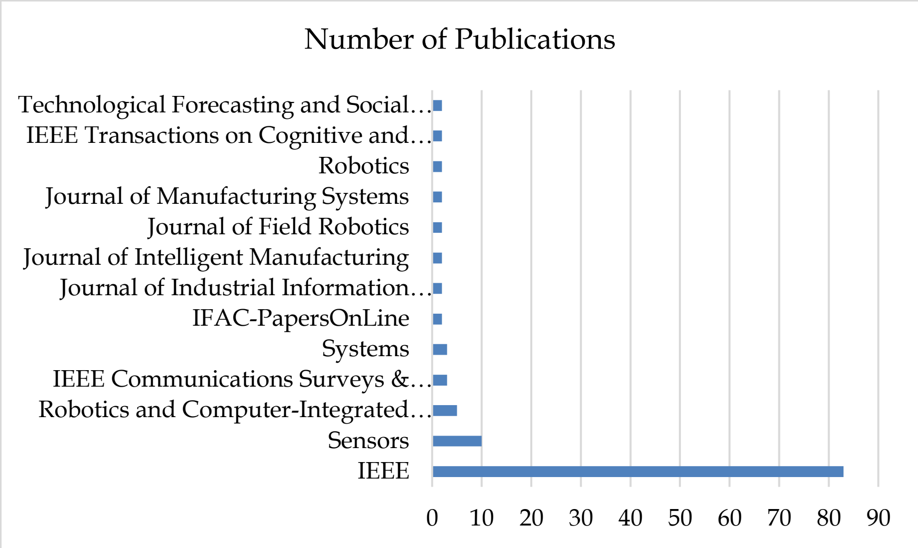
Topic	Qualitative Studies	Quantitative Studies	Mixed Methods
WS - Digital Twin Integration	Luxenburger et al. (2024)	Wang, S., et al. (2024), Wang, H., et al. (2023),	Roy and Singh (2024), Jimenez and Maire (2023)
WS - Risk Assessment and Management	Fernández et al. (2022)	Grimmeisen et al. (2023), Tosoni et al. (2022), Baniqued et al. (2024)	
WS - Ergonomics and Worker Well-Being	Ávila-Gutiérrez et al. (2022)	Li et al. (2023)	Berti and Finco (2022), Constantinescu et al. (2019), Kolesnikov et al. (2023), Longo et al (2023), Davila-Gonzalez and Martin (2024), Berti and Finco (2022)
HRI – Extended Reality and Digital Twin Integration		Xie et al. (2024), Li et al. (2022), Yin et al. (2023), Feddoul et al. (2023)	Alimam et al. (2023)
HRI – Digital Twin and AI Integration	Proia et al. (2021)	Rožanec et al (2022), Coronado et al. (2024)	Asad et al. (2023), Khosravy et al. (2023), Krupas et al. (2024),
HRI – Control Techniques and Safety	Bhattacharya et al. (2023), Tallat et al. (2023)		Kuts et al. (2022), Mincă et al. (2022), Maruyama et al. (2021), Müller et al. (2023), Tóth et al. (2023), Raffik et al. (2023), Piccarozzi et al. (2024)
ME – Real-Time Monitoring	Zhang et al. (2023)	Xiao et al. (2023), El-Agamy et al. (2024), David et al. (2018)	Peter et al. (2021)
ME – Optimization and AI Integration	Franciosi et al. (2023)	Xiang et al. (2023), Vilar-Dias et al. (2023), Mourad et al. (2023)	Ouahabi et al. (2024), Qu et al. (2024), Cimino et al. (2023)
ME – Advanced Manufacturing Systems		Leng et al. (2023), Mihai et al. (2022), Vilar-Dias et al. (2023)	Lago et al. (2023), Kamdjou et al. (2024), Kovič et al. (2024)

Source: Own elaboration.

The included studies were published in a variety of journals, reflecting the interdisciplinary nature of research on digital twins and Industry 5.0. The distribution of publications per journal is illustrated in Figure 3, highlighting the journals with the highest number of contributions.

Figure 3.

Number of Publcations per Journal (two or more publications)



Source: Own elaboration.

3.1. Worker Safety

The integration of digital twins into Industry 5.0 frameworks significantly enhances worker safety through real-time monitoring, intelligent sensing, and proactive risk management. Wang, Zhou et al. (2024) developed a deep learning-enhanced digital twin framework for human-robot collaborative manufacturing. This framework detects unsafe conditions and triggers autonomous decisions to prevent hazards, maintaining high detection accuracy even in challenging environments. Similarly, Wang et al. (2023) introduced a safety management model using a high-fidelity Digital Twin Workshop (DTW) and semantic reasoning to improve the detection of unsafe states, providing real-time safety solutions.

Li et al. (2023) advanced this concept by combining augmented reality (AR) with deep reinforcement learning (DRL) for safe human-robot interaction. Their system uses AR glasses for visual augmentation and DRL for collision avoidance, validated in practical scenarios. In another approach, Grimmeisen et al. (2023) presented an automated risk assessment framework for ROS-based robotic systems. This methodology integrates digital twins with hybrid risk models to provide real-time adaptive safety measures, validated on a robotic manipulator.

Moreover, Fernández et al. (2022) utilized the VIBE neural network to track workers' activities, creating real-time 3D models to enhance workplace safety through advanced computer vision and AI techniques. Complementing this, Kolesnikov et al. (2023) incorporated human factors into digital twins by using wearable sensors to collect data on workers' conditions and make real-time adjustments to workflows, thereby enhancing safety.

Berti and Finco (2022) reviewed digital twin integration with human factors, highlighting frameworks like the WEM-platform, which provides immediate feedback on ergonomic risks. Additionally, Constantinescu et al. (2019) developed digital twins for exoskeleton-centered workplaces to reduce physical strain and prevent musculoskeletal disorders (MSDs).

Building on these safety enhancements, Jimenez and Maire (2023) introduced ErgoTwin, a digital twin model for monitoring postural risks using wearable sensors. This system provides continuous feedback to improve worker postures. He et al. (2024) extended this concept with a Human Digital Twin (HDT) framework that integrates multi-source data and AI for continuous monitoring and assessment, thereby enhancing workplace safety and ergonomics.

In the realm of training, Longo et al. (2023) proposed "training on-the-go", leveraging digital twins and prescriptive analytics to train industrial workers in non-routine tasks, thus enhancing safety and efficiency. Davila-Gonzalez and Martin (2024) further introduced a framework integrating HDT with AI and emotional analytics for continuous monitoring of workers' physical, mental, and emotional states, promoting overall worker well-being.

Wang, Zhang et al. (2024) emphasized a human-centric approach in their review of the HDT within Industry 5.0, advocating for real-time monitoring and feedback on workers' conditions. This approach was echoed by Luxenburger et al. (2024), who implemented interactive digital twins for online planning and worker safety, utilizing AR technology to visualize safety aspects and prevent collisions in shared workspaces.

Baniqued et al. (2024) introduced a multimodal immersive digital twin platform for managing cyber-physical robot fleets in nuclear environments. This platform enhances situational awareness and safety through VR interfaces. Meanwhile, Ávila-Gutiérrez et al. (2022) proposed a model for Occupational Safety and Health (OSH) 5.0, integrating digital technologies for real-time monitoring and proactive safety measures aligned with the Sustainable Development Goals (SDGs).

Lastly, Tosoni et al. (2022) explored digital twins for Cyber-Physical Production Systems (CPPSs) with fault modeling techniques to ensure functional safety. Similarly, Berti et al. (2023) developed HDT systems for monitoring workers' postures and dynamically rescheduling tasks to reduce safety risks. Roy and Singh (2024) integrated Extended Reality (XR) with digital twins for immersive simulations, improving safety and performance in nuclear environments.

In summary, these studies collectively highlight the critical role of digital twins in enhancing worker safety in Industry 5.0 by providing real-time monitoring, intelligent sensing, and proactive risk management. The integration of advanced technologies such as AI, AR, and IoT with digital twins supports continuous improvement in safety measures, creating safer and more efficient industrial environments.

3.2. Human Robot Colloboration

The integration of digital twins significantly enhances human-robot collaboration (HRC) in Industry 5.0, creating more intelligent, efficient, and safe collaborative environments. Various studies highlight different approaches and technologies contributing to these advancements. Xie et al. (2024) developed an XR-based human-robot collaboration assembly system that integrates extended reality (XR) technologies, including virtual reality (VR) and augmented reality (AR), with blockchain and collaborative network architecture. This system creates virtual avatars representing physical operators and robots, enhancing real-time operations through pre-planning, online task optimization, and AI-driven decision-making, demonstrated effectively in a gearbox assembly case study.

Building on this foundation, Coronado et al. (2024) presented an innovative approach integrating human-centric systems for Industry 5.0 by bridging the Robot Operating System (ROS) with NEP+, a human-centered development framework. Their architecture facilitates real-time data exchange and enhances collaboration between humans and robots, demonstrated through a human-in-the-loop collaborative assembly case study. Similarly, Yin et al. (2023) surveyed AR-assisted digital twin technologies for human-centric industry transformation, emphasizing AR's role in improving interaction through intuitive visualizations and real-time feedback, leading to smarter decision-making and efficient human-robot collaboration.

Li et al. (2022) proposed an AR-assisted digital twin-enabled robot collaborative manufacturing system with human-in-the-loop control. This system maps digital twins of robots to their physical counterparts and visualizes them in AR glasses, allowing intuitive control and real-time updates, validated through precise teleoperation tasks. In parallel, Proia et al. (2021) reviewed control techniques for safe, ergonomic, and efficient HRC, categorizing contributions based on safety, ergonomics, and efficiency, highlighting innovative control methods and state-of-the-art methodologies.

Furthermore, Kuts et al. (2022) examined digital twin technology as a validation tool for industrial robot manipulation, comparing traditional interfaces with DT-based VR interfaces. Their study highlighted the importance of integrating human factors into DT systems to ensure effective adoption. Expanding on this, Mincă et al. (2022) presented a digital twin approach for multifunctional technology in flexible manufacturing, integrating robotic systems and a mobile visual servoing system (MVSS) to enhance productivity and reduce waste.

Maruyama et al. (2021) introduced a digital twin-driven HRC system using digital human (DH) technology to enhance safe and flexible manufacturing. Their system integrates virtual robots, DHs, and production management modules, capturing workers' full-body motions for ergonomic assessment and dynamically scheduling tasks to balance workloads. This integration exemplifies how digital twin technologies can be used to optimize human-robot collaboration by ensuring ergonomic safety and task efficiency.

Further contributing to the field, Feddoul et al. (2023) conducted a systematic literature review exploring the advancements in digital twin technology and robotics interfaced with XR technologies within Industry 4.0. Their review highlights how immersive environments improve design, monitoring, programming, and training by integrating digital twins, robotics, and XR technologies such as AR and VR. This integration facilitates augmented perception, allowing real robots to interact with virtual objects and enhancing training and simulation without physical prototypes.

Asad et al. (2023) explored the development and implementation of Human-Centric Digital Twins (HCDTs) in industry, focusing on enabling technologies and strategies to enhance human-robot collaboration. The HCDT framework integrates motion sensors, biological sensors, AI, simulation tools, and visualization technologies to create a comprehensive digital representation of human operators. This integration allows for real-time monitoring, ergonomic assessments, and adaptive human-robot interactions, ensuring safety and efficiency. In parallel, Khosravy et al. (2023) examined the role of human-collaborative AI within Industry 5.0, focusing on integrating societal values and sustainability. Their survey discusses how AI, digital twins, and collaborative robots (cobots) enhance human-robot collaboration by enabling real-time monitoring, simulation, and optimization of industrial processes.

Similarly, Bhattacharya et al. (2023) reviewed the role of human-in-the-loop (HIL) systems in smart manufacturing, highlighting the integration of cyber-physical systems (CPS), AI, and human-machine interfaces (HMI). Their review underscores the importance of HIL in enhancing human-robot collaboration by ensuring that humans remain central to the manufacturing process. Meanwhile, Raffik et al. (2023) discussed advancements in human-robot collaboration facilitated by collaborative robots (cobots) within Industry 5.0. Their review highlights the integration of IoT, 6G systems, blockchain technology, digital twins, AI, and XR to create intelligent hybrid workspaces.

Tallat et al. (2023) explored the transition from Industry 4.0 to Industry 5.0, emphasizing the importance of integrating human creativity with advanced robotic and AI technologies. Their survey highlights collaborative robots (cobots) and the Internet of Robotic Things (IoRT) as central elements of Industry 5.0, enabling real-time monitoring and data exchange for enhanced human-robot interactions. Similarly, Piccarozzi et al. (2024) provided an overview of the transition from Industry 4.0 to Industry 5.0, focusing on enabling technologies, challenges, and opportunities. They emphasize the need for a holistic and human-centric approach in management studies to understand and define Industry 5.0.

Contributing to the development of human-robot collaboration metrics, Müller et al. (2023) introduced a novel metric to measure and improve situation awareness in collaborative robots (cobots) using intelligent digital twins (iDTs). This approach ensures that cobots possess high levels of situation awareness, essential for effective human-robot collaboration. Additionally, Tóth et al. (2023) introduced the Industry 5.0 collaboration architecture (I5arc), focusing on integrating innovative technologies with human actors in a value-driven, human-centric approach.

Finally, Alimam et al. (2023) explored the concept of the Digital Triplet (D3) as an advanced evolution of the Digital Twin (DT), focusing on human-machine integration. The D3 integrates human cognitive activities into physical and cyberspace, enhancing real-time human interactions with both physical and virtual systems. Similarly, Krupas et al. (2024) reviewed enabling technologies and methods essential for creating human-centric digital twin (DT) applications to facilitate human-machine collaboration (HMC) in Industry 5.0.

In summary, these studies collectively illustrate the advancements in human-robot collaboration achieved through the integration of digital twins, AI, XR, and advanced control techniques. By providing real-time monitoring, intuitive interfaces, and adaptive control systems, these technologies enhance the efficiency, safety, and overall interaction between humans and robots in Industry 5.0.

3.3. *Manufacturing Efficiency*

The integration of digital twins significantly enhances industrial efficiency by providing real-time monitoring, optimization, and advanced decision-making capabilities. Various studies illustrate these advancements through different approaches and technologies.

Zhang et al. (2023) propose a service-oriented digital twin framework for discrete manufacturing workshops, leveraging an industrial IoT platform to enhance monitoring, visualization, and supervision of workshop data. This comprehensive architecture ensures seamless integration and real-time interaction between physical and virtual environments, enhancing production efficiency. Implemented in a movable-arm production workshop, it demonstrated its effectiveness in improving intelligent human-machine interactions, production monitoring, and workflow efficiency.

Building on the transition from Industry 4.0 to Industry 5.0, Xiang et al. (2023) focus on personalized manufacturing, human-robot collaboration, and advanced technologies such as AI, IoT, and beyond 5G communications. AIoT-driven digital twins optimize production processes by providing real-time data from connected sensors and actuators, enhancing operational efficiency and decision-making capabilities. Collaborative robots (CoBots) integrate human creativity with robotic precision and speed, improving productivity and consistency through safe human-robot interactions, motion planning, and real-time task optimization.

Similarly, Vilar-Dias et al. (2023) present a methodology integrating digital twins with particle swarm optimization (PSO) algorithms to enhance industrial systems' performance and efficiency. This framework continuously updates the model with real-time data, allowing for accurate predictions and better decision-making. Case studies involving a DC motor, and a hydraulic actuator demonstrated the methodology's effectiveness in adapting to changing conditions and identifying faults, leading to improved system performance and maintenance practices.

El-Agamy et al. (2024) conducted a comprehensive bibliometric study on digital twin technology in smart cities, highlighting the integration of IoT for real-time data collection and machine learning for predictive analysis. Digital twins enable urban planners to simulate and visualize potential changes, ensuring optimized and efficient urban operations. This study identifies key trends in digital twin research and suggests advanced models and better data management frameworks to address challenges such as data integration, scalability, and security.

Mourad et al. (2023) propose a novel model for optimizing control engineering tools by leveraging digital twin capabilities and components of Cyber-Physical Metaverse Manufacturing Systems (CPMMS). Their approach involves developing a decision matrix based on utility procedures and integrating fuzzy weighted zero-inconsistency interval-valued spherical fuzzy rough sets (IvSFRS–FWZIC) and combined compromise solution (CoCoSo) methods. This model optimizes control engineering tools using digital twin capabilities, demonstrated through a case study validating its applicability and robustness in enhancing CPMMS.

Qu et al. (2024) explored digital twin technology to improve efficiency in cross-belt sorting systems used in the express delivery industry. Their human-machine integrated digital twin enables interaction between biological humans, virtual humans, and physical logistics equipment, creating a comprehensive digital representation of the sorting system. This system optimizes task allocation based on real-time data, maintaining high efficiency while safeguarding worker health, as demonstrated in an express distribution center.

Mihai et al. (2022) surveyed enabling technologies, challenges, and future prospects of digital twin technology. They highlight the potential of digital twins to reshape industries by offering seamless monitoring, analysis, evaluation, and predictions through real-time data communications. The survey emphasizes the importance of continued research and development to address challenges such as data accumulation, communication, and interdisciplinary collaboration.

Kovič et al. (2024) explored the impact of changing collaborative workplace parameters on assembly operation efficiency. Using a digital twin-based model, their research revealed that optimizing parameters such as robot speed, sound levels, and visual barriers can significantly improve assembly efficiency. These findings highlight the importance of balancing multiple factors to enhance productivity.

Peter et al. (2021) provided a guide on implementing smart factories using digital twin technology. Their study outlines integrating critical Industry 4.0 technologies, demonstrating significant improvements in production efficiency and process optimization through real-time monitoring, simulation, and preventive maintenance planning.

Xiao et al. (2023) introduced TS-DP, a data processing algorithm designed to enhance the efficiency of distribution digital twin grids in Industry 5.0. By leveraging contrastive learning and advanced convolutional techniques, TS-DP improves time series predictions and classifications, supporting real-time applications such as fault diagnosis and intelligent dispatching, enhancing system reliability.

Lago et al. (2023) presented a methodology for enhancing digital twins of semi-automatic production lines by digitizing operator skills. This approach integrates human factors into digital twins to manage and optimize human performance, improving overall production efficiency and quality, as demonstrated in a simulated manufacturing assembly line.

Cimino et al. (2023) discussed the role of digitalization in empowering field operators in manufacturing through intelligent Decision Support Systems (DSS) within the Industry 5.0 framework. Their proposed software architecture, which includes simulation-based digital twins and adaptive production planning, enhances situational awareness and decision-making capabilities, ensuring productivity, quality, and resilience in production systems.

Rožanec et al. (2022) presented an AI-driven architecture to support human-centric applications within Industry 5.0. By integrating active learning, explainable AI (XAI), and simulated reality, this architecture improves manufacturing processes while maintaining a focus on human-machine collaboration and safety. Practical applications such as demand forecasting and quality inspection demonstrate improvements in efficiency, accuracy, and safety.

Franciosi et al. (2023) explored the integration of human factors into digital twin-based joint production and maintenance scheduling. Their approach optimizes production and maintenance activities by considering worker skills, availability, and ergonomic factors, leading to significant improvements in production efficiency and worker satisfaction.

David et al. (2018) investigated the use of digital twins for enhancing production-based technical education. Their pedagogical framework integrates learning theories with digital twins, providing effective hands-on training and improving situational awareness in educational environments, demonstrated in flexible manufacturing systems at the university level.

Ouahabi et al. (2024) provided a comprehensive review of integrating digital twins into dynamic production scheduling. They emphasize the impact of digital twins on enhancing industrial efficiency through real-time monitoring, optimization, and prediction of production processes, suggesting future research directions to address current challenges.

Leng et al. (2023) presented ManuChain II, a blockchain-enabled smart contract system functioning as the digital twin of a decentralized autonomous manufacturing system. This system enhances resilience and efficiency in manufacturing processes through decentralized decision-making and coordination among distributed units, demonstrated through significant improvements in production efficiency and data transparency.

Kamdjou et al. (2024) analyzed performance optimization techniques for resource-constrained AR and VR environments operating with digital twins within the Industrial Internet of Things (IIoT). Their study explores techniques such as data compression, blockchain, and AI to improve performance and efficiency, significantly enhancing industrial efficiency in smart manufacturing systems.

These studies collectively demonstrate significant advancements in industrial efficiency achieved through the integration of digital twins, AI, IoT, and advanced data processing techniques. By providing real-time monitoring, optimization, and predictive capabilities, these technologies enhance the efficiency and reliability of industrial systems, aligning with the goals of Industry 5.0.

4. Discussion

The findings of this systematic literature review underscore the transformative impact of digital twin technologies in Industry 5.0, enhancing worker safety, facilitating human-robot collaboration (HRC), and increasing manufacturing efficiency. These advancements not only contribute to smarter, safer, and more productive industrial environments but also engage with and expand the current theoretical and practical frameworks within the field.

Digital twins significantly improve worker safety through real-time monitoring and proactive risk management. The frameworks developed by Wang et al. (2023; 2024) utilize deep learning and high-fidelity simulations to preemptively identify and mitigate unsafe conditions. This proactive approach represents a paradigm shift from reactive safety measures, aligning with theories advocating for anticipatory safety practices in industrial operations. The integration of augmented reality (AR) with digital twins, as highlighted by Li et al. (2023), further enhances cognitive functions, which is critical in dynamic settings. This synergy challenges traditional views on risk management by demonstrating how cutting-edge technology can transform safety protocols.

The role of digital twins in optimizing HRC is evident in their ability to enable real-time data integration and intelligent decision-making. Studies like those by Coronado et al. (2024) and Xie et al. (2024) show how integrating technologies such as XR and blockchain can create adaptable, efficient collaborative environments. This supports theories on the convergence of cyber-physical systems and human factors engineering, emphasizing the importance of ergonomic and cognitive considerations in HRC. Such findings are critical as they offer a nuanced understanding of how digital twins can bridge the gap between human capabilities and robotic efficiency.

Digital twins facilitate smarter manufacturing processes by integrating with IIoT and AIoT technologies, as demonstrated by Zhang et al. (2023) and Xiang et al. (2023). These technologies enable dynamic monitoring and real-time adjustments, essential for reducing downtime and maintaining high productivity. This practical application of digital twins challenges existing theories on static production systems, advocating for a more fluid and responsive manufacturing paradigm. The emphasis on human factors, discussed by Franciosi et al. (2023) and Lago et al. (2023), reflects a growing recognition of the need to balance technological advancements with ergonomic and safety considerations, reinforcing the theoretical framework that human-centric design is essential for sustainable industrial efficiency.

4.1. Limitations and Future Research

Despite the promising findings, several limitations exist in the studies reviewed, which need to be addressed to fully realize the potential of digital twins in Industry 5.0.

One major limitation is the reliance on high-quality, real-time data for the effective functioning of digital twins. Many studies, such as Wang et al. (2024) and Li et al. (2023), emphasize the importance of continuous, real-time data integration for monitoring and decision-making processes. However, the collection and management of such vast amounts of data can be challenging, particularly in environments with limited technological infrastructure. Data accuracy and integrity are critical, and any discrepancies can lead to incorrect predictions and unsafe conditions. This reliance on data quality raises concerns about the scalability of these solutions in diverse industrial settings.

Another limitation is the computational complexity and resource requirements of digital twin models. The frameworks proposed by Wang et al. (2023) and Grimmeisen et al. (2023) involve sophisticated algorithms and high-fidelity simulations that demand significant computational power and storage. This requirement can be a barrier for small and medium-sized enterprises (SMEs) that may lack the necessary resources to implement such advanced systems. Additionally, the integration of technologies like AR and AI, as discussed by Li et al. (2023) and Yin et al. (2023), further increases the complexity and cost, potentially limiting widespread adoption.

The studies also highlight the need for robust cybersecurity measures to protect the data and systems involved in digital twin applications. Xiang et al. (2023) and Zhang et al. (2023) discuss the integration of AI and IoT, which, while enhancing efficiency, also exposes the systems to potential cyber threats. Ensuring data security and system integrity is crucial, but it adds another layer of complexity and cost to the implementation process. This concern is particularly relevant for highly sensitive industries, such as healthcare and defense, where data breaches could have severe consequences.

Moreover, the human factors involved in the interaction with digital twins present another set of limitations. The studies by Kuts et al. (2022) and Proia et al. (2021) reveal that while digital twins can enhance human-robot collaboration, they also place additional cognitive and physical demands on human operators. The effectiveness of digital twin systems depends not only on technological robustness but also on the ability of human users to interact with these systems efficiently. There is a need for user-friendly interfaces and comprehensive training programs to ensure that operators can effectively use these advanced tools without experiencing fatigue or stress.

Additionally, the validation of digital twin models in real-world settings remains limited. Many studies, such as those by Peter et al. (2021) and Xiao et al. (2023), provide theoretical frameworks and case studies but lack extensive empirical validation. Real-world testing is essential to understand the practical challenges and limitations of implementing digital twins on a large scale. This gap highlights the need for more field studies and pilot projects to gather empirical data and refine the models for broader application.

Finally, the ethical and socio-economic implications of digital twin deployment are not thoroughly explored in the current literature. While digital twins offer numerous benefits, their widespread implementation could lead to significant workforce changes, potentially displacing workers or altering job roles. Studies like those by Franciosi et al. (2023) and Lago et al. (2023) touch on the integration of human factors but do not fully address the broader socio-economic impacts. Future research should consider these aspects to ensure that digital twin technologies are implemented in a socially responsible manner, promoting inclusive growth and minimizing negative impacts on the workforce.

5. Conclusions

In conclusion, this systematic literature review underscores the significant role of digital twin technologies in revolutionizing Industry 5.0 by enhancing worker safety, facilitating human-robot collaboration, and optimizing manufacturing efficiency. Leveraging AI, AR, and IoT, digital twins offer advanced data processing, intelligent sensing, and dynamic decision-making capabilities, as evidenced by studies from Wang et al. (2024), Li et al. (2023), and Zhang et al. (2023). These technologies foster smarter, safer, and more productive industrial environments. However, realizing the full potential of digital twins requires overcoming challenges related to data quality, computational complexity, cybersecurity, human factors, real-world validation, and ethical considerations. Addressing these issues is essential for the successful implementation of digital twins, enabling safer, more efficient, and human-centric industrial practices and contributing to a sustainable and inclusive future.

6. Referencias

Alimam, H., Mazzuto, G., Tozzi, N., Ciarapica, F. E., & Bevilacqua, M. (2023). The resurrection of digital triplet: A cognitive pillar of human-machine integration at the dawn of industry 5.0. *Journal of King Saud University - Computer and Information Sciences*, 35(10), 101846. https://doi.org/10.1016/j.jksuci.2023.101846

Asad, U., Khan, M., Khalid, A., & Lughmani, W. A. (2023). Human-centric digital twins in industry: A comprehensive review of enabling technologies and implementation strategies. *Sensors*, *23*(8), 3938. https://doi.org/10.3390/s23083938

Ávila-Gutiérrez, M. J., Suarez-Fernandez de Miranda, S., & Aguayo-González, F. (2022). Occupational safety and health 5.0—A model for multilevel strategic deployment aligned with the sustainable development goals of agenda 2030. *Sustainability*, *14*(11), 6741. https://doi.org/10.3390/su14116741

Baniqued, P. D. E., Bremner, P., Sandison, M., Harper, S., Agrawal, S., Bolarinwa, J., Blanche, J. Jiang, Z., Johnson, T., Mitchell, D., Lopez Pulgarin, E. J., West, A., Willis, M., Yao, K., Flynn, D., Giuliani, M., Groves, K., Lennox, B., & Watson, S. (2024). Multimodal immersive digital twin platform for cyber–physical robot fleets in nuclear environments. *Journal of Field Robotics*, *41*(5), 1521-1540. https://doi.org/10.1002/rob.22329

Berti, N., & Finco, S. (2022). Digital twin and human factors in manufacturing and logistics systems: State of the art and future research directions. *IFAC-PapersOnLine*, *55*(10), 1893-1898. https://doi.org/10.1016/j.ifacol.2022.09.675

Berti, N., Finco, S., Guidolin, M., & Battini, D. (2023). Towards human digital twins to enhance workers' safety and production system resilience. *IFAC-PapersOnLine*, *56*(2), 11062-11067. https://doi.org/10.1016/j.ifacol.2023.10.809

Bhattacharya, M., Penica, M., O'Connell, E., Southern, M., & Hayes, M. (2023). Human-in loop: a review of smart manufacturing deployments. *Systems*, *11*(1), 35. https://doi.org/10.3390/systems11010035

Cimino, A., Elbasheer, M., Longo, F., Nicoletti, L., & Padovano, A. (2023). Empowering field operators in manufacturing: a prospective towards industry 5.0. *Procedia Computer Science*, 217, 1948-1953. https://doi.org/10.1016/j.procs.2022.12.395

Constantinescu, C., Rus, R., Rusu, C. A., & Popescu, D. (2019). Digital twins of exoskeleton centered workplaces: Challenges and development methodology. *Procedia Manufacturing*, 39, 58-65. https://doi.org/10.1016/j.promfg.2020.01.228

Coronado, E., Ueshiba, T., & Ramirez-Alpizar, I. G. (2024). A path to Industry 5.0 digital twins for human–robot collaboration by bridging NEP+ and ROS. *Robotics*, *13*(2), 28. https://doi.org/10.3390/robotics13020028

David, J., Lobov, A., & Lanz, M. (2018, October). Learning experiences involving digital twins. In *IECON 2018-44th annual conference of the IEEE industrial electronics Society* (pp. 3681-3686). IEEE. https://doi.org/10.1109/IECON.2018.8591460

Davila-Gonzalez, S., & Martin, S. (2024). Human digital twin in Industry 5.0: A holistic approach to worker safety and well-being through advanced AI and emotional analytics. *Sensors*, *24*(2), 655. https://doi.org/10.3390/s24020655

El-Agamy, R. F., Sayed, H. A., AL Akhatatneh, A. M., Aljohani, M., & Elhosseini, M. (2024). Comprehensive analysis of digital twins in smart cities: a 4200-paper bibliometric study. *Artificial Intelligence Review*, *57*(6), 154. https://doi.org/10.1007/s10462-024-10781-8

Feddoul, Y., Ragot, N., Duval, F., Havard, V., Baudry, D., & Assila, A. (2023). Exploring human-machine collaboration in industry: A systematic literature review of digital twin and robotics interfaced with extended reality technologies. *The International Journal of Advanced Manufacturing Technology*, *129*(5), 1917-1932. https://doi.org/10.1007/s00170-023-12291-3

Fernández, M. M., Delrieux, C., & Muñoz, J. Á. F. (2022, July). Automated personnel digital twinning in industrial workplaces. In *2022 International Conference on Electrical, Computer and Energy Technologies (ICECET)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICECET55527.2022.9872882

Franciosi, C., Miranda, S., Veneroso, C. R., & Riemma, S. (2023). Investigating human factors integration into DT-based joint production and maintenance scheduling. In Alfnes, E., Romsdal, A., Strandhagen, J.O., von Cieminski, G., Romero, D. (Eds.), *Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures* (Vol. 689, pp. 633-648). Springer. https://doi.org/10.1007/978-3-031-43662-8_45

Grimmeisen, P., Golwalkar, R., Ma, Y., & Morozov, A. (2023). Automated and continuous risk assessment for ROS-based software-defined robotic systems. In *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)* (pp. 1-7). IEEE. https://doi.org/10.1109/CASE56687.2023.10260416

He, Q., Li, L., Li, D., Peng, T., Zhang, X., Cai, Y., Cai, Y., Zhang, X., & Tang, R. (2024). From digital human modeling to human digital twin: Framework and perspectives in human factors. *Chinese Journal of Mechanical Engineering*, *37*(9). https://doi.org/10.1186/s10033-024-00998-7

Jimenez, J. F., & Maire, J. L. (2023, September). ErgoTwin: A digital twin model for monitoring the postural risks on industrial workers. In Borangiu, T., Trentesaux, D., Leitão, P., Berrah, L., Jimenez, JF. (Eds.), *Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future. SOHOMA 2023. Studies in Computational Intelligence* (Vol. 1136, pp. 250-262). Springer. https://doi.org/10.1007/978-3-031-53445-4_21

Kamdjou, H. M., Baudry, D., Havard, V., & Ouchani, S. (2024). Resource-constrained extended reality operated with digital twin in industrial Internet of Things. In *IEEE Open Journal of the Communications Society* (Vol. 5, pp. 928-950). https://doi.org/10.1109/OJCOMS.2024.3356508

Khosravy, M., Gupta, N., Pasquali, A., Dey, N., Crespo, R. G., & Witkowski, O. (2023). Human-collaborative artificial intelligence along with social values in Industry 5.0: A survey of the state-of-the-art. *IEEE Transactions on Cognitive and Developmental Systems*, *16*(1), 165-176. https://doi.org/10.1109/TCDS.2023.3326192

Kolesnikov, M. V., Atmojo, U. D., & Vyatkin, V. (2023, October). Data-driven human factors enabled digital twin. In *IECON 2023-49th Annual Conference of the IEEE Industrial Electronics Society* (pp. 1-6). IEEE. https://doi.org/10.1109/IECON51785.2023.10311802

Kovič, K., Javernik, A., Ojsteršek, R., & Palčič, I. (2024). The impact of changing collaborative workplace parameters on assembly operation efficiency. *Robotics*, *13*(3), 36. https://doi.org/10.3390/robotics13030036

Krupas, M., Kajati, E., Liu, C., & Zolotova, I. (2024). Towards a human-centric digital twin for human–machine collaboration: A review on enabling technologies and methods. *Sensors*, *24*(7), 2232. https://doi.org/10.3390/s24072232

Lago Alvarez, A., Mohammed, W. M., Vu, T., Ahmadi, S., & Martinez Lastra, J. L. (2023). Enhancing digital twins of semi-automatic production lines by digitizing operator skills. *Applied Sciences*, *13*(3), 1637. https://doi.org/10.3390/app13031637

Leng, J., Zhu, X., Huang, Z., Xu, K., Liu, Z., Liu, Q., & Chen, X. (2023). ManuChain II: Blockchained smart contract system as the digital twin of decentralized autonomous manufacturing toward resilience in industry 5.0. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *53*(8), 4715-4728. https://doi.org/10.1109/TSMC.2023.3257172

Lewis, J., Schneegans, S., & Straza, T. (Eds.) (2021). *UNESCO Science Report: The race against time for smarter development* (Vol. 2021). Unesco Publishing. https://acortar.link/qOpnEw

Li, C., Zheng, P., Li, S., Pang, Y., & Lee, C. K. (2022). AR-assisted digital twin-enabled robot collaborative manufacturing system with human-in-the-loop. *Robotics and Computer Integrated Manufacturing*, 76, 102321. https://doi.org/10.1016/j.rcim.2022.102321

Longo, F., Padovano, A., De Felice, F., Petrillo, A., & Elbasheer, M. (2023). From "prepare for the unknown" to "train for what's coming": a digital twin-driven and cognitive training approach for the workforce of the future in smart factories. *Journal of Industrial Information Integration*, 32, 100437. https://doi.org/10.1016/j.jii.2023.100437

Luxenburger, A., Mohr, J., Merkel, D., Knoch, S., Porta, D., Paul, C., Widenka, J., Schäfers, P., Baumann, M., Lehnhoff, S., & Schwab, J. (2024, January). Interactive digital twins for online planning and worker safety in intralogistics and production. In *2024 IEEE International Conference on Artificial Intelligence and eXtended and Virtual Reality (AIxVR)* (pp. 66-74). IEEE. https://doi.org/10.1109/AIxVR59861.2024.00016

Maruyama, T., Ueshiba, T., Tada, M., Toda, H., Endo, Y., Domae, Y., Nakabo, Y., Mori, T., & Suita, K. (2021). Digital twin-driven human robot collaboration using a digital human. *Sensors*, *21*(24), 8266. https://doi.org/10.3390/s21248266

Mihai, S., Yaqoob, M., Hung, D. V., Davis, W., Towakel, P., Raza, M., Karamanoglu, M., Barn, B., Shetve, D., Prasad, R. V., Venkataraman, H., Trestian, R., & Nguyen, H. X. (2022). Digital twins: A survey on enabling technologies, challenges, trends and future prospects. *IEEE Communications Surveys & Tutorials*, *24*(4), 2255-2291. https://doi.org/10.1109/COMST.2022.3208773

Mincă, E., Filipescu, A., Cernega, D., Şolea, R., Filipescu, A., Ionescu, D., & Simion, G. (2022). Digital twin for a multifunctional technology of flexible assembly on a mechatronics line with integrated robotic systems and mobile visual sensor—Challenges towards Industry 5.0. *Sensors*, *22*(21), 8153. https://doi.org/10.3390/s22218153

Mourad, N., Alsattar, H. A., Qahtan, S., Zaidan, A. A., Deveci, M., Sangaiah, A. K., & Pedrycz, W. (2023). Optimising control engineering tools using digital twin capabilities and other cyber-physical metaverse manufacturing system components. *IEEE Transactions on Consumer Electronics*, *70*(1), 3212-3221. https://doi.org/10.1109/TCE.2023.3326047

Müller, M., Ruppert, T., Jazdi, N., & Weyrich, M. (2023). Self-improving situation awareness for human–robot-collaboration using intelligent digital twin. *Journal of Intelligent Manufacturing*, 35, 2045-2063. https://doi.org/10.1007/s10845-023-02138-9

Ouahabi, N., Chebak, A., Kamach, O., Laayati, O., & Zegrari, M. (2024). Leveraging digital twin into dynamic production scheduling: A review. *Robotics and Computer-Integrated Manufacturing*, 89, 102778. https://doi.org/10.1016/j.rcim.2024.102778

Peter, O. A., Anastasia, S. D., & Muzalevskii, A. R. (2021, June). The implementation of Smart factory for product inspection and validation A step by step guide to the implementation of the virtual plant of a smart factory using digital twin. In *2021 10th Mediterranean Conference on Embedded Computing (MECO)* (pp. 1-7). IEEE. https://doi.org/10.1109/MECO52532.2021.9460140

Piccarozzi, M., Silvestri, L., Silvestri, C., & Ruggieri, A. (2024). Roadmap to Industry 5.0: Enabling technologies, challenges, and opportunities towards a holistic definition in management studies. *Technological Forecasting and Social Change*, 205, 123467. https://doi.org/10.1016/j.techfore.2024.123467

Proia, S., Carli, R., Cavone, G., & Dotoli, M. (2021). Control techniques for safe, ergonomic, and efficient human-robot collaboration in the digital industry: A survey. *IEEE Transactions on Automation Science and Engineering*, *19*(3), 1798-1819. https://doi.org/10.1109/TASE.2021.3131011

Qu, Y., Zhao, N., & Zhang, H. (2024). Digital twin technology of human–machine integration in cross-belt sorting system. *Chinese Journal of Mechanical Engineering*, *37*(33). https://doi.org/10.1186/s10033-024-01012-w

Raffik, R., Sathya, R. R., Vaishali, V., & Balavedhaa, S. (2023). Industry 5.0: Enhancing human-robot collaboration through collaborative robots–A review. In *2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICAECA56562.2023.10201120

Roy, S., & Singh, S. (2024). XR and digital twins, and their role in human factor studies. *Frontiers in Energy Research*, 12, 1359688. https://doi.org/10.3389/fenrg.2024.1359688

Rožanec, J. M., Novalija, I., Zajec, P., Kenda, K., Tavakoli Ghinani, H., Suh, S., Veliou, E., Papamartzivanos, D., Giannetsos, T., Menesidou, S. A., Alonso, R., Cauli, N. Meloni, A., Reforgiato Recupero, D., Kyriazis, D., Sofianidis, G., Theodoropoulos, S., Fortuna, B., Mladenić, D., & Soldatos, J. (2023). Human-centric artificial intelligence architecture for industry 5.0 applications. *International Journal of Production Research*, *61*(20), 6847-6872. https://doi.org/10.1080/00207543.2022.2138611

Tallat, R., Hawbani, A., Wang, X., Al-Dubai, A., Zhao, L., Liu, Z., Min, G., Zomaya, A. Y., & Alsamhi, S. H. (2023). Navigating industry 5.0: A survey of key enabling technologies, trends, challenges, and opportunities. *IEEE Communications Surveys & Tutorials*, 26(2), 1080-1126. https://doi.org/10.1109/COMST.2023.3329472

Tosoni, F., Dall'Ora, N., Fraccaroli, E., & Fummi, F. (2022). The challenges of coupling digital-twins with multiple classes of faults. In *2022 IEEE 23rd Latin American Test Symposium (LATS)* (pp. 1-6). IEEE. https://doi.org/10.1109/LATS57337.2022.9937026

Tóth, A., Nagy, L., Kennedy, R., Bohuš, B., Abonyi, J., & Ruppert, T. (2023). The human centric industry 5.0 collaboration architecture. *MethodsX*, 11, 102260. https://doi.org/10.1016/j.mex.2023.102260

Ungureanu, A. V. (2020, August). The transition from industry 4.0 to industry 5.0. The 4Cs of the global economic change. In *16th Economic International Conference NCOE 4.0 2020* (Vol. 13, pp. 70-81). Editura Lumen, Asociatia Lumen. https://www.proceedings.lumenpublishing.com/ojs/index.php/lumenproceedings/article/download/319/342

Vilar-Dias, J. L., Junior, A. S. S., & Lima-Neto, F. B. (2023). An interpretable digital twin for self-aware industrial machines. *Sensors*, *24*(1), 4. https://doi.org/10.3390/s24010004

Wang, B., Zhou, H., Li, X., Yang, G., Zheng, P., Song, C., & Wang, L. (2024). Human digital twin in the context of Industry 5.0. *Robotics and Computer-Integrated Manufacturing*, 85, 102626. https://doi.org/10.1016/j.rcim.2023.102626

Wang, H., Lv, L., Li, X., Li, H., Leng, J., Zhang, Y., Thomson, V., Liu, G., Wen, X., Sun, C., & Luo, G. (2023). A safety managementapproach for Industry 5.0′s human-centered manufacturing based on digital twin. *Journal of Manufacturing Systems*, *66*, 1-12. https://doi.org/10.1016/j.jmsy.2022.11.013

Wang, S., Zhang, J., Wang, P., Law, J., Calinescu, R., & Mihaylova, L. (2024). A deep learning enhanced digital twin framework for improving safety and reliability in human robot collaborative manufacturing. *Robotics and Computer-Integrated Manufacturing*, 85, 102608. https://doi.org/10.1016/j.rcim.2023.102608

Xiang, W., Yu, K., Han, F., Fang, L., He, D., & Han, Q. L. (2023). Advanced manufacturing in industry 5.0: A survey of key enabling technologies and future trends. *IEEE Transactions on Industrial Informatics*, *20*(2), 1055-1068. https://doi.org/10.1109/TII.2023.3274224

Xiao, L., Han, D., Yang, C., Cai, J., Liang, W., & Li, K. C. (2023). TS-DP: An efficient data processing algorithm for distribution digital twin grid for Industry 5.0. *IEEE Transactions on Consumer Electronics*, 70(1), 1983-1994. https://doi.org/10.1109/TCE.2023.3332099

Xie, J., Liu, Y., Wang, X., Fang, S., & Liu, S. (2024). A new XR-based human-robot collaboration assembly system based on industrial metaverse. *Journal of Manufacturing Systems*, *74*, 949-964. https://doi.org/10.1016/j.jmsy.2024.05.001

Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of manufacturing systems*, 61, 530-535. https://doi.org/10.1016/j.jmsy.2021.10.006

Yin, Y., Zheng, P., Li, C., & Wang, L. (2023). A state-of-the-art survey on augmented reality assisted digital twin for futuristic human-centric industry transformation. *Robotics and Computer-Integrated Manufacturing*, 81, 102515. https://doi.org/10.1016/j.rcim.2022.102515

Zhang, Q., Wei, Y., Liu, Z., Duan, J., & Qin, J. (2023). A framework for service-oriented digital twin systems for discrete workshops and its practical case study. *Systems*, *11*(3), 156. https://doi.org/10.3390/systems11030156

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