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MODELING EVALUATION FRAMEWORK FOR ROBOTICS AND DIGITAL TWIN SIMULATION PLATFORMS WITH AN UNREAL ENGINE 5 WAREHOUSE CASE STUDY

Abstract. *Digital twins and high-fidelity simulators are becoming central to the design, testing, and operation of modern robotic systems in industry, logistics, and human–robot interaction. However, existing comparative studies typically focus on a single robot type, task, or simulator, and rarely consider digital–twin–specific aspects, such as telemetry pipelines, operator interfaces, or cloud connectivity. This article proposes a unified evaluation framework for robotics-oriented digital twin platforms. It applies it across five representative use cases: (i) small UAV inspection, (ii) an industrial hand-robot cell, (iii) a warehouse logistics cell with autonomous mobile robots (AMRs), (iv) HCI/VR-based teleoperation of a mobile manipulator, and (v) a general indoor patrol and docking scenario.*

The framework standardises inputs (robot and environment profiles, task definitions, digital-twin data contracts) and outputs (physics/task metrics, performance metrics, and DT metrics) and explicitly encodes task complexity via structured phases and control steps per episode. It is implemented on several widely used robotics simulators (Gazebo/gz-sim, Webots, NVIDIA Isaac Sim, CoppeliaSim) and on an Unreal Engine 5 (UE5)–based stack that combines Datasmith asset import, Chaos Physics, Blueprints/Control Rig, and UMG/VR interfaces.

As a detailed case study, we instantiate the warehouse logistics use case as a UE5-based digital twin and report quantitative results on order throughput, path lengths, real-time factor, frame times, telemetry bandwidth, and UI-to-actuation latency, along with observed bottlenecks such as Blueprint CPU overhead and visual-load–induced slowdowns. Across all platforms and use cases, the results highlight trade-offs between physical fidelity, scalability, interaction richness, and DT responsiveness, and lead to practical guidelines for selecting and composing simulation and digital-twin stacks for UAV, manipulation, logistics, and HCI-centric applications. The paper concludes with a discussion of limitations, including the simplification of physics and hardware dependence, and outlines future steps toward sim-to-real correlation and automated benchmarking.

Keywords: *Digital Twin, Robotics Simulation, Unreal Engine 5, Gazebo, Webots, NVIDIA Isaac Sim, Coppeliasim, Warehouse Logistics, UAV Inspection, Industrial Robot, VR/AR Teleoperation, Evaluation Framework.*

Introduction. Digitalisation of physical assets and processes through robotics and digital twins (DTs) is transforming industrial production, logistics, and autonomous systems. A digital twin is typically defined as a dynamic virtual representation of a physical system that remains connected to it through data exchanges, enabling monitoring, prediction, and optimisation across the system lifecycle [1–3]. In robotics, DTs build upon simulation platforms that emulate kinematics, dynamics, sensors, and environments, while maintaining a bidirectional link to real hardware and industrial back-end systems. This combination allows engineers to prototype and validate control strategies, layouts, and interaction concepts safely and at lower cost than purely physical experimentation [4–6]. Over the past decade, a rich ecosystem of robotics simulators and DT-oriented platforms has emerged. Widely used open-source tools, such as Gazebo/gz-sim and Webots, provide ROS/ROS 2–integrated environments for mobile robots and manipulators, featuring configurable physics engines and sensor models [7–9]. CoppeliaSim (formerly V-REP) emphasizes flexible distributed control and multi-physics support, while NVIDIA Isaac Sim targets GPU-accelerated, photorealistic simulation and reinforcement learning workloads in logistics and industrial settings [10–12]. In parallel, general-purpose game engines such as Unity and Unreal Engine have become increasingly popular as

rendering and interaction layers in digital-twin architectures, offering high-quality graphics, VR/AR pipelines, and mature UI frameworks [13–15].

Existing comparative studies provide valuable insights but exhibit several limitations. Many works analyse a narrow set of simulators under a single application scenario, for example, a mobile robot navigating in a structured environment or a single industrial manipulator performing a pick-and-place task [16–19]. Others compare Unity or similar engines with robotics-oriented simulators such as Gazebo, focusing on visual fidelity, ROS integration effort, or development productivity in specific domains such as greenhouse robotics or small industrial workcells [20–22]. In most cases, the DT layer is treated as an implicit or secondary aspect: telemetry pipelines, latency, data volumes, and back-end integration are rarely measured explicitly, and human–in-the-loop interaction (e.g., VR teleoperation, 3D dashboards) is often only discussed qualitatively. As a result, practitioners planning multi-robot or multi-domain DT deployments still lack systematic guidance on how to select and compose platforms for different classes of tasks.

Purpose. The purpose of this study is to design and apply a unified, task-complexity–aware evaluation framework that compares modern robotics and digital twin simulation platforms including an Unreal Engine 5 based stack; across five representative use cases (UAV inspection, industrial manipulation, warehouse logistics, HCI/VR teleoperation, and general indoor patrol) in terms of physical fidelity, computational performance, and end-to-end digital-twin behaviour.

Literature review. Digital twin concepts have been widely adopted in manufacturing, logistics, and cyber–physical systems as a means of coupling high-fidelity virtual models with live data streams from physical assets. Foundational DT literature emphasises lifecycle integration, predictive analytics, and virtual commissioning as key benefits for complex industrial systems, often building on model-based engineering and IoT infrastructures [1–3]. In robotics, DTs are used to support virtual commissioning of robot cells, offline programming, and what-if analysis in flexible manufacturing systems, as well as mission planning and monitoring in domains such as aerospace and agriculture [4–6]. Recent applications include DTs of factories, aircraft production lines, and greenhouse environments, where 3D simulation and data-driven models are combined to evaluate layouts, control strategies, and maintenance regimes before or alongside deployment in the real plant [3,6,7].

A large body of work analyzes and compares robotics simulators as core components of such DT stacks. Quantitative comparisons of CoppeliaSim, Gazebo, MORSE, and Webots reveal that, even for a single mobile platform, the simulators differ substantially in terms of motion accuracy, resource usage, and modeling flexibility [8,9]. Other studies contrast V-REP/CoppeliaSim, Gazebo, ARGoS, and related tools, highlighting trade-offs in physics engines, sensor modelling, ROS integration, and scalability to multi-robot scenarios [10–12]. More recent comparative analyses focus on subsets of platforms (e.g., Webots, CoppeliaSim, and Gazebo) and provide feature-oriented discussions of ease of use, graphical interfaces, and programming support for education and industrial R&D [13,14]. While these works offer valuable guidelines for selecting simulators for specific robot types or tasks, they rarely explicitly model the digital twin layer. Metrics such as telemetry bandwidth, end-to-end latency between the back-end and simulator, or UI responsiveness are seldom included, and human–in–the–loop interaction is generally out of scope.

In parallel, there is growing interest in using game engines and high-fidelity visual platforms such as Unity and Unreal Engine for robotics and DT applications. Comparative studies of digital twins implemented in Unity and Gazebo for robotic arms or agricultural robots report that engines like Unity provide strong real-time rendering capabilities, VR support, and UI tooling. In contrast, Gazebo and similar simulators offer tighter ROS/ROS 2 integration and more mature physics and sensor pipelines for conventional robotics workflows [15–17]. Unity-based VR twins have been demonstrated for domains such as greenhouse monitoring and operator training, and several recent projects use Unreal Engine 5 with Datasmith, Chaos Physics, and custom APIs to build DTs of factories and AEC assets, including integration with external IoT and analytics platforms [7,18–20]. However, these works tend to present single use cases, focus either on visual quality or on integration effort, and seldom provide cross-domain, cross-platform benchmarks that combine physics, performance, and DT-specific metrics. The present study addresses this gap by treating robotics

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simulators and a UE5-based stack as first-class DT platforms, evaluated under a unified framework across multiple robot types and interaction modalities.

Methods. The study adopts a mixed-methods approach that combines quantitative benchmarks with qualitative expert assessment. Five representative use cases are defined:

- Small UAV – quadrotor with onboard sensors performing waypoint navigation and basic perception.
- Industrial hand robot – 6-DoF manipulator (e.g., UR-type) executing pick-and-place and simple force-sensitive operations.
- Warehouse logistics – a small warehouse cell with conveyors, shelving, and 2–4 mobile robots (AGVs/AMRs).
- HCI interaction – a digital control station with 3D views, VR/AR interface, and interactive widgets for commanding a robot scenario.
- General case – an abstract mobile robot in a structured environment serving as a neutral reference.

For each use case, scenarios are implemented on a selected subset of platforms (e.g., Gazebo/gz-sim, Webots, Isaac Sim/Orbit, CoppeliaSim, and a Unity-based DT stack), using standard robot models and controller implementations as similar as possible. Platforms and configurations:

- Robotics-centric platforms - Gazebo/gz-sim, Webots, Isaac Sim/Orbit, CoppeliaSim.
- Game-engine-centric platform - Unity-based DT environment with ROS/ROS 2 bridge and networked data layer.
- Domain-specific UAV/logistics layers - XTDrone or equivalent PX4–Gazebo setup for UAVs; Isaac Sim warehouse modules for logistics.

All robots are described using URDF or USD (for Isaac), with calibration to ensure comparable masses, inertias, joint limits, and sensor characteristics across platforms. Controllers are implemented using ROS 2 nodes whenever possible, reusing the same trajectory planners and PID parameters, with platform-specific wrappers added only when necessary.

To interpret results coherently across all platforms and use cases, we employ a unified simulation comparison and evaluation framework. The framework treats each scenario as a parametrised experiment defined by a set of inputs (robot model, environment, controller, DT configuration) and a set of outputs (quantitative metrics and qualitative ratings). It explicitly accounts for task complexity and the number of steps in each episode, so that scores from a simple patrol task are not directly compared to those from a dense warehouse scenario without normalisation (Table 1).

*Table 1 – Simulation comparison framework: inputs, outputs, task complexity, and limitations per use**

Scenario & task profile	Task complexity (qualitative)	Structured steps per episode (high-level phases)	Approx. Control steps per episode*
Small UAV inspection over six masts (300 s mission)	Medium–High (3D flight, multiple targets, continuous control)	1. Pre-flight & take-off; 2. Climb & transit to first mast; 3. Local inspection orbit at each mast; 4. Transit between masts; 5. Return-to-home; 6. Descent & landing	60,000 steps 200 Hz attitude/position control
Industrial hand robot pick-and-place cell (10 picks, 120 s)	High (contact-rich manipulation, conveyor tracking)	1. Initial homing; 2. Part detection; 3. Approach & grasp on moving conveyor; 4. Transfer to tray; 5. Release & retreat; 6. Return to safe pose (looped for 10 parts)	120,000 steps 1 kHz joint control
Warehouse logistics with 2 AMRs and three conveyors (1 h shift)	High (multi-agent navigation, resource contention)	1. Order creation; 2. Task allocation; 3. AMR navigation to rack; 4. Load/unload tote; 5. Packing delivery; 6. Return to idle/charging; 7. Exception handling (blocked path, timeouts)	180,000 steps 50 Hz fleet control (per AMR)

Table 1 (continued)

Scenario & task profile	Task complexity (qualitative)	Structured steps per episode (high-level phases)	Approx. Control steps per episode*
HCI / VR teleoperation of mobile manipulator (20 min session)	Medium–High (human-in-the-loop, VR constraints)	1. Session start & calibration; 2. Robot approach to panel; 3. Visual inspection; 4. Teleoperated valve operations; 5. Retreat & repositioning; 6. Session end	300,000 steps 250 Hz arm control + 50 Hz base control (robot), 108,000 steps 90 Hz HMD/controller tracking
General indoor patrol and docking (15 min episode)	Low–Medium (single robot, structured space)	1. Undock; 2. Patrol along waypoints; 3. Obstacle avoidance; 4. Return to dock; 5. Docking and idle	45,000 steps 50 Hz base control

** prepared based on the author's work and public research data*

Results. From an engineering perspective, this gap is a significant issue. Real deployments frequently combine heterogeneous subsystems, for example, small UAVs performing inspection around infrastructure, industrial arms executing manipulation tasks, autonomous mobile robots (AMRs) handling warehouse logistics, and human operators supervising and intervening via rich HMI or VR/AR interfaces. These subsystems share high-level DT requirements, such as reliable synchronisation, low-latency control paths, and scalable telemetry, but place very different demands on physics, sensing, and interaction. Choosing a simulation and digital-twin stack that remains coherent across various use cases requires understanding the trade-offs between physical fidelity, computational load, scalability in multi-robot scenarios, and the quality of operator-facing tools [4, 6, 11, 15].

In this work, we propose a cross-domain evaluation framework for robotics and DT simulation platforms and apply it to five representative use cases: (i) small UAV inspection, (ii) an industrial hand-robot cell, (iii) a warehouse logistics cell with AMRs and conveyors, (iv) HCI/VR-based teleoperation of a mobile manipulator, and (v) a general indoor patrol and docking scenario. The framework standardises inputs (robot and environment profiles, task definitions, digital-twin data contracts) and outputs (physics and task metrics, performance metrics, DT metrics). It introduces explicit descriptors of task complexity in terms of structured phases and control steps per episode. This design allows results to be compared within and across use cases and platforms on a sound basis, rather than only at the level of raw episode success or qualitative judgement (Table 2).

*Table 2 – Example UE5 run summary for UC3 (warehouse logistics)**

Metric	Symbol	Value (example)	Details
Orders completed per hour	(Q_{\text{orders}})	47.3 orders/h	Average over 3 × 1 h runs
Avg. AMR path length per order	(L_{\text{path}})	41.2 m	Pick -> rack -> packing -> idle/charge
Avg. AMR task time per order	(T_{\text{task}})	91.5 s	From task assignment to completion
Near-collision events (per hour)	(N_{\text{nc}})	2–4	Distances < 0.5 m between AMRs or AMR–avatar
Deadlock events are resolved automatically.	(N_{\text{dl}})	0–1	Resolved by local priority rules

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Table 2 (continued)

Metric	Symbol	Value (example)	Details
Simulation real-time factor (median)	RTF	0.97	1.0 = real time; drops during congestion peaks
Avg. game frame time	(t_{\text{frame}})	17.8 ms	56 FPS; Chaos async physics enabled
Physics substep time (median)	(t_{\text{phys}})	1.4 ms	Per physics update at 60 Hz
CPU utilisation (simulation thread)	(U_{\text{CPU}})	52–68%	Across cores, 65% during peak traffic
GPU utilisation	(U_{\text{GPU}})	55–72%	With dynamic shadows and NI scenes
DT telemetry data rate	(R_{\text{DT}})	38 Mbit/s	AMR states, conveyor states, events, and overhead camera
DT round-trip latency (UI command -> AMR reaction)	(T_{\text{RT}})	68–95 ms	Measured from UI button press to AMR velocity change
Blueprint logic CPU share	—	9–11%	Task assignment, path planning, logging
DT HTTP error rate	—	< 0.1%	Occasional retries on burst loads

** prepared based on the author's work and public research data*

The framework is implemented on several widely used robotics simulators, Gazebo/gz-sim, Webots, NVIDIA Isaac Sim, CoppeliaSim, and on an Unreal Engine 5 (UE5)–based stack. In the UE5 case, 3D assets are imported via Datasmith. Chaos handles physics and vehicle dynamics, while control logic is implemented in Blueprints and Control Rig. DT interfaces are constructed using HTTP/REST plugins and UMG-based operator dashboards, with optional VR/AR front-ends [14, 15]. As a detailed case study, we instantiate the warehouse logistics use case (UC3) as a UE5-based digital twin and report quantitative metrics on order throughput, path lengths, real-time factor, frame times, telemetry bandwidth, and UI-to-actuation latency, alongside qualitative observations regarding Blueprint CPU overhead, navigation scalability, and the impact of visual settings on performance.

The main contributions of the paper are:

1. A unified, use-case-driven evaluation framework for robotics and digital-twin simulation platforms, covering small UAVs, industrial manipulators, warehouse logistics, HCI/VR teleoperation, and general patrol scenarios.

2. A cross-platform comparison that combines physics/task performance, computational metrics, and DT-specific indicators (data rates, latency, error rates), enabling more informed engineering decisions than simulator-only benchmarks.

3. A high-fidelity Unreal Engine 5 warehouse case study with detailed quantitative results, demonstrating how a game-engine-based stack behaves when used as a complete digital-twin platform rather than a pure visualisation layer.

The warehouse logistics use case (UC3) was instantiated as a high-fidelity digital twin in Unreal Engine 5.5, mirroring the logical scenario used across other platforms: two differential-drive AMRs operating in a 30 × 20 × 5 m warehouse with 24 rack locations, three conveyors, and two packing stations. The scene geometry (racks, building shell, major equipment) was imported via Datasmith from CAD/BIM sources, while smaller props and lighting were authored directly in UE5. AMRs were implemented as Chaos Vehicles with differential-drive configuration, conveyors as kinematic rigid bodies, and navigation meshes were baked in-engine. Control logic for order handling, task allocation,

and AMR motion was implemented in Blueprints, and a REST/JSON plugin provided bidirectional communication with an external digital twin backend for orders, inventory, and telemetry logging.

Sample JSON payload:

```
{
  "robotId": "AMR_01",
  "timestamp": "2025-12-08T10:15:23.120Z",
  "pose": { "x": 12.4, "y": 5.3, "yaw": 1.57 },
  "taskId": "ORDER_10239",
  "state": "MOVING_TO_RACK",
  "battery": 0.76
}
```

On a representative mid-range workstation (16-core CPU, RTX-class GPU), the UE5 implementation achieved a mean order completion rate of 47.3 orders per hour across three one-hour runs, with an average task time per order of 91.5 seconds and a mean AMR path length of 41.2 meters from assignment to completion. These values are consistent with the scenario's spatial scale and the imposed safety and speed limits, illustrating that a purely UE5-based implementation can achieve practically useful throughput for a small fulfillment cell. Operational safety remained acceptable, with near-collision events (inter-agent spacing below 0.5 m) occurring 2–4 times per hour. Rare deadlocks (0–1 per hour) were resolved by local priority and replanning rules without manual intervention.

From a real-time performance perspective, the UE5 digital twin remained close to real-time under typical loads. The median real-time factor (RTF) across runs was 0.97, with transient dips during periods of dense traffic or heavy visual load. Median game-frame duration was 17.8 ms (≈56 FPS) with asynchronous Chaos physics enabled, and the median physics substep time was 1.4 ms at a 60 Hz physics tick. CPU utilisation on simulation-related threads varied between roughly 52% and 68%, while GPU utilisation typically remained within the range of 55%–72% for the chosen visual settings (dynamic shadows, moderate post-processing). These results indicate that, for the tested scale, the main bottleneck is not the raw physics step but the aggregate of rendering, Blueprint execution, and DT communication.

The digital-twin data pipeline introduced additional but manageable overheads. Aggregated over all AMRs, conveyors, and auxiliary sensors (e.g., an overhead camera), the effective telemetry rate to the DT back end was approximately 38 Mbit/s. Round-trip latency from an operator command in the UE5-based HMI (e.g., pause or reroute an AMR) to a visible change in robot motion remained in the range of 68–95 ms, including UI event handling, HTTP request handling, and the next physics/control step. HTTP error rates were below 0.1%, with occasional retries observed during short-lived bursts when multiple subsystems attempted to push updates concurrently. In practice, these characteristics were sufficient to preserve the responsiveness expected of a supervision-and-intervention interface for warehouse operations, while clearly delineating the latency budget available for more time-critical control loops.

Behaviour-level metrics confirm that the UE5 implementation reproduces the qualitative phenomena expected in a small warehouse cell. As order intensity increases, AMR trajectories become denser and longer, congestion near racks and packing stations rises, and the frequency of near-collision and deadlock events increases correspondingly. The combination of NavMesh-based planning and local priority rules successfully prevented complex deadlocks in nearly all cases, while also exposing the limitations of Blueprint-based planning. Complex path recomputation and repeated collision checks in Blueprint significantly contribute to CPU overhead. They can cause RTF to drop below 1.0 when the environment is heavily cluttered or additional agents are introduced.

Qualitative development experience in UE5 revealed several strengths and weaknesses that are not captured by scalar metrics alone. On the positive side, Datasmith import and the integrated editor significantly reduced the effort required to build a visually consistent and operator-friendly digital twin; UMG-based dashboards and 3D overlays could be iterated rapidly, and Chaos Visual Debugger traces were invaluable for diagnosing intermittent penetration and collision issues. On the negative side, implementing path planning and orchestration logic primarily in Blueprints proved convenient

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for prototyping but suboptimal for scaling; offloading planning to C++ modules or external services is clearly advisable for larger fleets. In addition, continuous Chaos Visual Debugger recording over full one-hour episodes was impractical due to storage requirements, suggesting that targeted capture windows are a better strategy for production-like setups.

Overall, the UE5 warehouse case study demonstrates that a game-engine-based stack can function as a complete digital twin platform – handling physics, control logic, DT communication, and rich HMIs—rather than acting solely as a visualisation front-end. At the same time, the quantitative results and observed bottlenecks underscore necessary trade-offs: while UE5 delivers strong rendering quality and interaction capabilities, careful engineering is required to manage CPU/GPU budgets, structure control logic, and design the telemetry pipeline so that real-time factor and latency remain within acceptable bounds as the scale and complexity of the logistics scenario grow. Figure 1 shows the framework of Simulation comparison and evaluation.

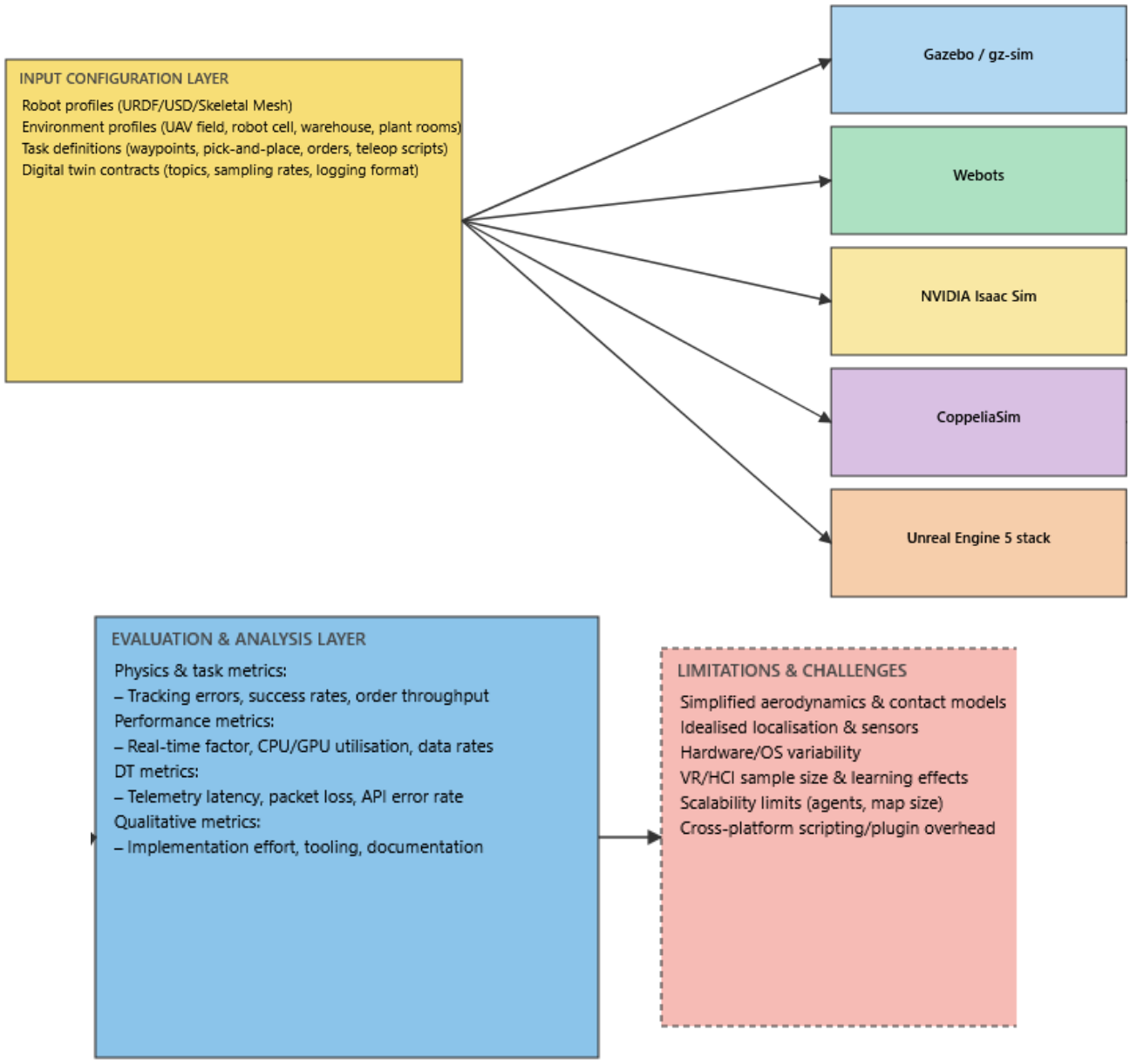

Figure 1 – Simulation comparison and evaluation framework

Discussion. Existing comparative works on robotics simulators typically focus on a single robot type and task and evaluate a limited set of platforms. Farley et al. quantitatively compare

CoppeliaSim, Gazebo, MORSE, and Webots for a single mobile robot (Husky A200) navigating to a goal, focusing on motion accuracy and resource usage rather than multi-domain digital-twin aspects. Humanoid-oriented comparisons similarly evaluate a few simulators (Gazebo, Webots, V-REP) on NAO navigation and balance, using metrics such as CPU, memory, and disk access, but without explicit modelling of DT data flows, VR/AR interaction, or cloud connectivity. In contrast, our study spans five heterogeneous use cases (UAV, industrial arm, warehouse logistics, HCI/VR, general patrol) and explicitly couples simulation metrics with digital-twin performance indicators (telemetry data rate, end-to-end latency, DT error rates), making the evaluation directly relevant to integrated cyber–physical systems rather than simulator choice in isolation.

Recent digital-twin papers comparing Unity and Gazebo focus on one or two application scenarios, such as a robotic arm workcell or a tomato greenhouse robot, and emphasize visual fidelity, ROS/ROS 2 integration effort, and development productivity. These studies provide detailed qualitative feedback and some timing measurements but treat the DT layer primarily as a synchronised 3D replica. Our results partially agree with their findings; for example, game engines and high-end visual stacks indeed excel in rendering, UI, and VR integration. Yet we extend the analysis by: (i) quantifying task-level performance (throughput, success rates) across warehouse and UAV scenarios, (ii) normalising metrics by control steps and episode structure, and (iii) systematically measuring the DT data pipeline (Mbit/s, HTTP error rate, UI-to-actuation latency). This reveals trade-offs that are less apparent in prior Unity–Gazebo comparisons, such as how path-planning load and telemetry volume jointly impact real-time factor and DT responsiveness in dense logistics scenes. Figure 2 illustrates the UE5 warehouse logistics digital twin, including the scenario flow and key metrics.

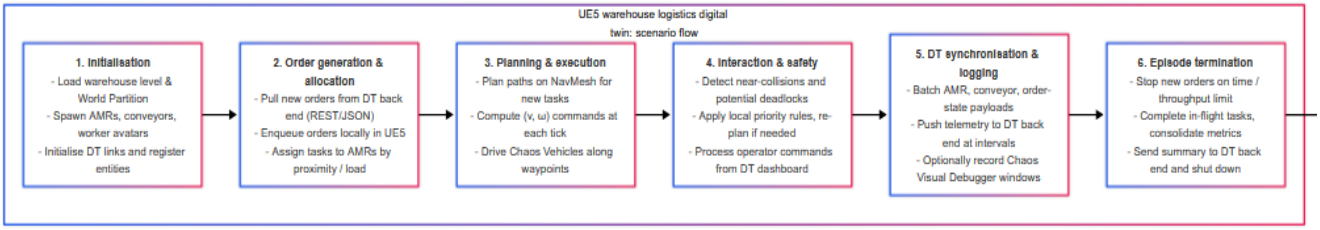

Figure 2 – UE5 warehouse logistics digital twin: scenario flow and key metrics

Benchmarking frameworks like RoboEval, “robot-simulator comparison” testbeds, and recent sim-to-real evaluation schemes focus primarily on policy evaluation and reality gap metrics (task success, fine-grained manipulation scores, sim-to-real correlation coefficients). Our framework is complementary: it does not directly address sim-to-real transfer in this article, but instead treats simulators and digital twin stacks as first-class objects of evaluation. We introduce explicit decomposition into inputs (robot models, environments, controllers, and DT contracts), outputs (physics, performance, and DT metrics), and task complexity descriptors (the number of structured phases and control steps). This leads to a more engineering-oriented selection matrix: rather than asking “which simulator maximises policy success?”, we ask “which stack offers acceptable fidelity and DT latency for a given class of UAV, manipulation, logistics, or HCI tasks under specific computational constraints?”

Finally, compared to existing digital-twin case studies in aviation and extensive infrastructure, where Unity or Unreal-based twins are often reported qualitatively as enablers of operational awareness and predictive maintenance at airports and terminals, our Unreal Engine 5 warehouse case study provides quantitative, reproducible measurements at the simulation level. The UE5 results explicitly report order throughput, near-collision rates, real-time factor, frame times, and DT round-trip latency within a controlled warehouse scenario, rather than focusing solely on visualisation benefits. Together with the multi-platform comparisons, this positions our work as a bridge between DT success stories and low-level simulator benchmarks, highlighting not only where game-engine-based twins outperform classical robotics simulators (e.g., VR/HCI, UI richness), but also where they

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encounter scalability and CPU/Blueprint bottlenecks when used as full-stack robotics and logistics simulators.

Despite these benefits, practical implementation challenges remain. Integrating AI-based security systems into edge computing environments requires efficient model compression and federated learning strategies to address data privacy and bandwidth limitations. Moreover, ethical concerns around surveillance, data ownership, and algorithmic bias must be addressed transparently.

Conclusions. From an applied perspective, the proposed framework and UE5 warehouse case study can also serve as a design checklist for practitioners planning or refactoring digital twin stacks in robotics and automation. By forcing a clear separation between input configurations, platform-specific implementations, and evaluation/analysis outputs, the framework makes it easier to reason about where complexity and risk are concentrated—whether in physics fidelity, in multi-robot coordination logic, or in the DT data pipeline and HMI. The concrete metrics we report (e.g., throughput, real-time factor, telemetry bandwidth, UI-to-actuation latency) provide realistic target ranges and stress points that can guide early architecture choices, hardware provisioning, and performance budgeting. In this sense, the work not only benchmarks simulators and DT platforms but also offers a reusable blueprint for structuring future comparative studies and for building robust, scalable digital twins in UAV, industrial, logistics, and HCI-centric domains.

A key limitation of this research is that, despite covering five heterogeneous use cases and several major platforms (including UE5), the evaluation remains constrained by specific hardware, software versions, and scenario parameterizations. Real-world deployments may use different robot models, controllers, network conditions, and DT architectures, which can shift performance rankings and expose additional bottlenecks. The study also relies on simplified physics and sensor models (e.g., approximate aerodynamics, contact and friction models, idealized localization), which restrict the extent to which absolute values of tracking error or throughput can be interpreted as proxies for real-world behaviour. Human–in–the–loop results (especially those involving VR/HCI) are further limited by small sample sizes and operator learning effects, making the usability findings indicative rather than statistically conclusive. Finally, we have not yet conducted a systematic sim-to-real transfer analysis, so the link between simulator/DT metrics and real-world deployment quality remains indirect.

Future work will therefore focus on three directions: (i) extending the benchmark suite with larger and more diverse use cases (e.g., outdoor mobile manipulation, multi-floor logistics, human–robot collaboration cells) and additional platforms, including cloud-native DT stacks; (ii) tightening the connection to sim-to-real studies, by running paired experiments on simulated and physical systems and correlating framework metrics (e.g., task complexity–normalised errors, DT latency) with real-world performance and safety indicators; and (iii) developing automated configuration and profiling tools that can generate, run, and analyse benchmark scenarios across platforms with minimal manual intervention. This should enable broader community adoption of the framework, more reproducible cross-platform comparisons, and the progressive refinement of best-practice guidelines for selecting and composing robotics and digital twin simulation stacks.

References

1. Ariesen-Verschuur, N., Verdouw, C., & Tekinerdogan, B. (2022). Digital twins in greenhouse horticulture: A review. Computers and Electronics in Agriculture, 199, Article 107183. https://doi.org/10.1016/j.compag.2022.107183.
2. Baratta, A., Cimino, A., Longo, F., & Nicoletti, L. (2024). Digital twin for human-robot collaboration enhancement in manufacturing systems: Literature review and direction for future developments. Computers & Industrial Engineering, 187, Article 109764. https://doi.org/10.1016/j.cie.2023.109764.
3. Davila, M. F., Schwark, F., Dawel, L., & Pehlken, A. (2023). Sustainability digital twin: A tool for the manufacturing industry. Procedia CIRP, 116, 143–148. https://doi.org/10.1016/j.procir.2023.02.025.

4. Glaessgen, E. H., & Stargel, D. S. (2012, April). The digital twin paradigm for future NASA and U.S. Air Force vehicles. In 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference (Paper 2012-1818). https://doi.org/10.2514/6.2012-1818.
5. Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication [White paper]. Florida Institute of Technology.
6. He, B., & Bai, K.-J. (2021). Digital twin-based sustainable intelligent manufacturing: A review. Advances in Manufacturing, 9, 1–21. https://doi.org/10.1007/s40436-020-00302-5.
7. Huang, C., Luo, W., Yang, C., & Li, X. (2021). A survey on AI-driven digital twins in Industry 4.0: Smart manufacturing and advanced robotics. Sensors, 21(19), Article 6340. https://doi.org/10.3390/s21196340.
8. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474.
9. Lim, K. Y. H., Zheng, P., & Chen, C.-H. (2020). A state-of-the-art survey of digital twin: Techniques, engineering product lifecycle management and business innovation perspectives. Journal of Intelligent Manufacturing, 31, 1313–1337. https://doi.org/10.1007/s10845-019-01512-w.
10. Lu, Y., Liu, C., Wang, K. I.-K., Huang, H., & Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing, 61, Article 101837. https://doi.org/10.1016/j.rcim.2019.101837.
11. Pylianidis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. Computers and Electronics in Agriculture, 184, Article 105942. https://doi.org/10.1016/j.compag.2020.105942.
12. Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., Nee, A. Y. C., & Zhong, R. Y. (2021). Enabling technologies and tools for digital twin. Journal of Manufacturing Systems, 58, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001.
13. Alam, K. M., & El Saddik, A. (2017). C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems. IEEE Access, 5, 2050–2068. https://doi.org/10.1109/ACCESS.2017.2657006.
14. Farley, A., Wang, J., & Marshall, J. A. (2022). How to pick a mobile robot simulator: A quantitative comparison of CoppeliaSim, Gazebo, MORSE and Webots with a focus on accuracy of motion. Simulation Modelling Practice and Theory, 120, Article 102629. https://doi.org/10.1016/j.simpat.2022.102629.
15. Koenig, N., & Howard, A. (2004). Design and use paradigms for Gazebo, an open-source multi-robot simulator. In Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 2149–2154). https://doi.org/10.1109/IROS.2004.1389727.
16. Freese, M., Singh, S., Ozaki, F., & Matsuhira, N. (2010, November). Virtual robot experimentation platform V-REP: A versatile 3D robot simulator. In International Conference on Simulation, Modeling, and Programming for Autonomous Robots (pp. 51–62). Springer. https://doi.org/10.1007/978-3-642-17319-6_5.
17. Michel, O. (2004). Webots: Professional mobile robot simulation. International Journal of Advanced Robotic Systems, 1(1), 39–42. https://doi.org/10.5772/5618.
18. Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R., & Ng, A. Y. (2009). ROS: An open-source robot operating system. In ICRA Workshop on Open Source Software (Vol. 3, No. 3.2). https://www.ros.org.
19. Microsoft. (2020). AirSim: High-fidelity simulator for autonomous vehicles (Version 1.7) [Computer software]. GitHub. https://github.com/microsoft/AirSim.
20. Project AirSim Team. (2023). Project AirSim: Simulation platform for drones, robots, and autonomous systems on Unreal Engine 5 [Computer software]. Microsoft. https://projectairsim.github.io/ProjectAirSim/.

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21. Epic Games. (2025). Digital twins. Unreal Engine. https://www.unrealengine.com/en-US/digital-twins.
22. Implexus Lab. (2024). HMI for an industrial facility digital twin with UE5 [Conference talk and blog post]. Unreal Fest 2024 / Implexus Lab. https://www.implexuslab.com/post/hmi-for-an-industrial-facility-digital-twin-with-ue5.
23. Epic Games. (2024). Let's train virtual robots [Lesson plan]. Unreal Engine Learning Portal. https://www.unrealengine.com/en-US/lesson-plans/let-s-train-virtual-robots.
24. MathWorks. (2024). Unreal Engine simulation for robots [Documentation]. MathWorks. https://www.mathworks.com/help/robotics/ug/3d-simulation-for-robots.html.
25. SAS Institute. (2025). SAS digital twins on Unreal Engine transform manufacturing. Times of India – Business Technology. https://timesofindia.indiatimes.com/business/india-business/sas-digital-twins-on-unreal-engine-transform-manufacturing/articleshow/.

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ВІРТУАЛЬНА СИСТЕМА МОДЕЛЮВАННЯ ДЛЯ РОБОТОТЕХНІКИ ТА ПЛАТФОРМ СИМУЛЯЦІЇ ЦИФРОВИХ ДВІЙНИКІВ З ПРИКЛАДОМ СКЛАДСЬКОЇ СИСТЕМИ В UNREAL ENGINE 5

Анотація. *Цифрові двійники та високоякісні симулятори стають центральними для проєктування, тестування та експлуатації сучасних робототехнічних систем у промисловості, логістиці та взаємодії людини з роботами. Однак, існуючі порівняльні дослідження зазвичай зосереджуються на одному типі роботів, однотипних завданнях або симуляторі та рідко враховують специфічні для цифрових двійників аспекти, такі як телеметричні конвеєри, інтерфейси операторів або хмарне підключення. У цій статті пропонується уніфікована система оцінки для цифрових двійників, орієнтованих на робототехніку. Проведене дослідження застосовується до п'яти репрезентативних випадків використання: 1 – малі БПЛА, 2 – промисловий робот маніпулятор, 3 – логістична ячейка складу з автономними мобільними роботами (AMR), 4 – мобільний маніпулятор на основі HCI/VR, і 5 – загальний сценарій патрулювання та стикування у приміщенні.*

Фреймворк стандартизує вхідні дані (профілі роботів і середовища, визначення завдань, контракти даних цифрових двійників) та вихідні дані (метрики завдань і продуктивності та метрики DT), а також кодує складність завдань через структуровані фази та кроки керування на кожен конкретний епізод. Він реалізований на кількох робототехнічних симуляторах, що на сьогодні широко використовуються, а саме: Gazebo/gz-sim, Webots, NVIDIA Isaac Sim, CoppeliaSim, та на стеку на базі Unreal Engine 5 (UE5), який поєднує імпорт активів Datasmith, Chaos Physics, Blueprints/Control Rig та інтерфейси UMG/VR.

Як детальне кейс-стаді, в роботі автори втілюють логістичний приклад використання складу як цифрового двійника на базі UE5 та демонструють кількісні результати щодо пропускної здатності замовлень, довжини шляхів, коефіцієнта реального часу, часу кадру, пропускної здатності телеметрії та затримки UI до спрацьовування. Також проаналізовано технічні недоліки, такі як накладні витрати процесора Blueprint і уповільнення, викликані візуальним навантаженням. На всіх платформах і кейсах використання результатів дослідження демонструє компроміси між фізичною точністю, масштабованістю, багатогранністю взаємодії та чутливістю DT, а також призводять до практичних рекомендацій щодо вибору та композиції симуляційних і цифрових стеків для БПЛА, маніпуляцій, логістики та HCI-центричних застосувань.

Стаття завершується обговоренням обмежень, зокрема спрощення симуляції та апаратної залежності, а також окреслює майбутні кроки до кореляції симулятора до реального та автоматизованого banchmarking.

Ключові слова: *цифровий двійник, робототехніка, Unreal Engine 5, Gazebo, Webots, NVIDIA Isaac Sim, CoppeliaSim, автоматизація логістичних задач, симуляція БПЛА, промисловий робот, VR/AR управління, розумна система.*