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An Industry 5.0 Compliant Human-Robot Collaboration Digital Twin Framework for African Medium Scale Enterprises

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Abstract

Industry 5.0 emphasizes human-robot collaboration, where Digital Twins (DTs) connect physical and digital operations for efficient, flexible work. Existing DT frameworks often focus on full-system autonomy or prediction, overlooking structured, task-level coordination between Human and Robot Digital Twins (HDT and RDT). This paper introduces a minimal, modular framework that enables shared task-based collaboration between HDT and RDT agents. Built on the Cross Domain Digital Twin (CDDT) design pattern, it supports real-time, role-specific interaction. The framework provides a scalable foundation for collaborative DT systems aligned with Industry 5.0, offering a practical base for future human–robot coordination research.

A. Introduction

A Digital Twin (DT) is a live, virtual replica of a physical system or entity, kept in constant sync through real-time, two-way data exchange. As Juárez-Juárez et al. (2021) explain, a true DT not only reflects the state of its physical counterpart but can also influence it enabling dynamic monitoring, control, and decision-making in smart environments. While DTs have played a major role in automating systems under Industry 4.0, that phase largely focused on machine-centred efficiency and left little room for direct human-machine collaboration. Industry 5.0 builds on these foundations by placing humans back at the centre, promoting interaction between human workers and intelligent systems such as collaborative robots ("cobots") to achieve more resilient, sustainable, and personalized operations (Maddikunta et al., 2022; Nahavandi, 2019). Within this shift, Human Digital Twins (HDTs) have emerged as digital representations of workers that capture their physical, physiological, and behavioural states in real time. As shown in both conceptual and applied work (Miller & Spatz, 2022; Modoni & Sacco, 2023), HDTs offer new ways to monitor health, ergonomics, and performance in complex work environments. In parallel, Robot Digital Twins (RDTs) have evolved to model robotic systems in real time tracking kinematics, internal states, and control signals to support predictive maintenance, coordination, and task planning. Ramasubramanian et al. (2022) emphasize that modern DTs now attempt to mirror entire Human–Robot Collaboration (HRC) setups, not just individual components. As HDTs and RDTs continue to mature, they lay the foundation for more integrated, intelligent, and adaptive work systems making their collaboration a critical next step in Industry 5.0 settings.

Despite the growing adoption of Digital Twins in industrial and collaborative systems, most current implementations treat Human Digital Twins (HDTs) and Robot Digital Twins (RDTs) as separate entities with limited or no direct interaction. Existing HDT frameworks often focus on monitoring human physiology or ergonomics (Modoni & Sacco, 2023; Miller & Spatz, 2022), while RDTs typically manage robotic state, path planning, and predictive maintenance (Ramasubramanian et al., 2022). However, in real-world work environments especially those aligned with Industry 5.0, humans and robots frequently share tasks, coordinate actions, and depend on each other for task completion. Yet there is a noticeable lack of lightweight, practical frameworks that allow HDTs and RDTs to collaboratively interact at the task level in real time. Most systems fall short in modelling such shared interactions or providing a common interface, such as a shared task list, through which responsibilities can be assigned, tracked, and executed collaboratively. This disconnect hinders the potential for seamless, synchronized human-robot workflows in real-world applications.

The project aims to design and implement a collaborative framework that enables Human Digital Twins (HDTs) and Robot Digital Twins (RDTs) to interact through a shared coordination system within a work environment. The goal is to move beyond passive monitoring by allowing both digital twins to participate in task planning and execution through a common, real-time interface. To achieve this aim, the project will pursue the following objectives: study existing literature and frameworks related to HDTs, RDTs, and human–robot collaboration to understand current capabilities and limitations, design a lightweight, task-based collaboration model that serves as a shared layer between HDTs and RDTs centred around a real-time shared database, develop a prototype proof-of-concept that simulates real-time task execution, demonstrating a basic collaborative interaction loop, evaluate the system's effectiveness in enabling communication between human and robot twins, with a focus on simplicity, responsiveness, and clarity of interaction.

This study contributes both practically and academically to the ongoing development of Digital Twin systems in collaborative work environments. From a practical perspective, the proposed framework addresses a growing need for lightweight, real-time coordination between humans and robots in shared tasks particularly in contexts such as manufacturing, logistics, and smart factory operations. By introducing a shared task layer between Human and Robot Digital Twins, the system supports more efficient and flexible interactions without requiring complex robotic automation or heavy infrastructure. Academically, the project bridges a noticeable gap in existing literature by demonstrating how two distinct types of digital twins can be connected through a task-driven collaboration model. While most research treats these twins in isolation, this study offers a simple, prototype-level solution for enabling interaction between them. The work also lays a foundation for future exploration into autonomous task negotiation, role adaptation, and multi-agent coordination using Digital Twins, particularly in Industry 5.0-aligned systems.

This study also focuses on the design and development of a simplified collaborative framework where Human Digital Twins (HDTs) and Robot Digital Twins (RDTs) can interact through a shared, real-time task list in a simulated work environment. The implementation will be limited to a python-based prototype. The scope does not include integration with physical robots, use of biometric sensors, or deployment in a real-world industrial setting. Likewise, the Robot Digital Twin will simulate task reception and acknowledgment but will not perform intelligent task planning or physical execution. The project emphasizes the collaborative interaction layer between DTs rather than the underlying AI or control systems, offering a focused and achievable model for human–robot task coordination at the prototype level.

This project will adopt an Object-Oriented Analysis and Design (OOAD) approach to model the system's structure and components, allowing for modular development and clear separation of responsibilities between the human and robot digital twin elements. The collaborative framework will be guided by the Cross-Domain Digital Twin (CDDT) design pattern, with the primary implementation focusing on the Data and Service layers where real-time task updates and twin behaviour modelling take place. Although the CDDT design pattern promotes systems that are Autonomous, Collaborative, and Evolvable (ACE), this project will concentrate specifically on the Collaborative aspect, demonstrating task-level interaction between Human and Robot Digital Twins.

B. Literature Review

Industry 5.0 builds on the foundations of Industry 4.0 by reintroducing the human element into digital manufacturing and cyber-physical systems, emphasizing collaboration between humans and intelligent machines. Chaurasia et al. (2025) highlight three defining principles of this new paradigm: human-centricity, sustainability, and resilience marking a shift away from purely efficiency-driven automation and toward systems where human workers actively interact with robotic counterparts. This transition aligns with the rise of collaborative robots (cobots), adaptive interfaces, and AI systems designed to augment, rather than replace, human capabilities. Nahavandi (2021) similarly frames Industry 5.0 as a corrective evolution, rebalancing the over-automation tendencies of Industry 4.0 by fostering personalized and human-friendly production environments. Marinelli (2023) offers a practical perspective, presenting a taxonomy of human–robot collaboration modes such as pre-programming, adaptive manipulation, and imitation learning. He also emphasizes the need to address safety, ergonomic design, and mutual trust in shared workspaces highlighting both the potential and complexity of human–robot task sharing in real-world industrial settings. Together, these studies establish a clear foundation for exploring frameworks that enable dynamic, task-level interaction between human and robot agents in digitally enhanced environments.

B.1 Digital Twin Technology

Digital Twins (DTs) are virtual counterparts of physical systems that enable real-time monitoring, simulation, and decision-making through continuous data synchronization and feedback. A typical DT architecture includes layers that mirror the physical world, process its data, and coordinate tasks in connected systems. A foundational model has been outlined comprising the physical asset, its digital representation, and the infrastructure that supports interaction between them. Within this layered design, recent studies have emphasized the significance of the Data Layer, where live inputs from sensors, logs, or operator commands are collected and structured to represent the physical system accurately. On top of this, the Service Layer handles behavioural modelling, simulation, and system-level responses based on predefined logic or real-time input. These layers form the operational core of what is known as the Cross Domain Digital Twin (CDDT) design pattern, a modern approach to building scalable, interconnected DT systems across different roles or domains.

Human Digital Twins (HDTs) extend the general Digital Twin concept by modelling individual humans in real time, integrating physiological, behavioural, and interaction data to support human-centric systems. Modoni & Sacco (2023) introduce the "Human-CENTRO" framework, presenting an HDT architecture used in an Industry 5.0 manufacturing case study that captures worker movements, task inputs, and interactions within a collaborative environment. This work demonstrates how HDTs can mirror human actions digitally, enabling continuous monitoring and feedback loops in practical settings. Miller & Spatz (2022) further consolidate understanding by offering a unified definition and structure for HDT systems, noting that while they hold significant potential for enhancing design, training, and ergonomics, standardized schemas and multi-domain data integration remain underdeveloped in current implementations. Together, these studies show how HDTs are both conceptualized and applied, highlighting frameworks for real-time worker models and pointing out the critical need for structured, interoperable human representations.

Robot Digital Twins (RDTs) are virtual counterparts of robotic systems designed to mirror their physical state, simulate behaviour, and support intelligent control and automation. Unlike general-purpose DTs, RDTs are tightly coupled with actuators and control systems, enabling them to both monitor and influence robotic behaviour in real time. Delgado et al. (2020) define RDTs as software architectures that enable real-time reflection of robot motion, support decision-making, and enhance transparency in cyber-physical applications. Similarly, Zhang et al. (2020) emphasize the role of RDTs in smart manufacturing environments, where they are used to coordinate robot operations, manage predictive maintenance, and simulate process adjustments before physical execution. Ullah et al. (2020) extend this concept to autonomous vehicle systems, illustrating how DTs enable remote control, behaviour monitoring, and cybersecurity enhancements for mobile robotic platforms. Collectively, these studies demonstrate that RDTs are not passive data models, but active control entities embedded within automation workflows making them critical enablers of real-time responsiveness and system-level coordination in increasingly intelligent work environments.

Human–Robot Collaboration (HRC) within Digital Twin (DT) systems represents a growing research focus, aiming to synchronize human and robotic agents in shared work environments. Unlike traditional automation, DT-enabled HRC systems require both the Human Digital Twin (HDT) and Robot Digital Twin (RDT) to dynamically exchange data, interpret intent, and co-manage tasks in real time. Ramasubramanian et al. (2022) highlight the technical challenge of achieving accurate, bidirectional synchronization between human and robot DTs, especially in contexts requiring shared physical and digital awareness. Kousi et al. (2021) present a DT-based system for collaborative assembly lines, showing how integrated simulation models can reconfigure workflows by factoring in both human flexibility and robotic precision. These approaches emphasize the importance of continuous feedback loops, contextual alignment, and adaptive coordination, yet they also expose the complexity of deploying such systems in practical settings. Most existing frameworks rely on domain-specific architectures and tightly coupled control systems, leaving a gap for lightweight, task-focused models that simplify the collaborative interface. These insights directly inform the rationale for this study's pursuit of a streamlined DT collaboration framework centred on real-time task sharing between HDT and RDT agents.

Across the reviewed literature, significant strides have been made in developing Human and Robot Digital Twins (HDTs and RDTs) as independent systems, each with their own sensing, modelling, and control capabilities. However, there remains a noticeable gap in the design of lightweight, modular frameworks that enable real-time collaboration between HDTs and RDTs at the task level. Existing approaches to human–robot collaboration using DTs often rely on complex architectures, tightly integrated physical systems, or high-fidelity simulation environments, which can limit accessibility and scalability. Additionally, while the Cross Domain Digital Twin (CDDT) design pattern offers a structured, multi-layered foundation for building collaborative DT systems, much of the focus in literature has been on autonomy or system evolution leaving the collaborative ("C") aspect of ACE underexplored in practical, task-driven contexts.

This project addresses that gap by focusing specifically on the Data and Service Layers of the CDDT framework, proposing a simplified implementation that facilitates live task sharing between an HDT and RDT. In doing so, it contributes a foundational structure for collaborative DT systems in work environments, aligning with Industry 5.0 principles while remaining feasible for real-world adoption.

B.2 Cross-Domain Digital Twin Design Pattern

Cross-Domain Digital Twin (**Figure 1**) is a five-layer design pattern for digital twins across domains, that supports implementation of the ACE design dimensions, namely: **A** for Autonomous and Artificial Intelligence (AI); **C** for Collaborative and Conversational; and **E** for Evolvable and Extensible. It assumes a Cloud of Digital Twins (CoDT) where each DT is a proxy for a physical object, via the IoT and all DTs interconnect on the cloud. CDDT support cross-domain DT implementation through the ACE model, i.e. DT implementations across diverse domains can have one or a combination of the following attributes: AI-driven or Autonomous, Collaborative and/or Conversational, and Evolvable or Extensible. The layers include:

Data Layer: The bottom Data layer provides cloud storage called "DataStore" and a Connector component. The Connector reads and writes data to and from the DataStore which then formats sensor streams from physical objects or other DTs. The Connector also raises events for the upper layers.

Service Layer: The Service layer above holds models of the physical asset, and it is driven by Connector events. This layer implements the real-world behaviours of the DT.

Application Layer (Base & Composite DT): At this layer, CDDT defines a base CDDT class for any single-twin, and a CompositeDT class for twins composed of multiple parts. A simple DT inherits CDDT, when it needs subparts it "evolves" into a CompositeDT that contains multiple child DTs.

Intelligence Layer (AI): This layer adds two higher-level twin types, the CollectionDT and NetworkDT. The CollectionDT represents a collection of similar DTs and the NetworkDT represents a possibly heterogeneous network of DTs. These classes accumulate large volumes of data suitable for machine learning and analytics.

Autonomous Layer: The top Autonomous layer evolves Composite, Collection, and Network DTs into AutonomousCompositeDT, AutonomousCollectionDT, and AutonomousNetworkDT via AI reinforcement and imitation learning. These fully-fledged autonomous DTs can conversationally collaborate with each other.

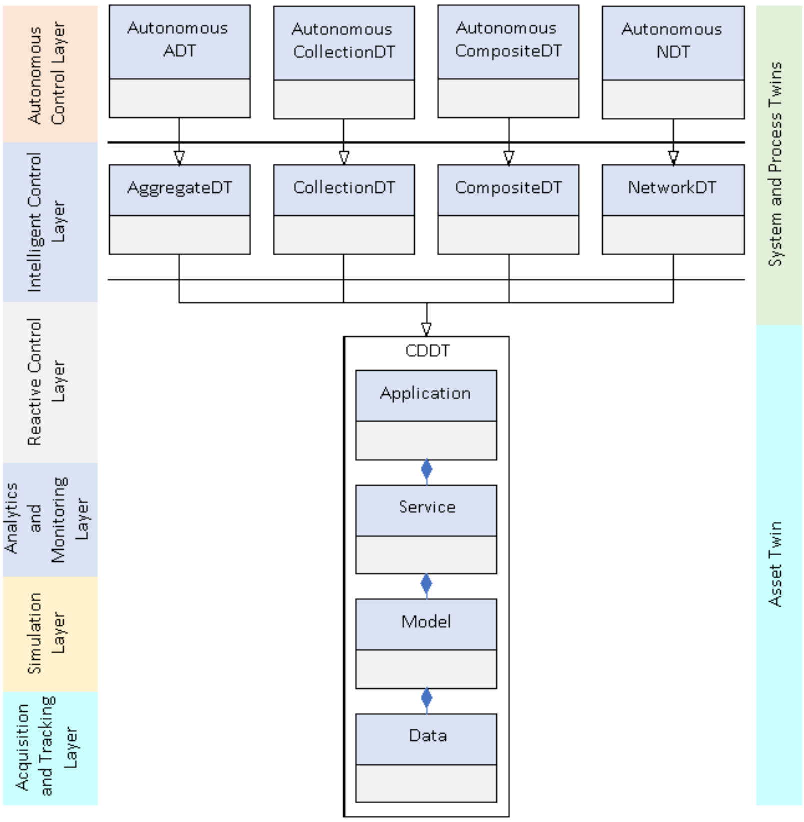


Figure 1. Cross-Domain Digital Twin Design Pattern

B.3 Digital Twin Framework for Human-Robot Collaboration

This section presents the methodological approach adopted in designing the proposed collaborative digital twin framework. The design is grounded in the Cross-Domain Digital Twin (CDDT) design pattern and incorporates the Human (or Worker) Digital Twin (H/WDT), Robot Digital Twin (RDT), Product Digital Twin (PDT) and Production Line Digital Twin (PLDT).

The objective is to provide a lightweight and modular structure that enables task-level synchronization and workflow orchestration in a manufacturing context. By leveraging JSON-based datastores with timestamped logs and role-specific connectors, the framework ensures traceability, autonomy, and real-time coordination between human, robot, and product agents while remaining implementation-agnostic and scalable.

B.3.1. Functional Requirements

The proposed Human–Robot Collaborative Digital Twin (HRC-DT) framework is defined by three core functional requirements (FRs) that guide the design of the constituent Digital Twins and the overall orchestration logic. These requirements are essential for ensuring the system provides resilient, traceable, and modular support for collaborative production environments.

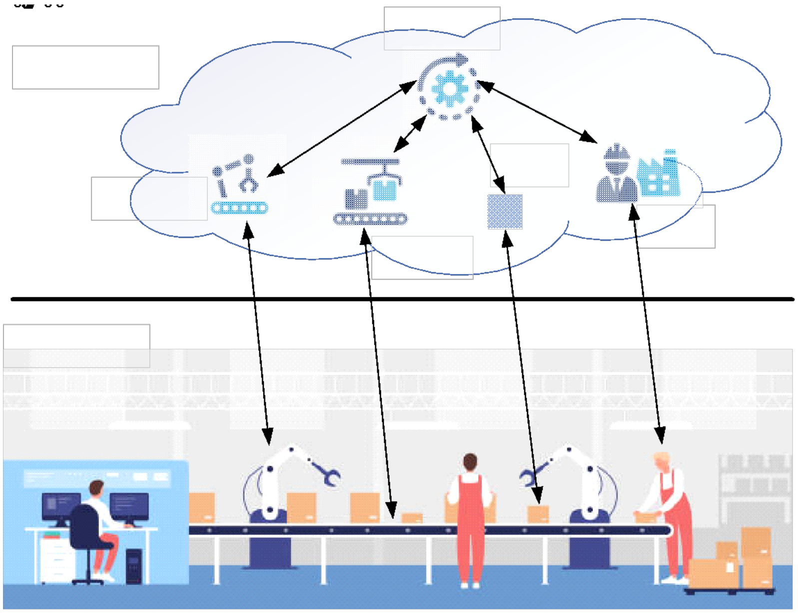


Figure 2. A Production Line with Human-Robot Collaboration showing the Internet of Digital Twins on the Cloud Infrastructure and Human Workers and Physical Assets in the Physical Layer

FR1: Task-Level Synchronization and State Management

The framework must provide mechanisms to ensure real-time, reliable task synchronization between the HDT and RDT agents. This requirement dictates that the HRC-DT must continuously manage task handoffs, prevent system deadlocks and ensure the physical product's status is always accurately reflected in its digital counterpart. The successful completion of a station by any agent must immediately trigger the system to transition the product to the next assigned task, maintaining a perfectly synchronized state across the collaborative workspace.

FR2: Comprehensive Traceability and History Logging

The framework must establish and maintain an immutable, timestamped log of all agent actions and state transitions. This traceability capability is fulfilled by the Product Digital Twin (PDT), which serves as the permanent record of the product's entire lifecycle. Every action taken by the HDT or RDT must be recorded with associated metadata and a precise timestamp.

FR3: Agent-Agnostic Workflow Definition and Assignment

The framework must utilize an agent-agnostic master workflow definition that separates process rules from execution logic. It should define the complete sequence of tasks but allow for tasks to be explicitly and modularly assigned to either a human (HDT) or a robot (RDT).

B.3.2 Non-Functional Requirements

To ensure the framework is practical, scalable, and compliant with the dynamic demands of Industry 5.0, the following Non-Functional Requirements (NFRs) govern the system's quality attributes:

NFR1: Real-Time Responsiveness (Performance)

The framework must operate with minimal latency to ensure smooth, safe, and fluid collaboration between human and robot agents. Specifically, the HRC-DT must complete its core orchestration loop—from receiving an agent's Task Complete notification to issuing the Next Task Assignment to the subsequent agent—with a maximum delay not exceeding 100 milliseconds (ms). This rapid response time is critical for guaranteeing safety during physical handoffs and minimizing operator idle time.

NFR2: Resilience and Fault Tolerance (Availability)

The system must demonstrate resilience by maintaining continuity and data integrity during component failures. The framework shall be capable of gracefully handling the temporary disconnection or failure of either the HDT or RDT agent. In such an event, the system must automatically pause the specific product's workflow that relies on the failed agent, provide an appropriate diagnostic message to the remaining operational agent, and hold the product's state for subsequent recovery, ensuring no data loss in the PDT log.

NFR3: Workflow Reconfigurability (Flexibility)

The design must ensure easy and rapid adaptability to changes in the production process. The production sequence rules, which are externalized in the PLDT, must be modifiable by authorized personnel (e.g., a supervisory Digital Twin) through a simple configuration update (e.g., updating a JSON structure). The framework must be able to adopt this updated workflow for any new product instances immediately upon initialization, without requiring the recompilation or restart of the core HRC-DT orchestration logic.

B.3.3 Human-Robot Collaborative Framework Digital Twin Design

The proposed framework uses the Cross-Domain Digital Twin (CDDT) design pattern as a foundation, for building the Product Digital Twin (PDT), the Production Line Digital Twin (PLDT), the Human Digital Twin (HDT) and Robot Digital Twin (RDT) upon it. The architecture is organized into three layers, namely the Data Layer, the Service Layer, and the Application Layer, each with distinct responsibilities.

At the application layer, the AggregateDT acts as an overarching construct designed to encapsulate collaborative systems. In the context of the car manufacturing case study, the Human–Robot Collaboration Digital Twin (HRC-DT) is defined as an AggregateDT. It is composed of two CompositeDTs, the Human Digital Twin (HDT) and Robot Digital Twin (RDT), together with two base CDDTs, the Product Digital Twin (PDT) and Production Line Digital Twin (PLDT). Unlike the CompositeDT, whose internal structure is fixed and whose sub-DTs are not interchangeable, the AggregateDT flexibly binds together heterogeneous DTs in a way that preserves the aggregate’s collaborative identity while allowing its constituent members to be swapped or replaced as needed. This flexibility is central to modelling collaboration, since different HDTs, RDTs, or PLDT configurations may be integrated into the same aggregate structure without altering its overarching role.

Each member DT under the AggregateDT maintains its own Data Layer and Service Layer. The CompositeDTs (HDT and RDT) exemplify this by embedding hierarchies of sub-DTs: the HDT may include elements such as a HeartDT or BrainDT, while the RDT may contain an ArmDT or SensorDT. Their Data Layers capture operational states such as biometrics, motion sequences, and tool availability, while their Service Layers provide the corresponding execution logic, including skills and task control routines. Similarly, the base CDDTs operate with their own data and service responsibilities. The PDT Data

Layer records the state of an individual product, its identity, production history, and the tasks it has completed along the production line, while the PLDT Data Layer defines the overall workflow, specifying station sequences, assignments, and routing logic. Their Service Layers ensure execution by mapping tasks to stations in the case of the PLDT, and by recording product progress in the case of the PDT.

The AggregateDT itself does not replicate these underlying data or services. Instead, it provides orchestration logic that draws on the states of the PDT and PLDT while simultaneously coordinating the execution logic of the HDT and RDT. In doing so, the AggregateDT functions as the collaborative glue of the framework, ensuring synchronized execution between human and robot entities. At the same time, lightweight user interfaces are provided for each DT, such as dashboards for the HDT, monitoring panels for the RDT, PLDT, and product trackers for the PDT while the HRC-DT interface presents a higher-level view of the orchestration. This layered separation of concerns highlights how the AggregateDT enables flexible, modular collaboration while respecting the autonomy of its constituent digital twins.

B.3.3.1 Human Digital Twin

The Human Digital Twin (HDT) serves as the digital proxy for the human operator within the collaborative system, acting as a crucial enabler for Industry 5.0's human-centric principles. Its primary function is not merely to simulate human presence, but to monitor the operator's current state and translate it into actionable data for the collaborative framework. This ensures that task assignments are optimized for safety, efficiency, and worker well-being. The HDT’s operation relies on a continuous stream of information inflow. Input data to the HDT includes both physiological metrics (e.g., heart rate, estimated fatigue levels, cognitive load captured via wearable sensors) and contextual data (e.g., current location, task engagement status, skill proficiency score from the worker profile). Upon receiving this information, the HDT processes the data to assess the human agent's readiness and capability for the next assigned task. This involves advanced logic that evaluates key Industry 5.0 metrics, such as the Well-being Score and Skill Development Rate, ensuring that the proposed collaboration scenario remains sustainable and ethical. The output of this processing is a dynamic capability profile and a simple task readiness status which is shared with the HRC-DT orchestrator.

Conversely, the HDT is responsible for directing and supporting the physical human. Information outflow from the HDT to the human operator includes explicit task assignments received from the HRC-DT (e.g., "Proceed to Station 3: Insert Component A") and real-time contextual feedback. This feedback is crucial for safety and efficiency, encompassing safety alerts (e.g., proximity warnings regarding the robot) and performance data aimed at continuous skill improvement. This closed-loop interaction establishes the HDT as the essential interface between the human worker and the digital coordination layer.

B.3.3.1 Robot Digital Twin

The Robot Digital Twin (RDT) functions as the essential digital counterpart to the physical robotic system. While its primary concern is operational efficiency and resource management, within this framework, the RDT’s crucial role is to maintain the integrity and stability of the collaborative environment by accurately reporting its status and capabilities to the HRC-DT orchestrator. The RDT's function begins with a continuous stream of input data captured directly from the physical robot. This data includes operational telemetry such as the robot’s current position, speed, active program status, and real-time joint torque readings. Additionally, the RDT receives maintenance data (e.g., error logs, predicted component wear) and, critically, task assignment requests issued by the aggregate HRC-DT. The core logic of the RDT involves processing this information to validate and simulate task execution. When a task is assigned, the RDT checks for operational constraints (e.g., payload limits, required maintenance checks) and simulates the predicted execution time. This validation ensures that the robot is physically and logically capable of executing the command without failure or compromising safety. The RDT ultimately determines its task readiness status and communicates its operational availability to the HRC-DT.

Finally, the RDT facilitates the physical work cycle through its information outflow back to the robot controller and the wider framework. This outflow includes specific motion commands (e.g., "Execute Pick-and-Place routine at Station 4") and, when necessary, real-time adjustments to parameters such as speed and force, particularly in safety-critical zones. Most importantly, upon completion of a task, the RDT issues a definitive Task Complete notification to the HRC-DT, triggering the progression of the product through the collaborative workflow.

B.3.3.1 Product and Production Line Digital Twins

The operational context and process definition for the framework are provided by the Product Digital Twin (PDT) and the Production Line Digital Twin (PLDT). These two components serve as the foundational knowledge base and state repository for the entire collaborative system. The Production Line Digital Twin (PLDT) defines the Master Workflow. It is conceived as a read-only blueprint that details the standardized, sequential arrangement of all work stations and tasks along the production path. Crucially, the PLDT explicitly assigns each individual task to either the HDT or the RDT, thereby pre-defining the required agent and ensuring structured collaboration. This static definition governs the possible paths of any product through the system. In contrast, the Product Digital Twin (PDT) is a dynamic entity that serves as the single source of truth for a specific physical product instance. Every new product entering the line inherits the PLDT’s workflow structure.

The PDT's primary responsibility is to maintain the product's current status and its complete execution history. When an agent (HDT or RDT) completes a task, the PDT is updated with a timestamped log detailing the agent, the completed task, and any relevant metrics. This continuous logging provides unassailable traceability and allows the HRC-DT orchestrator to determine the product's precise location and its next required step in the workflow. Together, the PLDT sets the rules, and the PDT tracks the adherence to those rules.

B.3.3 Collaboration Framework Digital Twins

The Human–Robot Collaborative Digital Twin (HRC-DT) serves as the Aggregate Digital Twin (AggregateDT) and the central intelligence hub of the entire proposed framework. It is the core component responsible for achieving and managing task-level synchronization, effectively acting as the collaborative glue that binds the HDT, RDT, PDT, and PLDT into a cohesive system. Its function is to transcend the individual capabilities of the agents to ensure reliable, efficient, and safe collaboration.

The HRC-DT's logic revolves around a continuous synchronization loop driven by status updates. Its primary role is to monitor the production status and coordinate the transition of the product between the human and robot agents. This coordination is initiated when the HRC-DT receives a Task Complete notification from the currently executing agent (either the HDT or the RDT). Upon this event, the orchestrator immediately updates the relevant PDT instance, logging the task completion, the responsible agent, and the execution timestamp to ensure permanent traceability. The HRC-DT then consults the PLDT to identify the next task required for the product based on its newly updated state. Finally, using the PLDT's predefined task assignment, the HRC-DT identifies the Next Agent and issues the specific Next Task Assignment command to that agent's Digital Twin. By strictly adhering to this precise orchestration logic, the HRC-DT manages the handovers, prevents system deadlocks, and guarantees that every product instance correctly follows the master workflow defined by the PLDT.

B.3.4 Data Model of the Product and Production Line DT

The proposed framework focuses on the Production Line Digital Twin (PLDT) and the Product Digital Twin (PDT) for its collaboration. These entities encapsulate the workflow definitions and product-specific execution histories that enable synchronization between human and robot contributions. Their structures are lightweight and implemented in JSON format to facilitate modularity and extensibility. Table 1 summarizes the data model of both datastores. The proposed framework focuses on two primary datastores for its collaboration, the Production Line Digital Twin's (PLDT) and the Product Digital Twin's (PDT). These entities encapsulate the workflow definitions and product-specific execution histories that enable synchronization between human and robot contributions. Their structures are lightweight and implemented in JSON format to facilitate modularity and extensibility. Table 1 summarizes the data model of both datastores.

Table 1. Data Model for PDT and PLDT

Datastore	Key Attributes	Description
PLDT	line_id, stations[], station_id, assigned_to	Defines the workflow of a production line, including its unique identifier, the ordered list of stations, and the assignment of each station to either the HDT or RDT.
PDT	product:id, line_id, stations_required[], stations_completed[], current_station, status, timestamp_log[]	Represents an individual product instance, recording its unique identity (e.g., RFID), the production line to which it is assigned, the sequence of stations inherited from the PLDT, its progress, current station, and timestamped history of completed tasks.

B.3.5 Digital Twins Use Cases

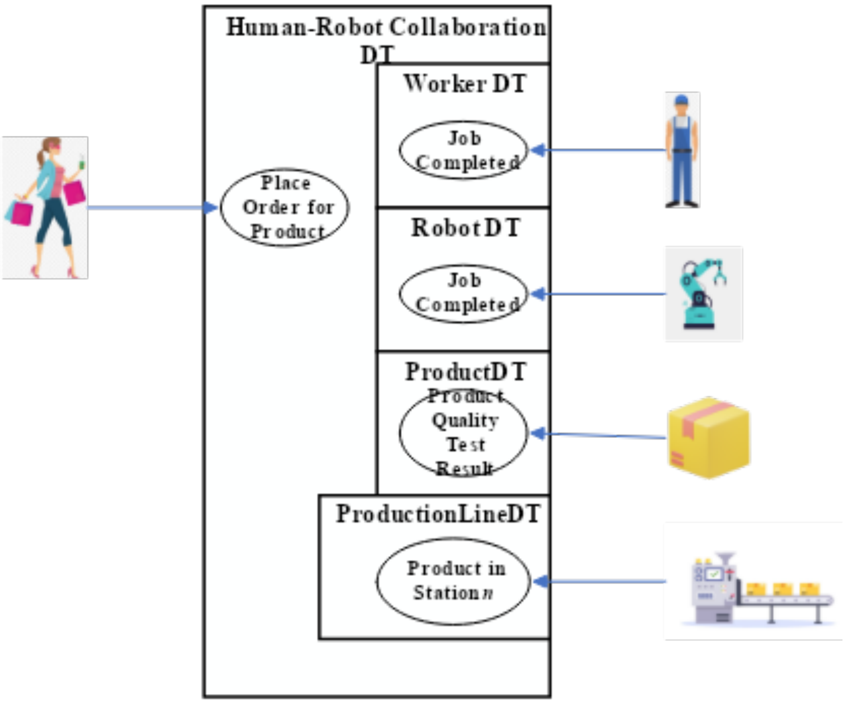


Figure 3. Use Case diagram

The proposed collaborative digital twin framework is demonstrated through a sequence of use cases that collectively describe the interaction between human, robotic, and product entities across the production workflow. Each use case represents a specific operational phase within the Human–Robot Collaboration Digital Twin (HRC-DT) and illustrates the manner in which digital and physical components synchronize to achieve autonomous production coordination.

B. 3.5.1 Customer Product Order

The use case begins with the customer placing an order for a customized product. Upon receiving this request, the HRC-DT initializes a corresponding Product Digital Twin (PDT) instance, assigning it a unique identifier such as an RFID tag that links the digital and physical representations of the product. The PDT automatically inherits its production workflow from the Production Line Digital Twin (PLDT), which defines the ordered sequence of stations and the assignment of tasks to either the Human Digital Twin (HDT) or Robot Digital Twin (RDT). This initialization process establishes the foundation for traceability and ensures that each product follows a well-defined and individualized workflow throughout its lifecycle.

B. 3.5.2 Job Completion

The use case focuses on task execution and job completion within the production line. As the product progresses through the sequence of stations defined by the PLDT, the HDT and RDT perform their respective operations. The HDT represents human actions—such as verifying input data, confirming assembly steps, or performing manual inspections—while the RDT mirrors the automated actions executed by robotic systems. Upon completing their assigned tasks, each digital twin updates its status to "Job Completed," transmitting this information to the HRC-DT alongside relevant timestamps and task identifiers. These updates provide a continuous and verifiable record of progress within the PDT, forming the basis for real-time monitoring and post-process analysis.

B.3.5.3 Station Transition

The use case describes the coordination logic that governs station transitions. Once both the HDT and RDT have reported successful completion of their respective tasks, the HRC-DT interprets these signals in relation to the PLDT's workflow structure. It then authorizes the product to advance to the next station, updating the PLDT to reflect the new state of progress. This ensures that operations proceed sequentially and synchronously, preventing inconsistencies between human and robotic activities. The HRC-DT thereby maintains control over the flow of production, guaranteeing that each product advances only when all preceding conditions are satisfied.

B.3.5.4 Product Activation and Synchronization

The use case illustrates the completion and synchronization of a product's digital lifecycle. When the final production station has been executed, the PDT consolidates all recorded data, including task timestamps, completion status, and quality test results. The HRC-DT then finalizes the product record, marking the PDT as "Completed" and synchronizing the aggregated results across all participating digital twins—the HDT, RDT, and PLDT. This final synchronization establishes full lifecycle traceability and verifies that the product's digital and physical states are aligned. The resulting dataset enables post-production evaluation of human–robot collaboration performance, validating both the accuracy and efficiency of the digital twin framework.

B.4 System Components and Interaction Flow

The proposed framework is realized through five interacting digital twins: the Production Line Digital Twin (PLDT), the Product Digital Twin (PDT), the Human Digital Twin (HDT), the Robot Digital Twin (RDT), and the Human–Robot Collaborative Digital Twin (HRC-DT). Each of these components assumes a distinct role, yet they operate together in a coordinated fashion to ensure seamless workflow execution.

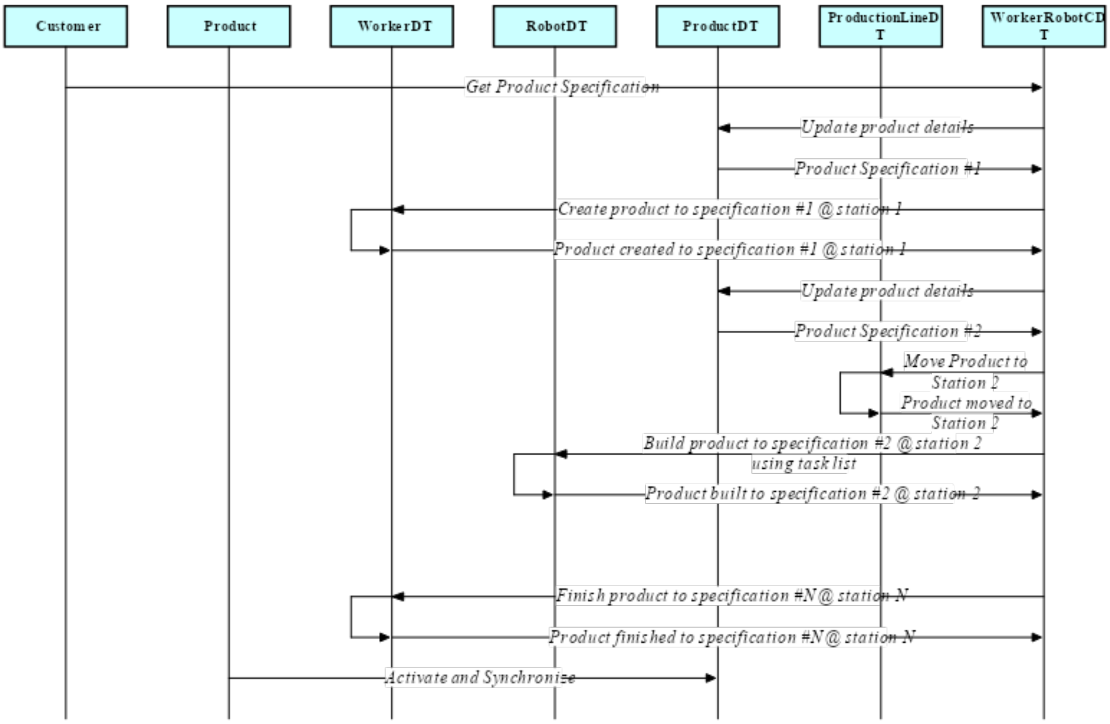


Figure 4. Sequence of interactions between digital twins in the proposed framework

The PLDT serves as the global reference for workflow definition.

It encodes production lines as sequences of stations, each station explicitly assigned to either the HDT or the RDT. By maintaining this information as a datastore, the PLDT establishes the order of execution and the distribution of responsibilities across human and robotic agents.

The PDT represents a single product instance as it traverses the workflow defined by the PLDT. Upon initialization, the PDT inherits the sequence of stations from the PLDT and maintains a record of its current state, completed tasks, and pending operations. Each update is timestamped to preserve traceability, thereby allowing the system to reconstruct the product's history if needed. The PDT thus functions as the dynamic log of the product's lifecycle.

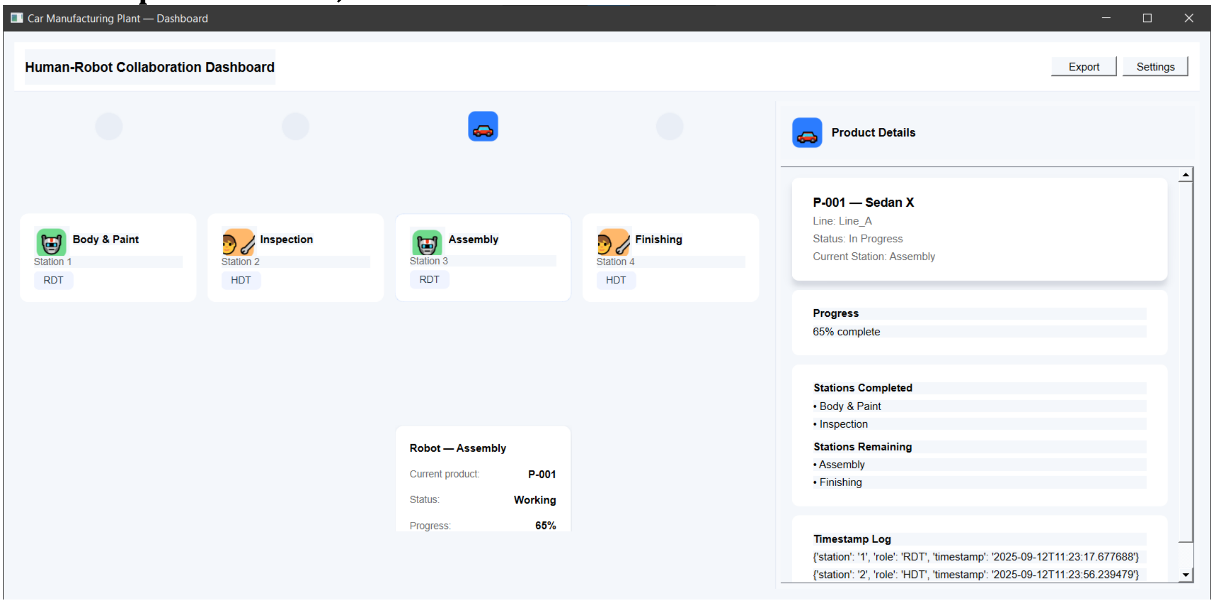
The HDT and RDT, each modelled as CompositeDTs, operate with their own internal Data and Service Layers but interact with the PDT to advance execution. The HDT reflects human actions such as inputting a product's RFID tag or confirming task completion, while the RDT reflects robotic execution, which may be automated within the simulation. In both cases, their interaction with the PDT ensures that product progress is consistently recorded according to the workflow dictated by the PLDT.

At the aggregate level, the Human–Robot Collaborative Digital Twin (HRC-DT) embodies the AggregateDT construct. It continuously monitors updates to the PDT, cross-references them with the PLDT, and orchestrates synchronization between the HDT and RDT. In this way, the AggregateDT ensures that human and robot actions remain coordinated while preserving modularity, since its constituent DTs (the HDT, RDT, PDT, and PLDT) can be interchanged or reconfigured without disrupting the aggregate structure.

The overall interaction begins when the HDT initializes a product by registering its RFID tag, which creates a new PDT entry linked to one of the production lines defined in the PLDT. As the product advances, each station is addressed in turn according to the PLDT definition. At human-assigned stations, the HDT confirms task completion, while at robot-assigned stations, the RDT records robotic operations. Each action updates the PDT with a timestamped log entry. The HRC-DT then interprets this update against the PLDT to determine the next station, thereby advancing the workflow. This cycle repeats until all required stations are completed, at which point the PDT is marked as finalized and the product is considered complete.

Through this interaction flow, the framework demonstrates how an AggregateDT can coordinate multiple heterogeneous DTs while retaining their individual autonomy. The PLDT ensures consistency of workflow definition, the PDT captures product-specific progress, the HDT and RDT enact their respective execution roles, and the HRC-DT guarantees synchronized coordination across all participants.

C. Implementation, Results and Discussion



Robot — Assembly
Current product: P-001
Status: Working
Progress: 65%

P-001 — Sedan X
Line: Line_A
Status: In Progress
Current Station: Assembly

Progress
65% complete

Stations Completed
• Body & Paint
• Inspection

Stations Remaining
• Assembly
• Finishing

Timestamp Log

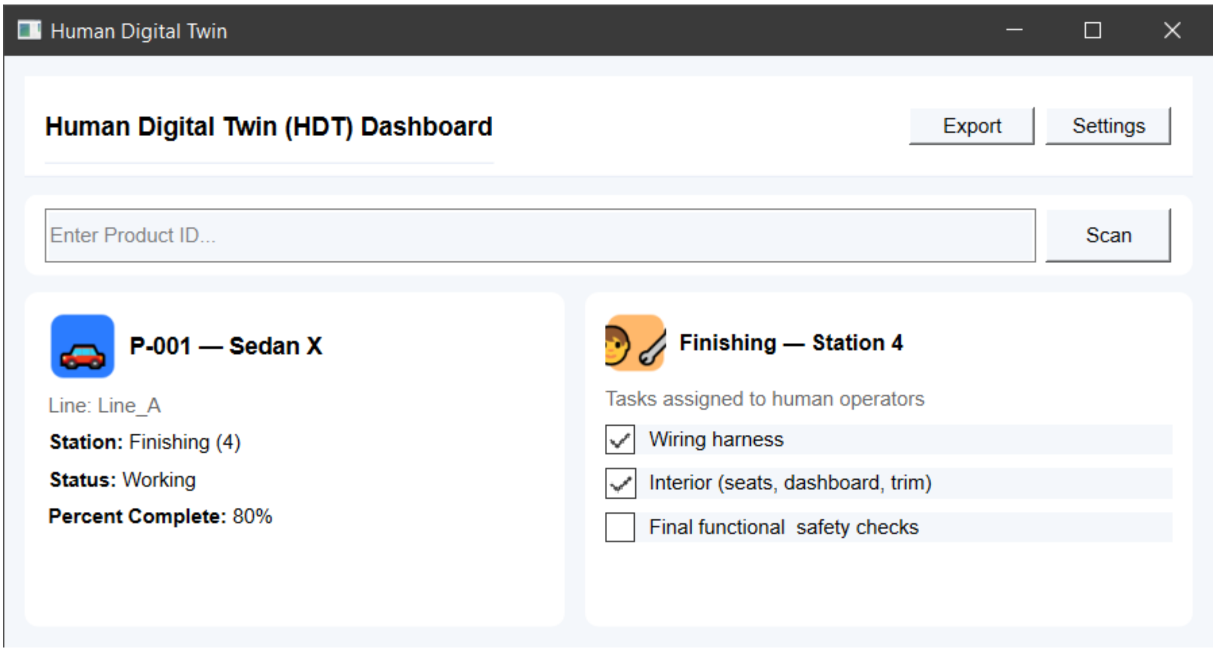
```
{'station': '1', 'role': 'RDT', 'timestamp': '2025-09-12T11:23:17.677688'}
{'station': '2', 'role': 'HDT', 'timestamp': '2025-09-12T11:23:56.239479'}
```

Figure 5. Main dashboard showing production line, product states, and active stations.

The proof-of-concept implementation of the collaborative digital twin framework demonstrates the coordination of human and robotic agents in a manufacturing workflow through the Cross-Domain Digital Twin (CDDT) pattern. The framework consists of the Production Line Digital Twin (PLDT), the Product Digital Twin (PDT), the Human Digital Twin (HDT), and the Robot Digital Twin (RDT). The PLDT defines the ordered sequence of stations for each production line, explicitly assigning tasks to either human or robot agents. The PDT captures the state of individual products as they traverse the workflow, maintaining information about the current station, completed stations, and timestamped logs of task execution, thereby ensuring traceability.

C.1 Implementation

Products are initialized by the HDT, which links each product to its corresponding production line as defined in the PLDT. Upon initialization, the PDT inherits the sequence of stations from the PLDT, setting the first station as the current active task. Human and robotic agents interact with the PDT to advance the product through its assigned workflow. Human actions, such as confirming task completion at a station, and robotic executions are reflected immediately in the PDT, updating both the current station and the log of completed tasks. The Human–Robot Collaborative Digital Twin (HRC-DT) continuously monitors these updates and determines progression to subsequent stations, maintaining synchronized execution between the human and robotic entities. **Figure 5** illustrates the collaborative dashboard interface during product initialization and progression through the assigned stations.



Human Digital Twin (HDT) Dashboard

P-001 — Sedan X

Line: Line_A

Station: Finishing (4)

Status: Working

Percent Complete: 80%

Finishing — Station 4

Tasks assigned to human operators

- ☑ Wiring harness
- ☑ Interior (seats, dashboard, trim)
- ☐ Final functional safety checks

Figure 6. HDT dashboard for product input and interactive completion of human-assigned finishing tasks.

The user interfaces, implemented as dedicated dashboards, provide clear and modular views for each digital twin. The main dashboard offers a production-wide perspective, displaying the current station of a product, its overall status, and the percentage of completion. Station cards distinguish between robot- and human-assigned tasks, and operators can expand details to view product histories, completed stations, and timestamped logs. Concurrently, the HDT dashboard provides a task-level view for human operators, enabling them to input a product ID, view product details, and interactively confirm completion of human-assigned finishing tasks. Screenshots from the simulation (**Figure 6**) demonstrate the dashboards updating as products advance from robot-operated to human-operated stations, confirming correct inheritance of station sequences from the PLDT and accurate logging of completed tasks.

Task execution is simulated with timing mechanisms to replicate realistic workflow durations, with human or robot agents executing tasks autonomously according to their assigned stations. Each completed station is recorded in the PDT along with a timestamp and the responsible agent, preserving a comprehensive execution history. The results indicate that products follow the defined sequence of stations accurately, with HDT and RDT agents completing tasks autonomously. The timestamped logs within the PDT provide accountability and allow reconstruction of product histories, confirming the framework's reliability in maintaining synchronized execution.

Overall, the implementation confirms that the proposed collaborative digital twin framework enables modular, synchronized, and traceable execution of human–robot workflows. The integration of JSON-based datastores with lightweight dashboards provides an accessible and extendable platform for monitoring, visualization, and autonomous task execution. The proof-of-concept successfully demonstrates the coordination of HDT and RDT agents, the inheritance of workflows from PLDT to PDT, and the real-time progression of multiple products in a shared digital environment.

C.2 Results and Discussions

The implementation of the proposed collaborative digital twin framework successfully demonstrated the autonomous progression of products through a defined production workflow. Each product, instantiated within the Human-Robot Collaboration Digital Twin (HRC-DT), inherited its sequence of stations from the Production Line Digital Twin (PLDT). Human Digital Twin (HDT) and Robot Digital Twin (RDT) agents executed tasks according to their assigned stations, updating the PDT with timestamped logs to maintain an accurate record of progress. Products progressed sequentially through their respective production lines, with HDT and RDT actions correctly synchronized. Task completion at each station was reliably logged, allowing for traceability of all operations.

The successful implementation of the proof-of-concept prototype directly validates the three core functional requirements (FRs) established for the Human–Robot Collaborative Digital Twin framework:

FR1: Task-Level Synchronization and State Management.

This requirement was confirmed by the system’s demonstrated ability to reliably manage handoffs between the simulated HDT and RDT agents. The results show that the HRC-DT orchestrator successfully monitored the completion of one agent's task and immediately assigned the successor task to the correct subsequent agent, ensuring the product always progressed sequentially and without interruption according to the workflow rules. This validates the core capability of the synchronization loop.

FR2: Comprehensive Traceability and History Logging.

The system’s successful fulfillment of this requirement was verified by the automatic and mandatory execution of the Create Timestamp action upon every task completion. The implementation results demonstrate that the Product Digital Twin (PDT) instances maintained complete, unalterable logs containing the agent ID, the task performed, and the exact time of execution. This provides the necessary foundation for auditing and reconstruction of the product history, confirming the framework's commitment to robust data integrity.

FR3: Agent-Agnostic Workflow Definition and Assignment.

The modularity and flexibility inherent in the design were validated by the structure of the Production Line Digital Twin (PLDT). The prototype demonstrated that the workflow sequence, including the explicit assignment of tasks to either human or robot agents, was entirely defined externally within the PLDT's configuration. This confirms the separation between the process definition and the execution logic, proving that the HRC-DT orchestrator can interpret and execute any configured workflow without requiring a change to its core synchronization mechanism.

Overall, the results validate that the framework effectively orchestrates human-robot collaboration in a digital twin environment, ensuring synchronized execution, traceable progress, and reliable workflow management across multiple products and production lines.

D. Conclusions

The study presented a lightweight and modular framework for human and robot digital twin collaboration in manufacturing using a Cross-Domain Digital Twin (CDDT) pattern. By integrating the Production Line Digital Twin (PLDT), Product Digital Twin (PDT), Human Digital Twin (HDT), and Robot Digital Twin (RDT), the framework enables synchronized execution of tasks, traceable progress of individual products, and autonomous coordination between human and robotic agents. The Aggregate DT structure ensured modularity by allowing base and composite DTs (HDT, RDT, PDT, PLDT) to interoperate seamlessly under the HRC-DT. The proof-of-concept implementation demonstrated that products correctly inherit workflows from the PLDT, progress sequentially through assigned stations, and maintain timestamped logs for accountability. The results confirm that the framework effectively supports task-level synchronization, real-time monitoring, and modular scalability, providing a reliable platform for evaluating human–robot collaboration in a digital twin environment.

E. Challenges and Future Work

While the proposed framework successfully demonstrates human–robot collaboration at a proof-of-concept level, several limitations and avenues for future research remain. First, the current implementation is constrained to lightweight simulations with JSON-based datastores, which may not scale efficiently for large, complex production environments. Second, the timing and execution of tasks are simplified, lacking full integration with real-world sensors or robotic control systems. Third, the framework currently assumes deterministic workflows without accommodating dynamic changes in production priorities or unexpected interruptions beyond simple pausing.

Future work will focus on enhancing the framework's scalability, robustness, and real-world applicability. Potential directions include integration with industrial-grade databases and PLCs for real-time production data, implementing advanced scheduling and prioritization algorithms to handle concurrent and dynamic workflows, and incorporating predictive analytics for human–robot task optimization. Additionally, expanding the visualization layer to provide richer, interactive monitoring interfaces will improve operator situational awareness and support decision-making in complex manufacturing environments.

F. References

[1] A. A. Malik and A. Brem, "Digital twins for collaborative robots: A case study in human–robot interaction," Robotics and Computer-Integrated Manufacturing, vol. 68, p. 102092, 2021. doi: 10.1016/j.rcim.2020.102092.

[2] A. Chaurasia, A. Yadav, D. Mishra, V. Agarwal, and K. Chaurasia, Transitioning from Industry 4.0 to Industry 5.0, pp. 270–276, 2025. doi: 10.1201/9781003641544-50.

[3] A. K. Ramasubramanian, R. Mathew, M. Kelly, V. Hargaden, and N. Papakostas, "Digital Twin for Human–Robot Collaboration in Manufacturing: Review and Outlook," Applied Sciences, vol. 12, no. 10, p. 4811, 2022. doi: 10.3390/app12104811.

[4] D. M. Botín-Sanabria, A.-S. Mihaita, R. E. Peimbert-García, M. A. Ramírez-Moreno, R. A. Ramírez-Mendoza, and J. d. J. Lozoya-Santos, "Digital Twin Technology Challenges and Applications: A Comprehensive Review," Remote Sensing, vol. 14, no. 6, p. 1335, 2022. doi: 10.3390/rs14061335.

[5] E. G. Kaigom and J. Roßmann, "Value-driven robotic digital twins in cyber–physical applications," IEEE Transactions on Industrial Informatics, vol. 17, no. 5, pp. 3609–3619, 2021. doi: 10.1109/TII.2020.3011062.

[6] G. E. Modoni and M. Sacco, "A Human Digital-Twin-Based Framework Driving Human Centricity towards Industry 5.0," Sensors, vol. 23, no. 13, p. 6054, 2023. doi: 10.3390/s23136054.

[7] M. E. Miller and E. Spatz, "A unified view of a human digital twin," Human-Intelligent Systems Integration, vol. 4, no. 1, pp. 23–33, 2022.

[8] M. G. Juarez, V. J. Botti, and A. S. Giret, "Digital twins: Review and challenges," Journal of Computing and Information Science in Engineering, vol. 21, no. 3, p. 030802, 2021.

[9] M. Marinelli, "From Industry 4.0 to Construction 5.0: Exploring the Path towards Human–Robot Collaboration in Construction," Systems, vol. 11, no. 3, p. 152, 2023. doi: 10.3390/systems11030152.

[10] M. S. Dihan et al., "Digital twin: Data exploration, architecture, implementation and future," Heliyon, vol. 10, no. 5, p. e26503, 2024. doi: 10.1016/j.heliyon.2024.e26503.

[11] N. Kousi et al., "Digital Twin for Designing and Reconfiguring Human–Robot Collaborative Assembly Lines," Applied Sciences, vol. 11, no. 10, p. 4620, 2021. doi: 10.3390/app11104620.

[12] X. Xu, Y. Lu, B. Vogel-Heuser, and L. Wang, "Industry 4.0 and Industry 5.0: Inception, conception and perception," Journal of Manufacturing Systems, vol. 61, pp. 530–535, 2021. doi: 10.1016/j.jmsy.2021.10.006.

[13] Y. Wang, Z. Su, S. Guo, M. Dai, T. H. Luan, and Y. Liu, "A survey on digital twins: Architecture, enabling technologies, security and privacy, and future prospects," IEEE Internet of Things Journal, vol. 10, no. 17, pp. 14965–14987, 2023