

CONCEPTUAL FRAMEWORK FOR DIGITAL TWINS AND VIRTUAL COMMISSIONING IN INDUSTRY 5.0 INDUSTRIALIZED CONSTRUCTION

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ABSTRACT: The emergence of Industry 5.0 (I5.0) represents a transformative shift in industrialization, emphasizing human-centric, sustainable, and resilient production systems. I5.0 builds on Industry 4.0 (I4.0) technologies such as Digital Twins (DTs) for real-time monitoring, predictive analytics, and process optimization, and Virtual Commissioning (VC) for testing and validating automation systems in virtual environments before physical deployment. Additionally, I5.0 incorporates human-robot collaboration (HRC), AR/VR training for workers, predictive analytics, and smart reconfigurable manufacturing (SRM) to further advance its objectives. However, the integration of DTs and VC, particularly for I5.0 Industrialized Construction (IC) robotic assembly, remains underexplored. While standards like ISO 23247 and the Reference Architecture Model for Industry 4.0 (RAMI 4.0) provide frameworks for integrating DTs in I4.0 manufacturing, they lack specific requirements and practical guidelines for I5.0 IC. This study addresses the aforementioned gap by proposing a novel conceptual DT system architecture that integrates VC to support I5.0 principles, using ISO 23247, RAMI 4.0, and the Asset Administration Shell (AAS) as foundations. A comprehensive literature review and standards analysis identified essential requirements for IC, enabling a high-level DT-VC architecture. The framework aligns with ISO 23247's layers, RAMI 4.0's AAS, and I5.0 goals, enhancing resilience through its modularity that enables plug-and-produce DT-based SRM with predictive analytics. Meanwhile, VC improves efficiency in HRC and productivity. This work initiates integration guidelines, paving the way for future IC factories to adopt I5.0, with validation to refine its efficacy further ahead. The architecture ensures interoperability, governance, and scalability tailored to IC.

1. INTRODUCTION

Industrialized Construction (IC) is rapidly gaining adoption as robotic systems enhance productivity, safety, and efficiency in both off-site construction (OSC) and on-site installation (Dou et al. 2022; Tehrani et al. 2022). The emergence of Industry 4.0 (I4.0) has transformed manufacturing with automation and smart manufacturing systems (SMS), however, high initial costs, uncertain Return on Investment (ROI), technical complexities, and a skilled labor shortage (Attouri et al. 2022) pose significant challenges to the adoption of supporting technologies. Digital Twins (DTs), a primary emerging technology in I4.0, enhance the functionality of SMS by enabling real-time monitoring, analysis, and optimization (Soori et al. 2023). DTs are leveraged in processes like virtual commissioning (VC) to test and validate SMS early for enhanced efficiency, reducing costs, minimizing disruptions, and shortening lead times (Schamp et al. 2018). Industry 5.0 (I5.0) builds on the core concepts of I4.0 by introducing protocols focused on human-centricity, sustainability, and resiliency to add value to automated processes. By leveraging SMS and DTs as key enabling technologies (van Erp et al. 2024), I5.0 seeks to achieve a competitive advantage through the

integration of human creativity and machine precision (Aslam et al. 2020). Several standards have been developed that aim to ensure consistency and interoperability in DT integration in IC. The ISO 23247 standard outlines a reference architecture for DTs in manufacturing, emphasizing the essential requirements necessary for their development (ISO 2021a). Additional guidelines focused on specific DT components complement ISO 23247, serving as a comprehensive set of resources to enhance the integration of DT systems (Mao and Gong 2022). Additionally, the Reference Architecture Model for Industry 4.0 (RAMI 4.0) is a standardized framework for implementing I4.0-compliant solutions (DIN 2016). It provides a structured approach to factory digitization by utilizing the Asset Administration Shell (AAS) as the standard for asset representation. RAMI 4.0 serves as a foundational model for integrating smart manufacturing technologies like DTs, ensuring their alignment with Industry 4.0 principles (Lindner et al. 2023). Despite the increasing exploration of DTs in the construction industry for post-construction applications, there remains a significant gap in standard integration knowledge. While ISO 23247 and RAMI 4.0 provide guidelines for integrating DTs into I4.0 manufacturing, their direct applicability to the IC is still underexplored (Calvetti et al. 2025), and their adaptability to emerging I5.0 priorities around human-centricity, resilience, and sustainability remains uncertain.

This research proposes a conceptual high-level architecture for integrating DTs and VC for IC robotic assembly, aligned with ISO 23247 and RAMI 4.0 standards and I5.0 principles. The goal is to conceive a DT system to enhance IC automation and productivity, advancing toward I5.0 objectives, with empirical validation planned as a future step. The study is structured as follows: Section 2 provides background on DTs, VC, and standardization efforts. Section 3 outlines the methodology and presents a conceptual system architecture framework for DTs and VC in I5.0 IC, detailing requirements aligned with ISO 23247 and RAMI 4.0 reference architectures. Section 4 illustrates and discusses the system architecture's application via a hypothetical scenario, concludes the study, and identifies future research directions.

2. BACKGROUND

2.1 Robotic Assembly in Industrialized Construction from Industry 4.0 to Industry 5.0

I4.0 began in Germany in 2011, bringing digital technologies such as the Internet of Things (IoT), advanced robotics, DTs, and artificial intelligence (AI) to revolutionize manufacturing by enabling autonomous assembly through SMS (Lasi et al. 2014). The European Commission later introduced I5.0, extending I4.0 by emphasizing human-centricity, sustainability, and resiliency and prioritizing the capability of human intelligence to enhance the functionality of advanced technologies (Lv 2023). By 2030, modular construction, a type of off-site construction (OSC), is expected to reach a market value of \$130 billion in Europe and the U.S (Bertram et al. 2019). Despite its success in delivering cost-effective solutions, the sector continues to grapple with inefficiencies in shop floor production, as manual assembly remains labor-intensive and susceptible to errors, resulting in delays and elevated costs (Alqahtani et al. 2023). Automation and the integration of I4.0 technologies can alleviate these challenges by enhancing productivity, reducing labor costs, streamlining design and manufacturing, and mitigating assembly-related challenges (Gharbia et al. 2020). George et al. (2023) identified key innovations of I5.0 in OSC manufacturing, including smart reconfigurable manufacturing (SRM), which uses multi-functional production cells, plug-and-produce components, and SMS to enable resiliency to changes in assembly lines. These adaptable robotic systems enhance efficiency by streamlining assembly line transitions, improving customization and sustainability. I5.0 also leverages IoT networks and collaborative robots (cobots) that monitor data to enhance human-machine collaboration and safety on the shop floor. Additionally, augmented reality (AR) and virtual reality (VR) are used in training for workforce skill development (Piccarozzi et al. 2024). Circular production methods can also be implemented and optimized with the use of AI to identify and analyze opportunities for waste reduction. Although promising, technical infrastructure, regulatory compliance, and cybersecurity pose challenges to the adoption of I5.0 in OSC robotic assembly (George et al. 2023).

2.2 Digital Twins (DTs) and Virtual Commissioning (VC) in Manufacturing

ISO 23247 defines DTs in manufacturing as digital representations specifically designed to mirror an observable manufacturing element (OME) (ISO 2021b). OMEs include personnel, machinery, materials, processes, facilities, environmental conditions, products, and relevant documentation. DTs are especially useful because of the synchronization between the physical entity and its digital counterpart, where changes and status are reflected in near real time. The ISO 23247 standard defines a DT System as an interconnected framework that facilitates DT functionalities (ISO 2021b). This system comprises digital and physical entities, interoperable components, data exchanges, and models, with integrated interfaces enabling seamless data flow between the physical and digital realms (ISO 2021b). Aivaliotis et al. (2019), Ozturk (2021), Soori et al. (2023), and Intizar Ali et al. (2021) have emphasized the transformative potential of DTs in manufacturing, citing benefits such as enhanced efficiency, reduced costs, and improved product quality. DTs enable diverse applications, including process optimization, real-time monitoring, predictive maintenance, and safety enhancement. These capabilities drive continuous improvement and adaptability of assembly lines, minimize downtime for changes and inspections, and facilitate collaboration between human and machine.

VC leverages DTs to run advanced simulation to test and validate automation systems before physical construction of assembly lines (Albo and Falkman 2020). Unlike traditional commissioning, which involves on-site testing and often disrupts production, VC enables early detection of programming errors and production system flaws in a virtual environment, reducing lead times and costs while simplifying the commissioning process (Lee and Park 2014). The level of detail in VC models must align with the required testing scope. Plant-level simulations focus on metrics like overall equipment effectiveness (OEE), inventory, and throughput, while machine-level models require finer granularity to capture critical features such as failure behavior and kinematics (Puntel-Schmidt and Fay 2015). This balance ensures effective VC tailored to the application's needs. VC employs different methods to link control systems to simulation models: Software-in-the-Loop (SiL), which emulates control hardware for offline testing; Hardware-in-the-Loop (HiL), connecting real control hardware to real-time simulations; and Hybrid Commissioning or Reality-in-the-Loop (RiL), coupling real plants with virtual controls hence bridging the gap between purely virtual simulation and real-world commissioning (Striffler and Voigt 2023; Lee and Park 2014; Noga et al. 2022). Human-in-the-loop (HiTL), tailored for I5.0, integrates human operators into IC robotic assembly by leveraging Human DTs (HDTs). These HDTs provide detailed virtual models of human actions, surpassing simpler representations (Agote-Garrido et al. 2023). Additionally, HiTL utilizes VR/AR environments to improve equipment arrangement, worker training, and safety compliance while reducing risks and increasing efficiency (Albo and Falkman 2020; Rueckert et al. 2020; Dammacco et al. 2022). These methods collectively form a hierarchical VC framework, as shown in Figure 1, advancing from purely virtual (SiL) to hybrid (RiL) and human-integrated (HiTL) approaches, supporting I5.0's commissioning goals. For instance, BMW Group, a German automotive manufacturer, developed a comprehensive Factory DT, including realistic 3D human and operations simulation, serving as a training and information hub where employees interact using VR goggles (BMW Group 2024). Nonetheless, DTs in these contexts face implementation challenges such as high costs, integration technical complexities, and the need for specialized expertise (Abayadeera 2024). Additionally, low-quality data, unstable network connectivity, and the vast volumes of sensor-generated data pose risks to effectiveness and security, requiring advanced IoT algorithms for data accuracy and management (Soori et al. 2023). Addressing these barriers is essential to fully leverage DTs and VC for innovation and efficiency in I5.0 IC robotic assembly.

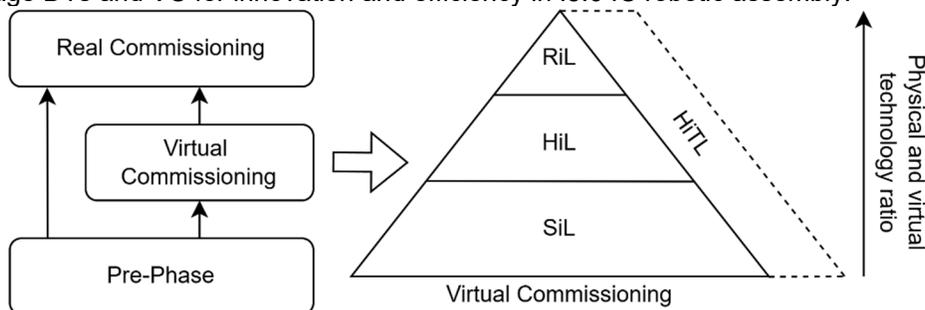


Figure 1: VC technological pyramid (Adapted from Korpai et al. 2024).

2.3 Standards and Reference Architectures

ISO 23247 provides a reference architecture for developing DTs in manufacturing. The standard is organized into four parts: Part 1 establishes foundational concepts, constraints, and requirements by clarifying essential terminology. Part 2 of the ISO 23247 standard outlines the reference architecture, which includes key entities such as the User Entity, DT Entity, Device Communication Entity, and OME Entity. These entities are further broken down into sub-entities, and sub-entities into functional entities responsible for the functionalities of the DT system. These functionalities can be added and scaled in a modular way, allowing for flexibility and adaptability. Part 3 focuses on the digital representation of manufacturing elements, distinguishing between static and dynamic information while integrating existing standards for accurate modeling (ISO 2021c). Part 4 specifies technical requirements for information exchange, utilizing four networks: the User Network (connecting users and the DT for services like visualization and analysis), the Service Network (linking DT sub-entities), the Access Network (transmitting data and commands between device communication, DT, and user entities), and the Proximity Network (enabling data collection and command transmission between device communication and OMEs). These networks ensure seamless communication and interoperability across the framework (ISO 2021d).

RAMI 4.0 is a three-dimensional reference architecture for I4.0, structured around Layers, Hierarchy Levels, and Life Cycle and Value Stream axes. The Hierarchy Levels Axis organizes assets into levels such as product, subsystem, and interconnected instances, enabling flexible information exchange. The Life Cycle and Value Stream Axis categorizes assets into type (shared properties) and instance (unique properties), managed via the AAS across development, production, and operation. Additionally, the Industrial Internet Reference Architecture (IIRA), developed by the Industrial Internet Consortium (IIC) and representing American Industrial Internet standards, offers a complementary alignment with RAMI 4.0, thereby extending its reach. The Layer axis in RAMI 4.0 mirrors the functional domains of IIRA's Functional Viewpoint but is more tailored to manufacturing, making it more suitable for applications within the manufacturing sector (Fraile et al. 2019). The AAS, an integral part of RAMI 4.0, is a standardized format that structures asset data through a header (identification) and body (sub-models describing asset functionality), ensuring interoperability and lifecycle management (Lindner et al. 2023). The Layers axis represents IT perspectives on asset digitization, aligning with the ISO 23247 framework. From bottom to top, the Asset Layer corresponds to OMEs, the Integration Layer enables data access, and the Communication Layer ensures standardized data exchange, matching the device communication domain in ISO 23247. The Information and Functional Layers structure data and define asset capabilities (e.g., analytics, simulations), aligning with the Digital Twin domain. The Business Layer links to the user domain, supporting decision-making through DT services (Melo et al. 2024). While the AAS primarily covers the Integration, Communication, and Information Layers of RAMI 4.0's Layers axis, the DT extends to the Functional and Business Layers, leveraging AAS sub-models for data structuring. This synergy between RAMI 4.0, AAS, and ISO 23247 enables advanced industrial digitization and DT development, creating a cohesive framework for SMS (Melo et al. 2024).

3. PROPOSED FRAMEWORK

The ISO 23247-2 reference architecture was utilized to develop a proposed framework for a DT system with VC capabilities. Essential requirements were derived from the literature review, focusing on interoperability and the I5.0 principles to inform the key functional entities selected for the framework. Human-centricity requirements include facilitating human-robot collaboration (HRC) by integrating human digital twins (HDTs), AR/VR, wearable technologies, and cobots. These technologies enable the use of HiTL VC to enhance worker safety and experience, allowing for training and practice of safety procedures in virtual shared environments. Additionally, they leverage VC simulations to test and optimize ergonomic conditions, reducing physical strain. For sustainability, it leverages VC to simulate and test material usage and energy consumption, optimizing resource efficiency, reducing waste, and minimizing carbon emissions. To ensure resilience, the system supports SRM, enabling adaptable production lines to respond to market changes, and incorporates predictive maintenance through AI-driven analytics to reduce downtime and operational risks. Distributed computing enhances real-time data processing and scalability, enabling

efficient handling of large volumes of sensor and IoT data. For interoperability, the framework relies on the AAS to facilitate seamless data exchange and real-time synchronization, while cybersecurity measures (e.g., encryption, access control) ensure system reliability and trust. These requirements collectively enable real-time decision-making, advanced analytics, and human-machine collaboration, driving innovation, efficiency, and adaptability in I5.0 manufacturing DT systems.

The proposed framework comprises five Layers. The Observable Manufacturing Elements (OME) Layer represents physical entities and operations in manufacturing, such as materials, equipment, and processes. Supported by the AAS, it ensures asset information is interoperable with the DT framework by way of sensors that monitor production, wearable technologies, and cobots. The Data and Device Control (DCDC) Layer manages data collection, preprocessing, and control from OMEs. Using standardized protocols and the AAS, it facilitates data exchange between physical and digital systems, ensuring real-time synchronization. The DT Core (DTC) Layer synchronizes with OMEs, hosting applications such as simulations and analytics tailored for I5.0 applications. It exchanges real-time, structured data with the User Interface and Visualization (UIV) and DCDC Layers. The UIV Layer oversees user interactions through interfaces like data dashboards, AR/VR, and synchronization with the Manufacturing Execution System (MES) and the Enterprise Resource Planning (ERP) system, enabling human-machine collaboration and training. Finally, the Cross Systems Integration (CSI) Layer operates across all Layers, providing key semantic data translation such as sustainability metrics and security support. Leveraging the AAS ensures real-time, context-aware data transformation to maintain integrity across the framework. Together, these Layers create a cohesive architecture that supports real-time synchronization, advanced analytics, and human-centric interactions, aligning with I5.0 principles.

As shown in Figure 2, this framework addresses user interface and key issues including: (1) the integration of all interconnected assets leveraging AAS, (2) real-time synchronization between the physical and virtual factories for interactive simulation and functionality tailored to I5.0 applications, (3) comprehensive data aggregation of all elements, flows, and services, and (4) flexibility and scalability through modular

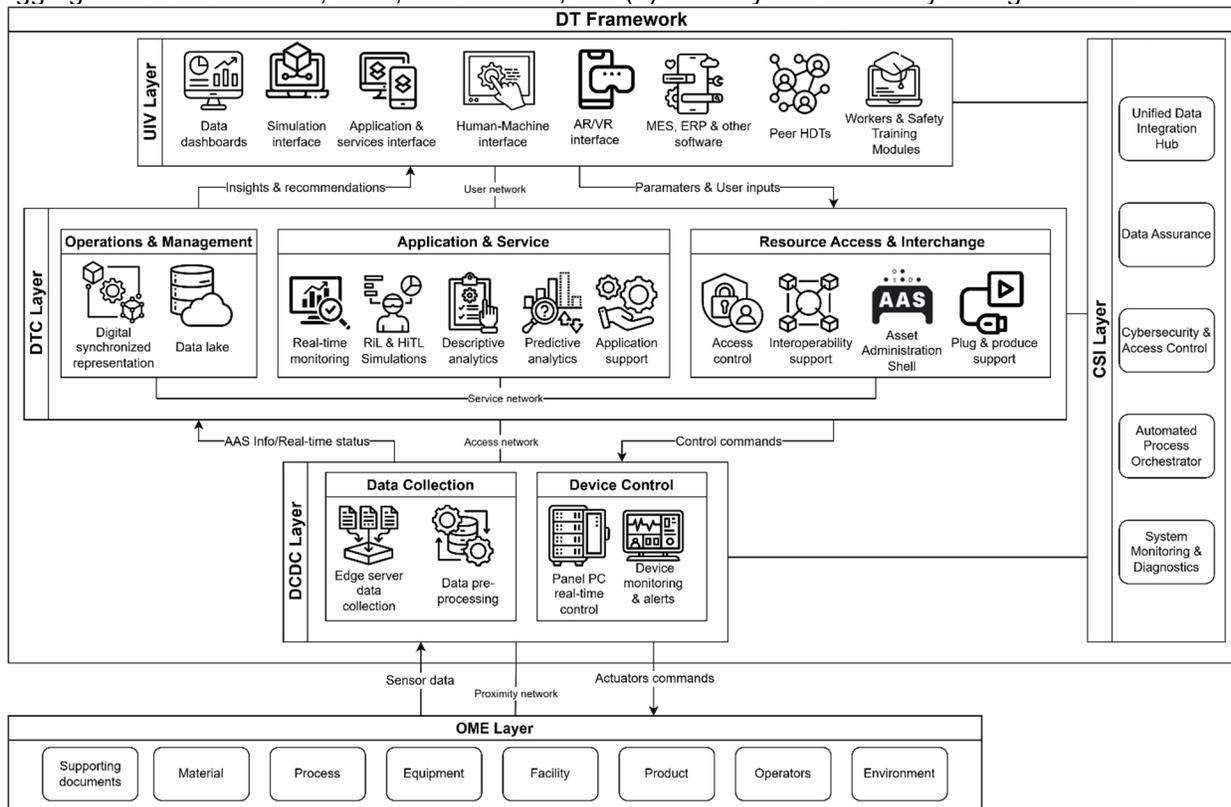


Figure 2: Proposed framework of a DT system integrating VC for I5.0 IC Robotic Assembly.

components. The Proximity Network links the DCDC and OME Layers, enabling real-time data collection and control. The Access Network connects the DCDC Layer with the DTC and UIV Layers, while the Service Network synchronizes data and hosts services within the DTC Layer. Lastly, the User Network facilitates interaction between the UIV and DTC Layers, supporting effective decision-making and user engagement. This integrated architecture ensures seamless communication and data exchange across all operational levels in the I5.0 IC robotic assembly.

The framework adheres to the ISO 23247 domain structure, enabling real-time synchronization, bidirectional data flow, predictive analytics, and what-if simulations to support VC workflows in I5.0 IC robotic assembly. For VC functional entities, the DT comprises sub-entities that support variable-detail OMEs models, process validation, control logic verification, error handling, and design and performance optimization of the production line. It also includes smart control functionality, supported by interoperable protocols like OPC UA and MQTT for real-time data exchange. The framework also integrates RAMI 4.0, leveraging AAS for standardized digital representation and communication interfaces for flexibility in I5.0 manufacturing.

4. DISCUSSION

The proposed architecture can be explained through a use-case scenario involving a panelized construction IC factory, providing a theoretical evaluation that approximates the conditions of a real-world assembly-based manufacturing system. Consider the hypothetical scenario of an IC panelized construction factory shopfloor comprised of independent and interconnected automated multifunctional production cells, each performing all required tasks to produce wall panels. The cells consist of advanced robotic systems equipped with specialized end-effectors for wall panel assembly. The DT system optimizes assembly processes and enables I5.0 applications compliant with ISO 23247 and RAMI 4.0, encompassing the interconnected Layers: OME, DCDC, DTC, UIV, and CSI. At its core, the DT system can leverage a 3D platform, such as NVIDIA Omniverse, for high-fidelity 3D visualization and utilize NVIDIA Isaac Sim for hosting and synchronizing the DTs models, enabling real-time simulation and validation, as referenced by (Ullrich et al. 2024). The AAS serves as the standardized I4.0 interface, ensuring seamless digital representation and communication of assets across the system. A distributed computing approach optimizes performance, with edge computing handling local sensor data preprocessing for low-latency decision-making, while a centralized data lake stores historical and operational data for AI-driven predictive analytics powered by NVIDIA's AI frameworks. System integration is achieved through Beckhoff's TwinCAT 3 industrial control platform, with OPC UA over TSN ensuring robust real-time communication and interoperability. The OME Layer encompasses physical assets such as multi-functional robotic stations enabling an SRM approach, safety and sustainability sensors, and operators utilizing wearable technologies, along with processes like component assembly and quality control. The DCDC Layer utilizes edge servers (e.g., Panel PCs) for sensor data collection (e.g., energy performance, carbon emission, etc.) and preprocessing, with TwinCAT 3 managing control logic and ABB IRC5 controllers executing robotic tasks. The DTC Layer hosts the DT in NVIDIA Isaac Sim, synchronizing it with the physical system and enabling real-time RiL and HiTL testing and validation. The test benches are organized into three levels: Machine, Process, and Shopfloor. At the Machine Level, systems such as the Power and Energy and HRC benches focus on optimizing energy use and ensuring safe interactions between humans and machines. The Process Level includes tools like the End-to-End Workflow and Circular Economy benches, which validate process integration and promote the sustainable use of materials. At the Shopfloor Level, solutions such as Production Scheduling, Resource Allocation, Ergonomics, and Worker Well-being benches enhance operational resilience and improve worker comfort. Historical data stored in a cloud-based data lake supports predictive analytics, while the AAS ensures structured data exchange and interoperability. The UIV Layer provides immersive visualization through the NVIDIA Omniverse 3D platform, supporting AR/VR interfaces and web/mobile apps for real-time monitoring, workers and safety virtual training modules, and interconnected peer HDTs. Finally, the CSI Layer ensures secure and efficient data integration, leveraging OPC UA, RESTful APIs, and orchestration engines to automate processes and coordinate system-wide operations.

By proposing key functional entities for each of the ISO sub-entities and integrating the AAS, the architecture standardizes asset management and ensures compliance with RAMI 4.0's Life Cycle and Layers Axes. A hybrid data management approach leverages Edge Computing for real-time processing and cloud storage for historical data, with AAS information maintained across both systems. Communication protocols like OPC UA over TSN and MQTT are proposed for ISO's proximity, access, service, and user networks, ensuring seamless interoperability. The DT architecture embodies the core principles of I5.0. By enabling immersive virtual environments, it revolutionizes training and safety, enabling risk-free skill development in complex scenarios such as MEP installations. Additionally, material optimization for wall panel production and energy consumption simulations contribute to enhancing the factory's sustainability. Factory resilience is enhanced through the VC of multi-functional production stations, demonstrating the potential to minimize factory spatial requirements, optimize investment strategies, and dynamically adapt to variable market demands. Lastly, the system's I5.0 potential extends to predictive maintenance and supply chain adaptability, creating a robust ecosystem capable of anticipating and mitigating potential disruptions.

5. CONCLUSION

This study investigated the integration of DTs and VC within I5.0 by proposing a high-level framework that provides a conceptual foundation for embedding DTs and VC into IC robotic assembly, facilitating a transition to I5.0. A theoretical use case of a panelized construction IC factory demonstrated the framework's application, with empirical validation planned for future research. The ISO 23247 and RAMI 4.0 standards, along with VC methods, were integrated with I5.0 principles to bridge the knowledge gap and provide guidelines for the integration of DT-VC architectures in IC factories. The proposed multi-layered framework aims to promote human-centricity through immersive training and safety applications, promote sustainability by monitoring and optimizing material usage and energy consumption, and improve resilience through adaptive manufacturing strategies and scalable system design. This work demonstrates the potential of DT-driven VC to revolutionize IC, paving the way for future advancements in flexible manufacturing ecosystems that translate to efficiency on the construction site.

Future research will focus on developing a prototype DT of a multi-functional robotic research cell for panelized construction, enabling the generation of empirical data to refine the architectural framework and establish performance metrics aligned with I5.0 objectives, thereby evaluating its efficacy. Investigations should also explore the scalability and interoperability of the DT system by integrating interconnected DTs and manufacturing software applications, enabling a comprehensive Digital Factory that optimizes production processes. Long-term field studies are crucial to assess adaptability, address implementation challenges, and enhance robustness in I5.0 IC robotic assembly. Collaborative industry partnerships will provide practical insights, support continuous refinement, and accelerate the commercialization feasibility of the DT system.

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