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EXPERIMENTING WITH DIGITAL TWINS: A LEGO®-BASED MODULAR TESTBED FOR SYSTEMATIC EVALUATION

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Abstract

Digital twins (DTs) promise improved decision-making under project uncertainty, but real-world implementations are costly and hard to compare. As DT research moves toward tighter feedback loops and greater autonomy, affordable and controllable environments for evaluating such DTs are lacking. This paper presents a modular DT testbed that combines LEGO®-based physical components with Raspberry Pi computers to support controlled variation of DT scenarios, feedback loops and automation levels. Two studies conducted in the testbed illustrate how DTs can be systematically evaluated across computational processes and physical execution. The testbed facilitates cost-effective and repeatable future research on autonomous DTs for construction management.

Introduction

DTs for construction management are receiving significant attention because project execution remains inefficient (Kookalani *et al.*, 2026). The basic promise is straightforward: link on-site conditions with a digital representation that supports situation awareness and more informed control. DT research has moved from isolated twins for a single building in operation to integrated systems intended to support complex project-level decisions (Whyte *et al.*, 2025). This shift matters because project disruptions are not isolated events; they emerge from complex interactions across trades, zones and time.

Current DT research follows two intertwined trajectories: speeding up feedback loops and increasing autonomy. Faster, more frequent data integration is motivated by the need for timely responses to disruptions and the desire for preventive action (Boje *et al.*, 2020). Accordingly, DT applications span timeframes from weekly coordination to more continuous monitoring under unstable conditions (Chacón *et al.*, 2024; Soman *et al.*, 2025). At the same time, DTs are envisioned to evolve from supporting data analysis in routine situations toward autonomous execution of non-routine actions, often realized through mobile on-site robotics (de Soto and Skibniewski, 2020; Agrawal *et al.*, 2023). However, accelerating feedback loops and automation levels do more than improve responsiveness; they reshape how work and decisions are distributed between humans and digital systems (Parasuraman, Sheridan and Wickens, 2000).

The value of DT implementations depends on alignment between automation level, organizational context, and intended use case, rather than on technical sophistication alone (Čustović *et al.*, 2025). Without such alignment and early user involvement, DTs risk underperforming when exposed to real project variability.

This situation creates a methodological bottleneck: transitioning DT concepts into operational prototypes and systematically studying their effects remain difficult. The inherent variability and the complex system-of-systems that characterize construction projects make it difficult to isolate the effects of specific DT features (Zhu *et al.*, 2024). It becomes unclear whether improvements are driven by the DT itself, by users' responses to it, or by coincidental project dynamics. While real-world DT studies provide valuable insights, they largely focus on monitoring and low-autonomy use cases and often depend on large, well-funded consortia (Brell-Çokcan and Schmitt, 2024; Soman *et al.*, 2025). As DT research shifts toward tighter feedback loops and greater autonomy, the field lacks affordable, controllable and repeatable environments that allow DT design choices to be tested and compared under realistic but manageable conditions.

To address this, we introduce a modular DT testbed that links digital intelligence with physical sensing and actuation in a miniaturized construction environment. The testbed builds on a LEGO®-based haptic simulation approach combined with Raspberry Pi single-board computers (SBCs), enabling controlled experimentation with bi-directional DTs and management strategies without access to full-scale construction sites. To support reuse and further development, the source code and digital models are available as supplementary data to this article.

Point of Departure

Digital Twins for Construction Management

DTs are virtual representations of physical objects, processes, or systems that are linked to the physical domain through bi-directional communication and are instantiated to perform specific operational or analytical functions (Čustović *et al.*, 2023; AlBalkhy *et al.*, 2024). The literature characterizes DTs as information systems that integrate heterogeneous data in real time, provide advanced analysis, predictive models for early disruption detection and automated recommendations (Sacks *et al.*, 2020; Saif, Doukari and Kassem, 2026).

Implementations and empirical testing are essential to demonstrate the functionality of a digital artifact beyond conceptual design (Tommelein, 2020). In construction, the dynamic nature of sites and the one-off character of projects make such testing significantly more difficult than in industries with stable and repeatable processes, such as manufacturing. Consequently, most field-based DT studies emphasize data acquisition and status visibility rather than active control. Virtual-to-physical interaction is generally realized by human managers, with DTs providing structured, timely input that informs planning adjustments and operational responses within existing supervisory workflows (olde Scholtenhuis and Soman, 2026). Even when DTs are designed to operate with limited autonomy, practical challenges persist.

Challenges with Digital Twin Implementations

Establishing fast feedback loops and high levels of DT autonomy in construction is difficult due to changing site conditions and organizational constraints (Saif, RazaviAlavi and Kassem, 2024). Chacón *et al.* (2024) show that technical feasibility alone is insufficient: although data collection and system deployment were successful, the insights generated were not adopted in site management procedures. Similarly, Zheng et al. (2025) report that data ownership concerns and commercial policies limit the application of DT systems in complex project settings involving multiple subcontractors. Soman *et al.* (2025) develop a comprehensive DT that integrates multiple production data streams to support weekly project meetings. Yet, despite the significant resources of a consortium setting, the study does not assess how the DT influenced managerial decisions or project performance, nor does it execute any physical work. Even when the DTs are deployed onsite, controlling the many interdependent variables to ensure research validity is very difficult.

In addition to methodological and organizational challenges, financial constraints strongly shape DT research. Deep process integration, real-time monitoring, and autonomous action typically require substantial investments (AlBalkhy *et al.*, 2024). For instance, the *Internet of Construction* project enabled controlled investigation by setting up a dedicated construction site with a simple load-bearing structure, but this was only possible through substantial financial and organizational resources of a large consortium (Brell-Çokcan and Schmitt, 2024). Higher levels of DT autonomy depend on cyber-physical systems capable of executing decisions, i.e., construction robotics. Although these have been widely studied, the significant capital investment required for robotic hardware has led to slow adoption (Walzer, 2025). Together, these examples illustrate the substantial practical constraints that limit testing of operational DT systems intended to support construction management.

Laboratory Environments for Construction Management Digitalization

Experiments are a valid method for evaluating the effectiveness of information system designs because they allow researchers to test defined design choices under controlled conditions (Hevner, March and Park, 2008). Laboratory testbeds provide a practical setting for such experiments. They enable researchers to specify the system design and boundary conditions, allowing selected parameters to be systematically controlled and varied across trials. Construction research has long relied on lab-like setups to address the scale, messiness, and risk of real projects, where controlled trials are hard to stage (Herbsman, 1986). In construction research, serious games have become a popular experimental tool, especially for studying lean construction practices (Bhatnagar *et al.*, 2023; Martinez *et al.*, 2023).

For DTs, however, the experimental requirements differ. DTs depend on a tight coupling between physical assets and virtual representations. This duality means that computer-only simulations or offline board games often cannot test key DT functions such as sensing, feedback, and control across physical and virtual layers. Laboratory testbeds for DT research, therefore, need to include both layers while still allowing researchers to control conditions and observe outcomes.

Only a few studies have built such DT-oriented laboratory setups, and they often address narrow technical goals. Jiang *et al.* (2022) use a 6-axis robot arm to simulate assembly processes of prefabricated modules. However, such robotic testbeds can be expensive, safety-critical, and difficult to reproduce when documentation is limited. Hasan *et al.* (2022) present a DT of a laboratory tower crane with a strong focus on physical realism and crane control. Yet, the setup does not connect DT capabilities to construction management decisions or project scenarios. Li *et al.* (2025) develop a DT testbed for status monitoring using computer vision. However, it focuses on monitoring and does not include actuators or user interfaces for instructing workers or coordinating actions. A further weakness across these efforts is their monolithic, purpose-built nature, which restricts replication and makes reconfiguration to other DT use cases difficult, especially when source code and reusable modules are not provided.

Taken together, the literature provides limited experimental means to test how DTs, when combined with robotics as autonomous hardware, affect construction management outcomes. Existing work tends to study DTs without meaningful physical actuation, or robots as isolated machines without management-related use cases. We address this gap by proposing a low-cost, scalable laboratory environment that integrates DT features from both the physical and virtual worlds to support controlled experiments in DT-enabled construction management.

Design Requirements

The development of the DT testbed is based on translating insights and challenges from prior DT studies into concrete system features. A primary requirement concerns representational breadth: the environment must support multiple construction use cases that can benefit from DTs, including project monitoring and control, dynamic replanning under uncertainty and workflow

analysis for performance evaluation. A second requirement addresses the virtual-to-physical twinning, requiring the inclusion of actuation for at least one mechanized site process, such as material lifting, to allow digital decisions to be evaluated against physical outcomes. A third requirement concerns decision authority, mandating support for both human-in-the-loop supervision and autonomous action execution in routine situations with explicit logging of decision rationales. In addition to these use-case-driven requirements, the testbed must realize system-level DT features including real-time communication, reliable data logging and querying, and adaptability across construction scenarios and scripting languages. We address these requirements through a combination of LEGO®-based haptic simulation with Raspberry Pi computers.

LEGO®-based mock-ups demonstrate effectiveness in modeling construction management tasks and in evaluating the impact of digital tools such as Building Information Modeling (BIM) or virtual reality (VR) (Sacks, Esquenazi and Goldin, 2007). Extending LEGO® bricks with programmable LEGO® motors enables actuation and creates closed-loop cyber-physical systems without extensive hardware development (Gawthrop and McGookin, 2004). The LEGO® Spike platform offers modular, preconfigured components that support rapid prototyping and system expansion.

Raspberry Pi SBCs provide a cost-effective yet performative computational backbone and are widely adopted as prototyping tools in scientific research across varying degrees of complexity (Mathe *et al.*, 2024). Their Linux-based ecosystem and compatibility with additional electronics hardware via GPIO interfaces and the Build HAT support integrated implementation of sensing, actuation, and computational functions.

Digital Twin Testbed

The DT testbed consists of (i) a LEGO®-based gantry robot and (ii) interactive workstations for human-DT interaction. Figure 1 presents the integrated setup.

Gantry Robot

The gantry robot serves as a programmable transport system for LEGO® elements, autonomously managing material flows, logging operational data and exchanging information with external services.

The mechanical structure consists of a crane track supported by four pillars on each side, carrying a crane bridge that moves longitudinally on four wheels. Mounted centrally on the bridge is a Raspberry Pi 5 SBC, fixed in position to ensure stable computation during operation. A LEGO® Build HAT is attached to the Raspberry Pi, enabling direct control of four motors that together define the robot's four degrees of freedom (DoF). Horizontal motion is realized through a trolley unit that travels across the crane bridge and carries the gripping mechanism. This gripper is guided by vertical rods and operates through a circular opening-and-closing motion. Except for two components, all mechanical elements are made from original LEGO® parts. A custom-designed container houses the Raspberry Pi computer. In addition, the gripper claws are 3D printed and shape-optimized to improve gripping reliability.

Actuation is achieved using LEGO® SPIKE motors, with each motor controlling a single DoF independently (see Figure 2). Calibration happens by moving each motor toward a fixed mechanical endpoint and detecting stalling. This sensor-free approach simplifies system design but implicitly assumes consistent mechanical behavior, which becomes a critical assumption as operational complexity increases.

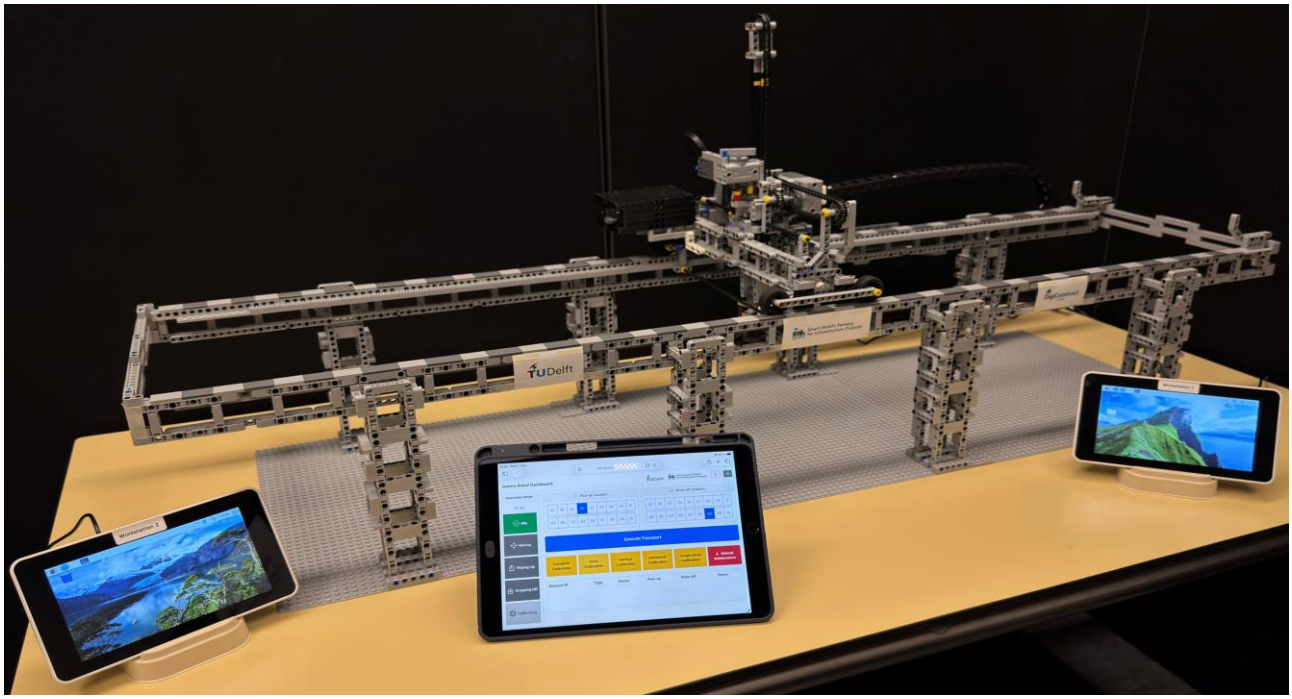


Figure 1: Overview of the modular digital twin testbed, consisting of the gantry robot and two interactive workstations. The tablet (optional) displays the gantry robot's web-based UI served via a FastAPI endpoint that is accessible from devices on the WLAN.

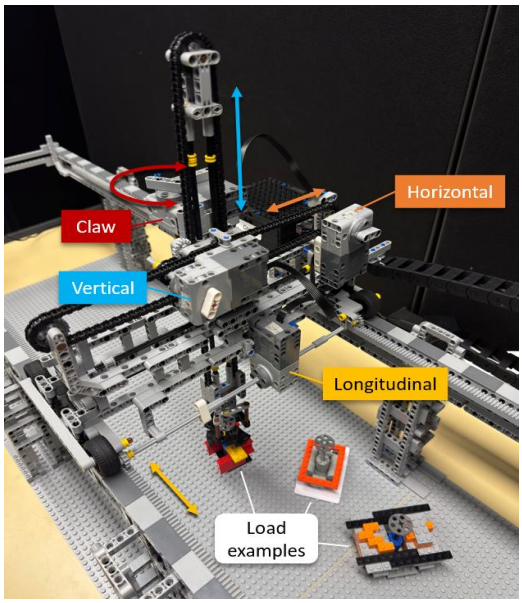


Figure 2: Gantry Bridge with 4 motors and 3 different examples of loads that can be transported.

The digital layer runs on a Linux distribution on the Raspberry Pi and is structured using Docker containers to enable adaptability. This digital system separates responsibilities into service, motor control, and storage containers. The service container functions as the system integrator, linking physical actuation, data storage, and order processing. It runs a FastAPI instance that exposes REST endpoints for querying system state and submitting transport commands, while a dedicated service script manages the order queue and database communication. Motor execution is delegated to a dedicated container that interfaces directly with the hardware through the BuildHAT Python library. Data storage is handled by a third container that supports interchangeable database systems for long-term storage of movements, transport requests and operation modes. Both GraphDB and MongoDB containers were tested in this setup.

User interaction is provided through a web-based interface served directly by the FastAPI framework using Jinja templates. The interface retrieves the gantry robot's operation mode via REST calls at configurable polling intervals and allows users to trigger calibration and transport commands by sending JSON payloads. This approach enables wireless control through common devices such as smartphones and tablets (Figure 1). While polling is sufficient for the demonstrated use cases, FastAPI also supports WebSockets.

Interactive Workstations

The interactive workstations represent the user-facing side of the DT testbed and operationalize direct human interaction within the distributed DT architecture. A workstation operates as an independent edge node, allowing for local data processing and storage. This configuration enables shifting interaction logic away from the actuated system core and toward decentralized components that remain tightly coupled via network communication.

Each workstation consists of a Raspberry Pi computer paired with a 7″ touchscreen. The touchscreen serves as the sole interaction modality, unifying user input and system feedback without reliance on external devices. By omitting actuators, the workstation maintains a clear functional boundary between interaction and physical execution within the DT architecture. At the same time, hardware extensibility remains available through Raspberry Pi's GPIO interface. For example, an RFID reader was connected in the testbed to explore contactless identification as a means of reducing repetitive user input and lowering the likelihood of interaction errors.

The digital architecture follows the same principles as the gantry robot by running Docker container services on a Linux platform (see Table 1). A minimal container setup is sufficient, consisting of a FastAPI-based service container that manages the touchscreen interface and communication logic, and a database container for persistent storage. The interface is generated using HTML Jinja templates and displayed directly on the touchscreen, reinforcing consistency across the gantry robot and the interactive workstations. Data exchange between the robot and workstations is implemented via REST-based communication, with WebSocket support available but not required for the demonstrated scenarios.

Digital Twin Experiments Performed with the Testbed

The following subsections describe how the testbed was used in other studies, illustrating its versatility and applicability for evaluating DT-focused research. Specific details on the experiment variables and evaluation criteria will be provided in separate publications. At the time of writing, they have yet to be published.

Agents in Construction (AiC) Ontology Verification

Study 1 used the testbed to functionally verify the *Agents in Construction (AiC)* ontology as an operational, machine-readable representation for real-time site coordination (Čustović, Cao and Soman, 2025). In this study, the AiC ontology served as the shared model for coordination-relevant facts. Accordingly, the evaluation examined whether information expressed using AiC concepts and relations could coordinate a construction process digitally across repeated runs.

Verification was conducted in the testbed because DT experiments on active construction sites often depend on enabling conditions that are difficult to ensure simultaneously, including integrated sensing and actuation, continuous capture of worker interactions, and uninterrupted wireless connectivity. The modular testbed provided these conditions in a controllable environment.

The coordination scenario was instantiated as a LEGO®-based simplified infrastructure assembly (see Figure 3). The elements of the infrastructure were decomposed into batches of LEGO® bricks within the gantry's carrying capacity and the workspace was segmented into multiple work zones plus a storage zone. Within this setup, the gantry robot operated as a transport agent moving

Table 1: Overview of Digital Twin Features of the Gantry Robot and the Interactive Workstations.

DT Feature	Gantry Robot	Interactive Workstation
User Interface / Visualization	Web-based UI (HTML / CSS / JavaScript)	Web-based UI (HTML / CSS / JavaScript); 7-inch mounted touchscreen UI
Computing Unit	Raspberry Pi 5, 8 GB RAM, BuildHAT	Raspberry Pi 5, 8 GB RAM
Application / Service Layer	Linux distribution; containerized with Docker	
Network Interface	REST API (FastAPI endpoints)	
Data Management	Time-series DB (e.g., MongoDB); graph DB (e.g., GraphDB); relational DB (e.g., PostgreSQL)	
Sensing	Internal motor state and telemetry from LEGO® SPIKE Prime / Powered Up Motors	RFID reader via GPIO interface
Actuation	LEGO® Spike motor actuation; 4 degrees of freedom (4-DoF)	-

materials between storage and site locations. The interactive workstations served as DTs for the human agents, displaying and enabling updates to information during execution. Four participants played different roles: two construction workers were building the LEGO® structure and used interactive workstations to request material delivery from the crane; a manager responsible for task assignment; and a packer assisting the gantry robot by positioning the pieces in the pickup area. In the unlikely event that the gantry robot fails to grip or release a load, this fourth operator serves as a human backup (DT has routine autonomy).

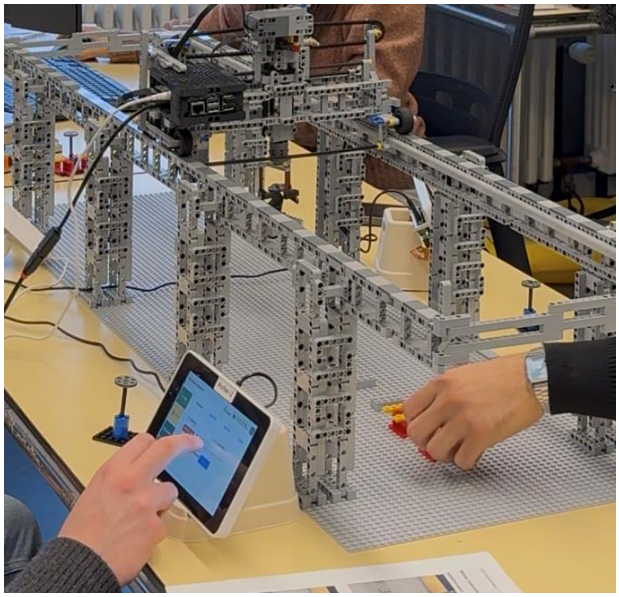


Figure 3: Scene from the AiC ontology verification experiment conducted using the DT testbed.

To perform the evaluation and monitor agents and agent-to-agent communication, the AiC ontology was implemented as the data model, and GraphDB was deployed on all Raspberry Pi computers. Participants viewed and updated operation modes, process lists, material and equipment usage, and locations as tasks advanced, while the manager exchanged process assignments with the workstations via REST calls; these interactions exercised coordination loops repeatedly and were captured for subsequent analysis.

The modular testbed enabled real-time investigation of DT-based site coordination that relied on the AiC ontology. It was possible to repeat the same coordination scenario and vary relevant variables (worker availability or the task execution sequence) while logging time-stamped coordination messages.

Serious Game with an Autonomous Site Crane

Study 2 examined how humans work when selected construction decisions and actions are taken autonomously by a DT. The goal was to simulate a site scenario in which workers collaborate and must coordinate around a shared, autonomous robotic resource.

Running comparable studies on live construction sites is difficult. Conditions on site vary in ways that are hard to control; the number of robots that can operate autonomously in changing environments is limited, and cost and safety constraints are high. Nevertheless, the development of such autonomous systems needs systematic evidence on how they shape coordination and work practices. We therefore used the DT testbed as a controllable, observable environment that supports repeatable autonomous execution together with structured human-DT interaction, allowing us to capture effects that would be hard to isolate on site.

These needs were operationalized in the DT testbed by using the gantry robot as an autonomous site resource. The robot followed scripts corresponding to predefined autonomy levels; in addition to the routine autonomous transport examined in Study 1, Study 2 incorporated shared-resource allocation decisions, which are common in construction (see Figure 4): the gantry robot DT decided which participant would be served next, requiring participants to plan and coordinate around a single robotic bottleneck. The testbed also enabled systematic variation in decision autonomy by altering the information available to the robot's decision scripts. In the routine autonomy condition, the robot relied on limited state data; in the non-routine autonomy condition, the gantry robot

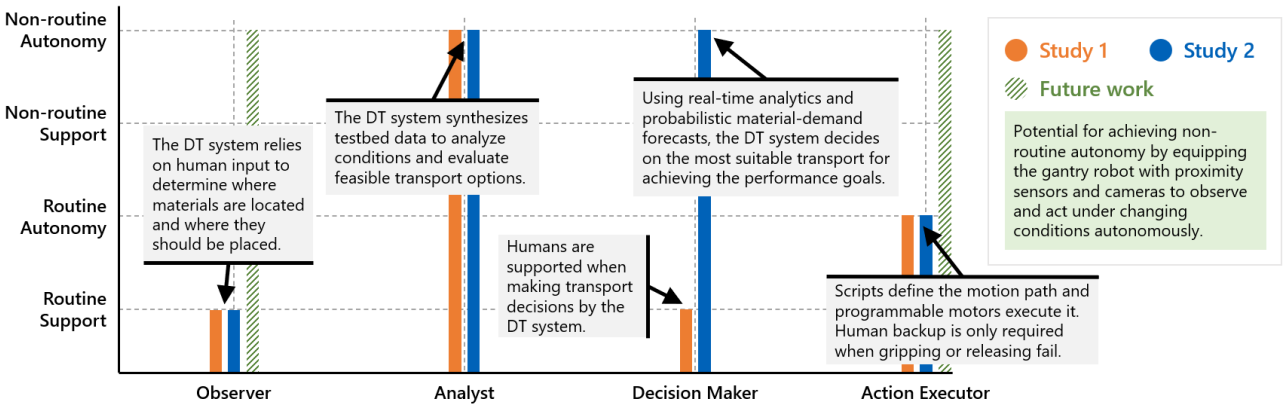


Figure 4: Different DT autonomy levels that were examined in the testbed mapped to the framework by Agrawal et al. (2023).

DT used real-time progress-data updates and probabilistic material-demand estimates. This design isolated the effects of autonomy and information availability while holding the physical system, task structure, and interaction channels constant.

Discussion

The laboratory testbed advances construction automation research by addressing a persistent gap at the decision-making and actuation layer of DTs. While many DT studies articulate data acquisition, integration and visualization in detail, their realization lacks fast feedback loops and high degrees of DT autonomy (olde Scholtenhuis and Soman, 2026). The programmable gantry robot introduces a tangible site actor that autonomously transports materials in routine situations while exposing operation conditions and commands through defined interfaces. The gantry robot supports systematic experimentation across different levels of autonomous analysis, decision-making, and action execution (see Figure 4). Combined with the interactive workstations, the modular DT testbed allows for controlled investigation of how human actors interact with and respond to automated execution. This aligns with the categorization of DTs that highlights human-system interaction and autonomy as defining dimensions in construction contexts (Agrawal *et al.*, 2023). Rather than assuming idealized coordination between human and digital actors, the testbed enables examination of frictions, delays, and behavioral adaptations that emerge under real-time conditions with immediate feedback.

At a broader level, the testbed supports scenario-based experimentation in which construction management conditions are deliberately constructed and compared (Li *et al.*, 2025). Real-time representation of site-like activities, combined with controllable execution, enables repeatable experiments that are rarely feasible in real construction projects. This capacity supports theory-driven inquiry into DT features, rather than one-off demonstrations of technological feasibility.

The contribution is further strengthened through the full-stack implementation of DT building blocks (AlBalkhy *et al.*, 2024; Saif, Doukari, and Kassem, 2026), spanning sensing, communication, storage, analytics, visualization, and action implementation, using embedded computing and containerized services. The reliance on low-cost hardware and open-source or free software addresses financial barriers that constrain DT experimentation and replication across institutions (Zhu *et al.*, 2024). The distributed interactive workstations extend this contribution by enabling a structured investigation of how information is distributed, interpreted, and acted upon by human participants, highlighting organizational and cognitive aspects that are often underrepresented in DT research (Čustović *et al.*, 2025). The modular hardware and software architecture positions the testbed as an evolving research platform that can be reconfigured or expanded with additional sensors and actuators. Docker containers can be replaced or redeployed across alternative hardware with minimal architectural change.

The testbed is intentionally simplified and therefore differs in scale and context from real construction sites, so the transferability of results must be explicitly assessed in follow-up studies. While the testbed provides the technological backbone for serious games to be conducted within it, the transferability of the resulting findings to real-world contexts depends on how well reality is modeled through game elements and mechanics (Freese and Bekebrede, 2025). Besides, the gantry robot is a material-movement actor rather than a building or assembly robot. It also inherits fundamental workspace constraints, limited DoFs, inability to reach around obstacles, and strong collision-avoidance requirements, which restrict the representation of complex access conditions or overhangs. Data quality further depends on human input at interactive workstations, which creates the risk of missing or inconsistent updates; audio hardware for voice control or automated sensing (e.g., computer vision) could reduce this dependency. The gantry robot cannot sense whether it has properly gripped a load, so it only supports routine autonomy for actions that require human backup. Precision and timing fidelity are limited by LEGO® motor accuracy, sensor-free calibration drift, and latency from containerization and REST-based communication, making the setup better suited for coordination and decision-logic studies than for high-precision or hard real-time control validation.

Conclusions

This paper introduced a scalable testbed for experimenting with DT capabilities in construction management scenarios. The testbed combines a LEGO®-based haptic simulation with programmable motors, Raspberry Pi 5 SBCs and touchscreen workstations, enabling a digital-physical feedback loops and human-DT interaction. The testbed can be reconfigured to represent different DT scenarios by changing the physical layout, the digital functions and the number of stations involved.

The testbed offers value for academia and industry. For researchers, it provides a replicable, configurable environment for testing a wide range of DT hypotheses under controlled conditions. Its design deliberately relies on consumer-ready hardware and software, reducing costs and setup effort and supporting adoption by other research groups. For the industry, it provides a concrete demonstration environment to communicate DT concepts to practitioners and to trial DT features against company-specific use cases before large financial commitments.

As an initial working prototype, the testbed provides a solid basis for extensions that improve realism and broaden the experimental scope. Key priorities are enhanced sensing for reliable state capture (e.g., precise position tracking with proximity sensors and RFID-based element detection), camera vision (fixed or gantry-mounted), more robust messaging, such as MQTT, to support scalable device communication, and wearable hardware that goes beyond an interactive workstation. Further avenues include integrating additional programmable controllers or components from the LEGO® SMART Play™ system (The LEGO Group, 2026) to represent other task types. Finally, future work can extend the setup with local AI models running on the gantry robot or the interactive workstations and develop educational programs around the testbed.

Supplementary Data

The source code for the gantry robot alongside the digital models of the LEGO® structure and the custom 3D-printed elements can be found in this repository:

https://github.com/DigiConstructLab-TU-Delft/Digital-Twin-Testbed/

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