

# Towards Agentic Intelligence in Digital Twins: Advances, Use Cases and Challenges

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**Abstract**—Digital twins (DTs) are emerging as a key approach for managing the growing complexity of 6G and beyond wireless networks. However, they lack closed-loop autonomy, multi-step reasoning, and the ability to act independently in dynamic environments. At the same time, agentic AI, where autonomous agents can perceive, reason, act, and learn, is maturing rapidly. Accordingly, this paper examines the convergence of agentic AI and DTs. We first review the building blocks of agentic AI, including agent architectures, multi-agent coordination, communication protocols and autonomy levels, and map them to DT-based network management. We then propose an architecture that places agents inside containerized DT sandboxes for automated security assessment. To evaluate this approach, we benchmark six frontier large-language models across 18 scenarios covering seven vulnerability categories. Building on the results obtained, the study also discusses cost trade-offs, per-category performance gaps, and deployment recommendations for different operational needs. Finally, it identifies open challenges and future directions for scaling agentic intelligence in network DTs.

**Index Terms**—Agentic AI, digital twins, large language models (LLMs), multi-agent systems, network security assessment, retrieval-augmented generation (RAG), autonomous network management

## I. INTRODUCTION

THE transition toward sixth-generation (6G) wireless networks introduces a level of complexity that existing management paradigms struggle to handle. Future networks must support massive device connectivity, ultra-low latency, and heterogeneous services spanning smart cities, industrial IoT (i.e., Industry 4.0), autonomous vehicles, and immersive metaverse applications [1]. In the meantime, over the last decade, digital twins (DTs) have emerged as a promising solution to this shift. By constructing virtual replicas of physical network infrastructure, DTs support operators to simulate configurations, predict failures, and optimize performance without disrupting live systems. Industry efforts such as the O-RAN Alliance’s DT radio access network (RAN) initiative further signal growing momentum toward standardized DT adoption in telecommunications [2].

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Although DT maturity has evolved over the past decade, the overall technology readiness level (TRL) of DTs currently remains between 5 and 7, according to research from industry, academia, and government research agencies [3], [4]. In other words, most DT implementations still function as passive simulation tools. They are able to mirror network state and support partial (and possibly offline) what-if analysis, but lack the ability to autonomously perceive changes, reason about responses, and act on the network in real time.

Agentic artificial intelligence (AI) offers a path to close this gap. The rapid advancement of large language models (LLMs) has enabled AI agents capable of autonomously executing complex technical tasks [5], with the promise of minimal human intervention. When embedded within a DT, such agents transform the twin from a passive mirror into an active decision-making system capable of closed-loop control. The market trajectory also reflects this trend. Gartner projects that by 2028, 33% of enterprise applications will integrate agentic AI capabilities, rising from less than 1% in 2024, signaling a rapid shift toward agent-driven architectures across industries, including the telecommunication [6].

### A. The Current Gaps in Digital Twin Maturity

In today’s DT development landscape, many existing approaches employ recent practices, such as service-oriented architecture and cloud computing, to host essential data and simulations; and AI models for what-if analysis, forecasting, etc. Despite their demonstrated value and significance, there are still major gaps that neither the industry nor academia have solved, as explained below.

- **Lack of closed-loop autonomy.** Current DT implementations primarily operate in an open-loop perspective, even though the promise behind the DTs is fully autonomous control. In practice, network data flows into the twin, simulations or ML models produce outputs, and then a human operator interprets the results and manually applies changes to the physical network. This human-in-the-middle bottleneck limits the speed at which DTs can respond to dynamic network events, such as traffic spikes, link failures, or security incidents, and eventually prevents DTs from operating as truly autonomous systems. While some recent efforts have explored reinforcement learning (RL) for automated control within DTs [7], these approaches are narrow in scope, i.e., trained for a single task (such as power control or handover optimization), and do not generalize across the diverse challenges of wireless networks.

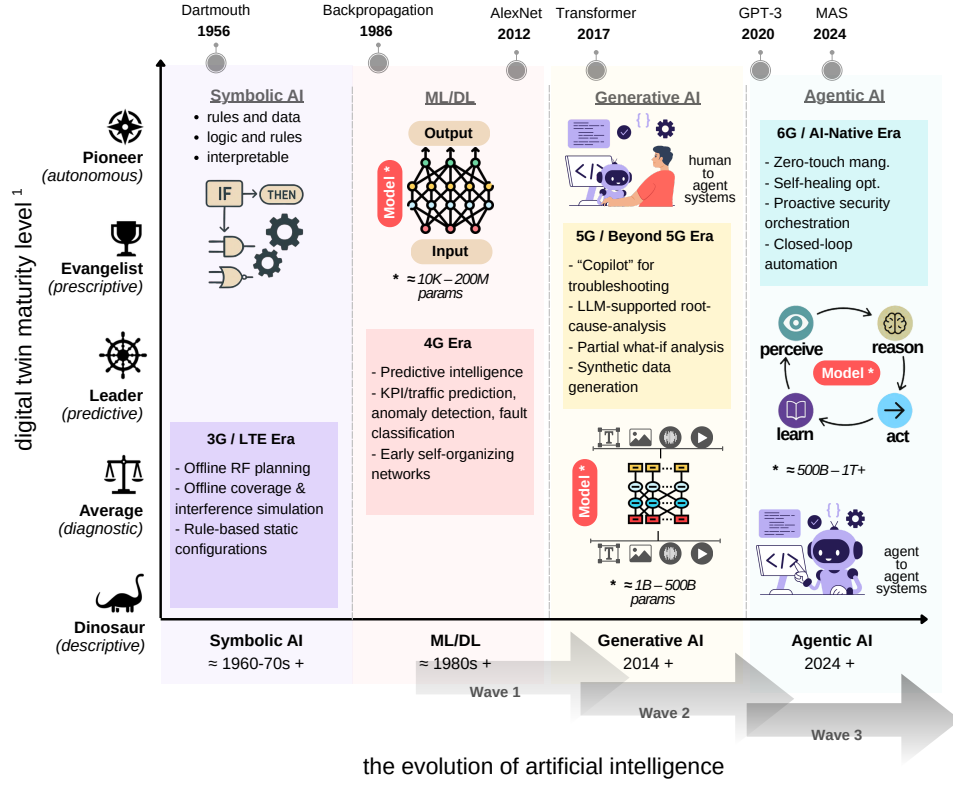


Fig. 1. Evolution of AI and its role as an enabler of digital twin maturity, together shaping applications in wireless networks.

<sup>1</sup>DT maturity levels follow the Digital Twin Consortium model (dinosaur → average → leader → evangelist → pioneer), progression from descriptive to autonomous, cross-domain digital twins.

- **Limited and task-specific intelligence.** The AI models (including machine learning (ML) and deep learning (DL) models) deployed within most DTs today are designed for predefined, well-scoped objectives. A model trained to forecast traffic load cannot also be used to predict resource allocation or detect security vulnerabilities. Each new task (or even the same task in a different domain or topology) requires a separate model, training data, and integration effort. This limitation makes current DT pipelines fragile and difficult to scale, slowing their overall maturity.
- **No reasoning or planning capability.** Closely related to the above, today's DT systems lack the ability to reason over multi-step problems. Given an objective such as "assess the security level of this network", existing DTs have no mechanism to decompose the goal into subtasks, select appropriate tools for each subtask, and adaptively revise the plan based on intermediate results.
- **Isolated twins with limited interoperability.** Current DT deployments are implemented as isolated, domain-specific systems. A DT developed for RAN optimization cannot directly interoperate with a DT for energy management or security monitoring. These systems rely on different data models, interfaces, and possibly update cycles, resulting in limited interoperability. Consequently, cross-domain data exchange is constrained, and each DT maintains only a partial, domain-specific view of the same underlying network.

- **Partial user interaction.** Most DTs are still operated through fixed dashboards and visualization panels. Some DT deployments are beginning to add LLM-based chat interfaces, but a chatbot alone does not solve the problem, without integrated reasoning and planning over the twin's models. In other words, DTs right now cannot accept open-ended "what-if" questions (e.g., traffic shifts across slices during peak hours) and produce structured answers and actionable outputs.
- **Insufficient data integration and contextual knowledge.** Current DTs rely on data from predefined sources, and their ML models are trained on historical datasets that can become outdated over time. Integrating new data sources, such as a new vendor application programming interface (API), external cross-domain data like weather information, or updated regulations, requires changes to the data pipeline and system redesign. DTs also lack the ability to automatically search for, retrieve, and integrate new external information during runtime.

These current DT gaps are also reflected in Fig. 1, which relates DT maturity to the evolution of AI and its impact on wireless communication technologies. The vertical axis represents DT maturity levels, named using the Infrastructure Maturity nomenclature (dinosaur, average, leader, evangelist, pioneer) of the Digital Twin Consortium<sup>1</sup>, a leading industry body that develops standards and best practices for digital

<sup>1</sup><https://www.digitaltwinconsortium.org/>

twin technologies. Each level is paired with the analytics capability it enables for network operation: descriptive, diagnostic, predictive, prescriptive, and autonomous, respectively. A dinosaur-stage twin only describes current and past network state through rule-based, offline tools. A leader-stage twin adds predictive intelligence, such as KPI forecasting and anomaly detection. An evangelist-stage twin becomes prescriptive, recommending actions and supporting copilot-style what-if analysis. A pioneer-stage twin acts autonomously in a closed loop across domains.

The horizontal axis of Fig. 1 traces the progression of AI from its early roots in the 1980s through to today’s agentic AI paradigms, through three waves (i.e., generation) of AI system design. First-wave relied on parameter learning, which is training fixed models on static datasets. Second-wave systems introduced *prompt engineering*: guiding pretrained LLMs (i.e. generative AI) through given single prompts (or called instructions). Third-waves, finally, agentic systems shift to what recent literature calls *mechanism engineering*. Viewed together, this timeline shows how advances in AI have historically enabled new capabilities in both digital twins and wireless systems. Progress in agentic AI reflects the growing promise of AI to support predictive insight and adaptive behavior in complex networks.

## B. Contributions

Undoubtedly, agentic AI will influence a wide range of industries. Digital twins and agentic AI are also converging together, and that convergence is what moves the twin from a passive mirror into an active, closed-loop system that can reason about a network and act on it. A few rare studies have started to use agentic AI for digital twins, for example to build and operate the twin itself [8]. But the picture, and the limits of this convergence, are still unclear. Most studies show a single agentic design on one or two use cases. What works, what fails, and what can run safely without a human are still open questions. In this article, we step back to show the big picture of how agentic AI can shape digital twins for network management, covering optimization, configuration, security, and edge/IoT. We then test the idea inside a network DT, using six language models over 540 runs. We measure not only accuracy, but also how stable the results are, because stability decides whether an agent can be trusted to act on its own. This gives a clearer view of where agentic digital twins are ready today and where they are not. Specifically, our contributions are as follows:

- We review the building blocks of agentic AI, covering single-agent design, multi-agent systems, communication protocols, and autonomy levels, and map them to DT-based network management, showing how each addresses a gap that keeps today’s digital twins underdeveloped.
- We present an architecture in which agents work inside the DT as a closed loop, using the twin as a safe sandbox to test actions before they reach the live network, and we illustrate it across several use cases: optimization, configuration, security, multi-domain, and edge/IoT.

- We introduce a reproducible open-source benchmark<sup>2</sup> that evaluates autonomous AI security agents across 18 scenarios and six LLM models, reporting statistical results.
- Through over 540 test runs, we identify strengths and limitations of current AI agents, including agent reliability, MAS coordination overhead, providing practical guidance for deploying agents for DT network management.

The remainder of this paper is organized as follows. Section II overviews advances in agentic AI and its foundations, and their role in enabling autonomous intelligent DTs, as well as discussing some use cases. Then Section III presents the overlay architecture for agentic intelligence in DTs, the proposed architecture, then shows the benchmark, experimental results and discuss lessons learned. Section IV discusses challenges, future directions and concludes the paper.

## II. RECENT ADVANCEMENTS ON AGENTIC AI AND USE CASES ACROSS DIGITAL TWINS

The term “agentic” distinguishes a new class of AI systems from both traditional ML/DL models and generative AI and conventional LLM usage. In traditional ML, a model is trained offline on a fixed dataset and deployed to perform a single task (such as traffic classification, load forecasting). In standard LLM interaction, a user submits a prompt and receives a single text response. Neither approaches involves the model taking actions, maintaining these actions across steps and pursuing goal over time. An agentic AI system, by contrast, operates through a repeated loop of four stages: *perceive*, *reason*, *act*, and *learn* [9], shown in Fig. 1 and detailed below.

- 1) *Perceive*: The agent perceives its environment by ingesting raw data and converts them into a representation the LLM can reason over. In a network DT context, this could include parsing network topology data, reading vulnerability scan results, or interpreting system logs. Perception can be multimodal, accepting text, structured/unstructured data, or even images (e.g., network topology diagrams).
- 2) *Reason*: The agent reasons over the perceived data using the LLM as a cognitive engine. Different techniques can be applied depending on the complexity of the task. In a direct response (i.e., zero-shot) approach, the agent produces an answer in a single step. In chain-of-thought (CoT), it reasons step by step, generating intermediate explanations before reaching a conclusion. In the ReAct approach, the most common one, the agent alternates between reasoning and acting (i.e. next stage) within a loop, deciding its next action based on the latest observation.
- 3) *Act*: The agent executes actions by invoking external tools, such as command-line utilities (e.g., `nmap`, `sqlmap`), APIs (e.g., cloud orchestrators, network controllers), simulators, or code interpreters. Tool use is what separates an agent from an LLM chatbot. Rather than describing what should be done, the agent does it. In a network DT, the action space might include running

<sup>2</sup><https://github.com/dt-harness/benchmark>

a port scan in the network, modifying a firewall rule, or deploying a configuration change to a twin network slice, before applying it to the real network.

- 4) *Learn*: Agents maintain both short-term memory (the current context window, which tracks the ongoing task state) and long-term memory (persistent storage of past experiences, retrieved via embedding-based lookup). Long-term memory enables agents to recall prior decisions, avoid repeating mistakes, and build cumulative knowledge across sessions. Retrieval-augmented generation (RAG) extends this further by allowing agents to dynamically query external resources, documentation, querying APIs or databases at runtime. Additionally, an approach, called *reflexion* adds a self-critique mechanism. After completing a task or encountering failure, the agent reflects on what went wrong and revises its approach.

#### A. Multi-agent System (MAS)

While a single agent can handle many tasks, some use cases might benefit from distributing work across multiple agents. In a multi-agent system (MAS), each agent generally has a defined role (e.g., scanner, analyst, planner, reporter), and the agents coordinate to accomplish a shared objective. MAS is an architectural decision in agentic AI systems, where it can drastically affect the output and performance [9], together with the approach in *perceive-reason-act-learn* stages. MAS architectures vary along three principal dimensions: i) agent composition, ii) topology type, and iii) interaction approach, as shown in Fig. 2 and explained below.

1) *Agent Composition*: In homogeneous configurations, all agents share the same capabilities. For example, they may run parallel monitoring operations, such as scanning multiple network slices at the same time or collecting sensor data simultaneously from distributed IoT nodes. In heterogeneous configurations, agents carry distinct roles, such as one agent may specialize in traffic anomaly detection, another in resource allocation. These heterogeneous agents with specialized roles are defined during the prompting or even using different underlying LLMs or foundation models. The third configuration, *evolving composition*, is particularly relevant for DTs, where agents that start with identical capabilities gradually develop specialized behaviors through interaction with the network.

2) *Topology Type*: Agents must exchange information with each other. The agents can be organized in a centralized (e.g., orchestrator and sub-agents) structure where an orchestrator delegates tasks and aggregates results; a decentralized (peer-to-peer) structure where agents communicate directly without central control; or a hierarchical structure with multiple levels of delegation. Alternatively, one can use a hybrid or even a dynamic structure, depending on the use case. However, it should be clearly defined and tested since the structure of this topology has direct consequences for performance [9].

3) *Interaction Type*: Even though creating a categorized clear list for the interaction type is not easy (since there are different naming standards in the literature), the interaction type describes how agents work together, and can be divided

into three categories considering network DT applications: *co-operative*, *competitive* and *coopetition*. Agents may cooperate toward a shared goal, compete in adversarial settings (e.g., red team and blue team in security simulations), or engage in coopetition, which is a mix of both. Within the *cooperative* settings, the sub-interaction types include consensus-based (agents vote and debate to reach agreement), task-oriented delegation (an orchestrator assigns subtasks), and teacher/student (an expert agent guides a less capable one).

#### B. Autonomy Levels and Human-Agent Interaction

Not all agentic deployments require full autonomy. Inspired by the five-level autonomy framework [10], which defines agent autonomy as a design decision independent of model capability, we adopt three broad categories that are relevant to network DT operations. At the *AI-assisted* level, the agent provides information and suggestions, but the human makes all decisions and initiates all actions. This corresponds to the lower end of the autonomy levels, where the human remains in full control and the agent serves as an on-demand support tool. At the *AI-delegated* level, the agent executes tasks within predefined boundaries and consults the human only for key decisions. The agent can plan, act, and use tools independently within its scope, but critical actions require human approval before proceeding. At the *AI-supervised* level, the agent operates autonomously and the human monitors outcomes rather than directing actions.

#### C. Use Cases

The first three reflect recent studies in the literature, while the last two illustrate how agentic AI can serve as an enabler for DT-based network management Fig. 2 maps each to its MAS design choices. In the Section III, a case study with empirical assessment will be discussed.

1) *Network Optimization and Resource Orchestration*: Recent works apply foundation-model agents to radio and cross-layer resource management in 6G. One study [11] proposes a cloud-edge-end framework for cell-free massive MIMO orchestration, where a cloud-hosted supervisor agent decomposes user intent into subtasks and reviews the outputs of lightweight specialist agents running at the network edge, following a hierarchical plan-and-execute pattern grounded in retrieved expert knowledge. A second framework, Agent-Net [12], is instead decentralized and places agents across the application, network, and physical layers with potentially conflicting objectives such as maximizing throughput while minimizing energy. The agents therefore operate under a coopetition pattern and learn through a model partition and sharing mechanism rather than iterative ReAct-style reasoning, as demonstrated in a DT-based industrial automation scenario.

2) *Network Configuration Automation*: One study [13] proposes a multi-agent framework over the network configuration protocol (NETCONF), built on CrewAI, in which four heterogeneous agents form a sequential pipeline. An intent agent rewrites ambiguous requests through chain-of-thought prompting, a retrieval agent performs self-reflective hybrid retrieval from a NETCONF knowledge base, a security agent

| Multi-agent System (MAS) |                                                                                                                                |                                                                                   |                  |                                                                                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Single-agent System (SAS) |  |  |  |  |  |  |  |
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| Dimension                | Configuration                                                                                                                  |                                                                                   | Dimension        | Configuration                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
| Agent Composition        |  <b>Homogeneous</b><br>Identical capabilities |  | Interaction Type |  <b>Cooperative</b>                         | <div>Agentic AI and DT-assisted Network Management Use Cases</div> <div><div><div>Multi-Domain Network DT</div><div>Enterprise-wide DT spanning campus, WAN, cloud, and edge networks</div><div></div><div>Homogeneous monitoring agents per domain report to hierarchical coordinators. Coopetition-based interaction enables cross-domain knowledge transfer.</div></div><div><div>Edge / IoT Network DT</div><div>Distributed, latency-sensitive IoT network with many DT nodes</div><div></div><div>Agents start identical but evolve specializations based on local conditions. Distributed topology avoids single points of failure.</div></div></div> |                           |  |                                                                                     |  |  |  |  |  |
|                          |  <b>Heterogeneous</b><br>Specialized roles    |                                                                                   |                  |  <b>Consensus-based</b><br>Debate & align   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
|                          |  <b>Evolving</b><br>Role emergence            |                                                                                   |                  |  <b>Task-oriented</b><br>Decompose & chain  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
| Topology Type            |  <b>Centralized</b><br>Hub-and-spoke          |                                                                                   |                  |  <b>Teacher-Student</b><br>Guide & feedback |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
|                          |  <b>Distributed</b><br>Peer-to-peer mesh      |                                                                                   |                  |                                                                                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
|                          |  <b>Hierarchical</b><br>Tree-based layers     |                                                                                   |                  |  <b>Competitive</b><br>Resource competition |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
|                          |  <b>Hybrid</b><br>Shared message              |                                                                                   |                  |  <b>Coopetition</b><br>Share & improve      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                           |  |                                                                                     |  |  |  |  |  |
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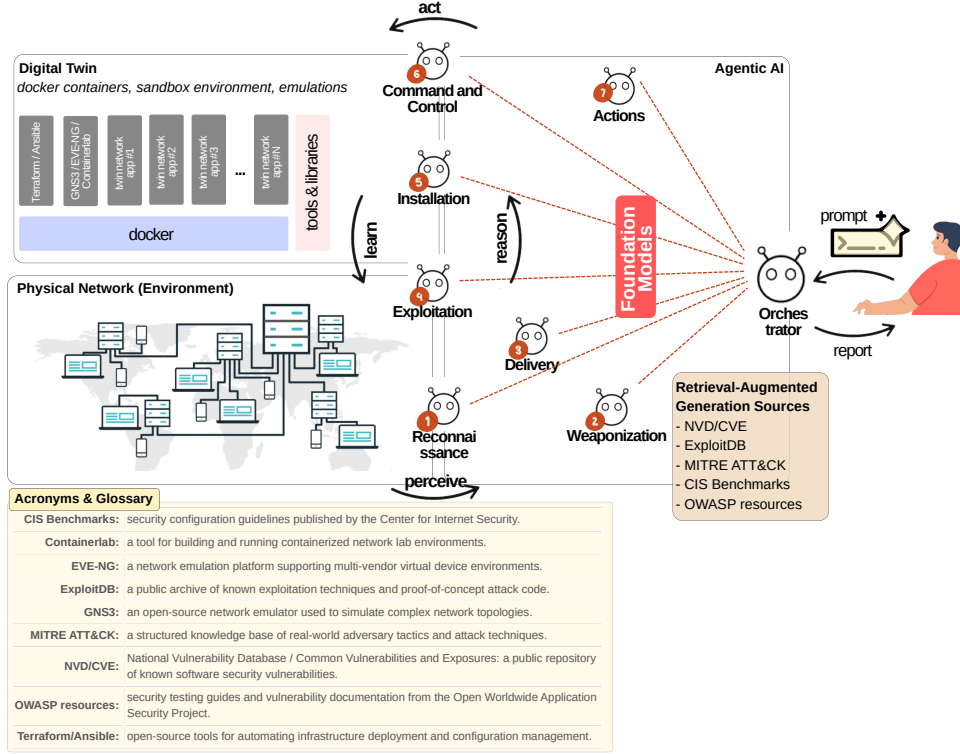


Fig. 3. An example agentic digital twin architecture for automated network security assessment. The orchestrator decomposes a user-defined security objective into seven kill-chain stages, each handled by a specialized agent that perceives, reasons, and acts inside a containerized DT sandbox.

TABLE I  
BENCHMARK SCENARIO CATEGORIES WITH REPRODUCIBILITY ANALYSIS

| Category            | Count     | IDs                     | Difficulty | Description                                     | Mean CV (%) | Mean Score (%) |
|---------------------|-----------|-------------------------|------------|-------------------------------------------------|-------------|----------------|
| CWE                 | 3         | CWE-78, CWE-79, CWE-89  | Medium     | Command injection, SQL injection                | 5.6         | 90.5           |
| OWASP Top 10        | 3         | A01, A02, A03           | Medium     | Broken access, crypto failures, injection       | 10.1        | 87.7           |
| Reconnaissance      | 2         | T1595.001, T1595.002    | Easy       | Network/service discovery                       | 7.8         | 83.6           |
| Post-Exploit        | 3         | T1082, T1083, T1087.001 | Hard       | System/file discovery, user enum                | 21.4        | 67.7           |
| Exploitation        | 2         | T1133, T1190            | Hard       | External remote services, exploit public-facing | 11.7        | 92.9           |
| CTF Web             | 4         | JWT, SQLI, XSS, IDOR    | Medium     | Auth bypass, injection, access control          | 4.2         | 86.2           |
| Operational         | 1         | SecOps                  | Hard       | Threat detection, incident response             | 17.7        | 81.5           |
| <b>Total / Mean</b> | <b>18</b> | —                       | —          | —                                               | <b>10.2</b> | <b>84.3</b>    |

which one agent scans its local node, a second checks the discovered services against CVE records through RAG, and a third produces recommendations. This keeps processing cost low and avoids a single point of failure, although the lack of a global view means repeated vulnerabilities across gateways are not aggregated.

### III. A CASE STUDY: AN EMPIRICAL ASSESSMENT OF AN AGENTIC AI DIGITAL TWIN IN CYBER SECURITY

We chose network security assessment as the benchmark domain and implement as a case study for three reasons. First, it needs the full perceive–reason–act–learn loop: the agent must read the network state, plan several steps, run tools, and act on the output. Second, it needs real tool use (for example, nmap and sqlmap), so it tests action and not only text answers. Third, security tasks have clear ground truth. A vulnerability is either found or not, and the required results can be checked automatically. Many other DT tasks, such as

resource optimization, do not have such clear ground truth, so fair and repeatable scoring is harder. For these reasons, we treat other domains as future work and discuss which findings are transferable in Section III-C.

Fig. 3 illustrates the proposed architecture. The design draws from the Lockheed Martin Cyber Kill Chain<sup>3</sup>, which models an intrusion as a seven-stage sequence: reconnaissance, weaponization, delivery, exploitation, installation, command and control (C2), and actions on objectives. Each stage is assigned to a specialized agent, and all agents are coordinated by a central orchestrator that handles task decomposition, context aggregation, and report generation. The agents interact with the physical network only through the DT layer, which provides isolated environments built on Docker containers. Each agent’s reasoning is powered by a foundation model

<sup>3</sup><https://www.lockheedmartin.com/en-us/capabilities/cyber/cyber-kill-chain.html>

and grounded through RAG queries to external knowledge bases such as NVD/CVE for vulnerability lookup and MITRE ATT&CK for attack-path planning. In our benchmark evaluation, we consolidated the seven kill-chain stages into the orchestrator agent. We then prepared a standalone single-agent baseline with an identical tool set. The difference with single agent is that, in the multi-agent setup the same suite is reachable through the orchestrator, which decomposes the objective into the kill-chain stages and delegates to sub-agents. The base agent prompts are also identical; only the coordination structure differs (direct execution in SAS and orchestrated delegation in MAS).

#### A. Benchmark Design

We grounded our benchmark in the MITRE ATT&CK framework and industry-standard vulnerability classifications (CWE, OWASP Top 10), selecting 18 scenarios across seven categories. Table I summarizes the scenario distribution. Each of the 18 scenarios was tested under multi-agent setup with each of the 6 models across 3 independent repetitions, yielding 324 total runs. Moreover, to assess whether architectural complexity improves performance, 4 models (MiniMax, Mistral, Flash, GPT-OSS) were additionally evaluated under single-agent configuration across the same scenarios (216 additional runs). The single- and multi-agent configurations use identical tool sets, scenarios, and base agent prompts; only the coordination structure differs. Other details regarding reproducibility, including agent and system prompts, the set of tools used, orchestration logic for multi-agent configurations, scenario definitions with ground-truth artifacts and the evaluation criteria, are available in our open-source repository. During the runs, we also saved the coefficient of variation (CV) to quantify the variability and consistency of model behavior across independent repetitions.

Each scenario specifies: (1) a clear objective (e.g., “enumerate all local user accounts on the target system”), (2) ground truth artifacts required for success (e.g., minimum 12 accounts discovered, privileged users identified), (3) recommended tools that needed to be used.

1) *Digital Twin Environment Design*: All scenarios execute within isolated Docker containers, as also seen in Fig. 3. Each container provides: (1) reproducibility through declarative configuration files that guarantee identical initial state across all test runs, (2) complete replica (i.e., twinning) of the specific production networks, (3) observability through comprehensive logging of all agent commands, tool outputs, and LLM reasoning traces. Containers are provisioned fresh for each test run and destroyed immediately after evaluation to prevent state leakage between trials. The main idea is providing a sandboxed testing environments with DT deployments, where proposed configuration changes or security assessments are validated against a twin before applying to the real infrastructure.

2) *Evaluation Approach*: We evaluate agent performance by three aspects: weighted cost (70% task completion and 30% methodology quality, i.e., tool selection), average time per run and average cost per run. For the task completion, we measured how many of the artifact were completed via

exact match, content match (using regular expressions), count extractions and tool chain verification. For the methodology quality, we scores tool usage through an additive point system (required tools + optional recommended tools).

#### B. Evaluated Large Language Models

We evaluate six representative foundation models selected to span commercial and open-source architectures, model scales, and training approaches. All models share: (1) native tool-use capabilities through function calling or structured output generation, (2) state-of-the-art reasoning performance on standard LLM benchmarks, and (3) context windows sufficient to maintain multi-step task state (128K – 1M tokens). The models tested include: *MiniMax M2*, a frontier Chinese open-source foundation model with reported strong performance on reasoning benchmarks; *Claude Code Haiku 4.5* and *Sonnet 4.5*, Anthropic’s production agentic coding assistants with built-in tool orchestration; *Mistral Large 3 675B*, the largest open-weights model in the evaluation; *Gemini 3 Flash*, Google’s cost-optimized model designed for high-throughput applications; and *GPT-OSS 120B*, an open-source architecture baseline.

#### C. Key Findings and Lessons Learned

Our evaluation of six LLM-based agents across 18 cybersecurity scenarios presents some insights that extend beyond the security benchmark use case and shows some outcomes regarding the viability of agentic intelligence for network DTs. Here, Fig. 4 summarizes the three principal dimensions of our analysis: task performance and reproducibility (Fig. 4 (a)), cost-effectiveness (Fig. 4 (b)), and multi-agent gains (Fig. 4 (c)). Table II provides the per-model resource profile, and Table I presents the overall performance of seven use case categories, 18 scenarios in total, by coefficient of variation (CV) value. Below, we discuss the main findings:

**Finding 1: Current LLM agents are operationally viable for DT-based security validation.** Across 324 independent runs, the six models achieve a grand mean accuracy of 84.3%, with all models exceeding the 75% threshold we defined as the minimum for unsupervised operation within a DT sandbox. This is a meaningful result, especially compared with some other benchmarks LLMs are tested (i.e., software engineering benchmarks, SWE-bench<sup>4</sup>), where agentic success rates remain substantially lower. The implication for DTs is that LLM agents can partially support autonomous network management within a sandboxed twin.

**Finding 2: Reproducibility (i.e., stability) is sufficient for DT developments, but not uniform.** Stability, measured by CV, is arguably more important than peak accuracy for network management, where an agent must produce consistent judgments across repeated evaluations of the same network state. We find that 80.9% of model–scenario pairs achieve CV < 15%, and the median CV across all 108 pairs is 5.9%, substantially below our initial hypothesis of 20%. However,

<sup>4</sup><https://www.swebench.com/>

TABLE II  
COMPREHENSIVE MODEL PERFORMANCE AND RESOURCE METRICS

| Model                                                                  | Mean Score (%)      | 95% CI       | Median CV (%)      | Time (s/run) | Cmds (/run) | Cost (\$/run) | Score-Pts per \$ |
|------------------------------------------------------------------------|---------------------|--------------|--------------------|--------------|-------------|---------------|------------------|
| Single-Agent System (SAS)                                              |                     |              |                    |              |             |               |                  |
| MiniMax M2                                                             | 87.5                | [83.6, 91.4] | 6.1                | 623          | 40.5        | 0.135         | 647              |
| Mistral Large 3                                                        | 85.9                | [80.7, 91.1] | 9.5                | 779          | 52.0        | 0.730         | 117              |
| Gemini Flash 3                                                         | 83.7                | [80.0, 87.4] | 4.9                | 527          | 18.9        | 0.036         | 2,342            |
| GPT-OSS 120B                                                           | 77.2                | [71.5, 82.9] | 8.4                | 228          | 17.1        | 0.060         | 1,278            |
| Built-in Tool Orchestration                                            |                     |              |                    |              |             |               |                  |
| CC-Sonnet                                                              | 85.1                | [80.1, 90.1] | 2.2                | 346          | 50.9        | 0.593         | 143              |
| CC-Haiku                                                               | 86.2                | [81.8, 90.5] | 4.2                | 348          | 53.6        | 0.228         | 378              |
| Single Agent System vs Multi Agent System Agent (SAS / MAS) Comparison |                     |              |                    |              |             |               |                  |
|                                                                        | Task Completion (%) |              | Method Quality (%) |              | Rounds      |               | Tokens           |
|                                                                        | SAS / MAS           |              | SAS / MAS          |              | SAS / MAS   |               | SAS / MAS        |
| MiniMax M2                                                             | 81.9 / 81.9         |              | 74.5 / 77.2        |              | 35 / 63     |               | 9678 / 7145      |
| Mistral Large 3                                                        | 84.7 / 74.9         |              | 68.5 / 69.1        |              | 25 / 70     |               | 5109 / 3652      |
| Gemini Flash 3                                                         | 79.6 / 81.0         |              | 66.5 / 71.5        |              | 21 / 27     |               | 2293 / 3003      |
| GPT-OSS 120B                                                           | 71.1 / 70.5         |              | 49.9 / 49.6        |              | 34 / 27     |               | 8204 / 7126      |

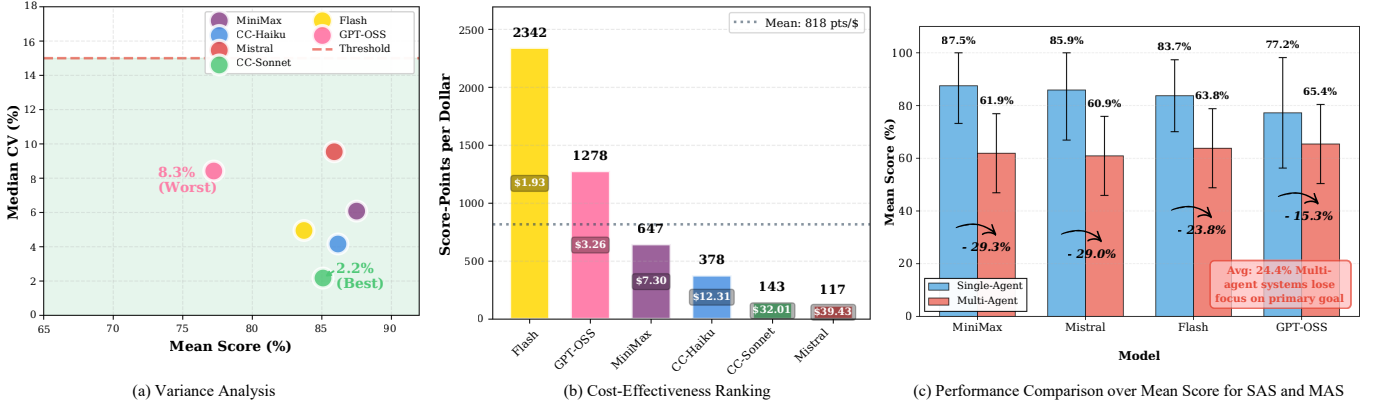


Fig. 4. Comprehensive performance, cost, and multi-agent analysis across six evaluated models. (a) Variance analysis: mean score versus median coefficient of variation (CV). Red dashed line marks the threshold, CV is lower than 15%. (b) Cost-effectiveness ranking: bar chart displaying score-points per dollar, sorted by performance. Models sorted left-to-right by cost-effectiveness. (c) Performance drift in multi-agent systems: grouped bars with error bars comparing single-agent versus multi-agent with task-oriented interaction type.

variance is not uniformly distributed. For example, post-exploitation tasks exhibit the highest instability (21.4% CV), while reconnaissance and web application assessment remain consistently stable. As for DTs, this suggests that agents can operate with almost-full autonomy on high-stability task categories (e.g., vulnerability scanning, configuration auditing), while unstable categories should trigger human-in-the-loop alerting systems.

**Finding 3: Model scale is not the primary determinant of network security task performance.** MiniMax-M2, a mid-scale model, achieves the highest absolute performance (87.5%) with the most balanced cross-category profile (only a 26.7 percentage-point range across task types and no category below 70%). Meanwhile, Claude Haiku, a smaller and faster model, achieves competitive accuracy (86.2%) with strong stability (88.9% of pairs). Conversely, Mistral Large, the most expensive open-source model evaluated, delivers comparable accuracy at 20× the cost.

**Finding 4: Multi-agent task delegation introduces sig-**

**nificant performance drifts.** Fig. 4 (c) presents the most consequential result for the architectural argument of this paper. The hierarchical multi-agent setup introduces a 24.4% average performance degradation compared to single-agent configurations. MiniMax drops from 87.5% (single) to 61.9% (multi), Mistral from 85.9% to 60.9%, Flash from 83.7% to 63.8%, and GPT-OSS from 77.2% to 65.4%. Moving from the single- to the multi-agent setup, the orchestration overhead also grows substantially. For example, MiniMax rises from 35 to 63 rounds and Mistral from 25 to 70 rounds. But this added effort is not converted into better outcomes. Task completion and methodology quality remain flat or decline. In other words, the gap between rising coordination cost and task outcome shows the context lost when the orchestrator delegates to sub-agents. For focused security assessments with well-defined objectives, single-agent configurations with comprehensive tool access and carefully engineered prompts outperform multi-agent architectures. Instead of architectural complexity, model capability, prompt engineering and tool curation emerge as

the primary determinants of agent effectiveness in DT security workflows directed toward the target. We emphasize that this result is specific to the tested topology and delegation strategy; other coordination designs, such as peer-to-peer or consensus-based, may behave differently and are left to future work.

**Finding 5: Security task categories reveal a maturity for agentic DT capabilities.** Table I exposes significant performance heterogeneity across task types, which we interpret as a *maturity* for agentic operations in network DTs:

- *DT-ready tasks* (mean accuracy >80%, low variance): reconnaissance, web application assessment, and cryptographic validation. These correspond to well-structured, tool-augmented tasks where the agent’s perceive–reason–act loop maps cleanly to existing network analysis workflows. DT operators can deploy agents autonomously for these categories with higher accuracy and stability (*AI-supervised level*).
- *Conditionally autonomous tasks* (mean accuracy 75–85%, moderate variance): network exploitation and defensive operations. The latter category exhibits the widest cross-model variance (57.7 percentage-point range), indicating that log analysis and threat correlation require model-specific reasoning capabilities. These tasks benefit from the more limited autonomy model, with human observer (*i.e., AI-assisted level*).
- *Human-supervised tasks* (mean accuracy <75%, high variance): post-exploitation. The open-ended, multi-step nature of post-compromise enumeration challenges current agent architectures. In a DT setting, these tasks should remain under supervised autonomy, with the agent proposing action plans within the twin for human review before execution (*i.e., AI-delegated level*).

**Operational Deployment Guidance.** Taken together, these findings suggest four deployment guideline for agentic DT systems, each matching a different operational priority:

- *Generality of findings:* The results come from one use case, so the paper actually assess two kinds of findings. The first concerns agent behavior and architecture: the viability threshold, the reproducibility analysis, the limited effect of model scale, the cost rankings, and the single- versus multi-agent comparison. These describe how agents behave rather than security itself, so we expect them to hold for other DT tasks that use a closed-loop twin environment with tools and RAG. The second is the task maturity analysis (Finding 5), which ranks task types by readiness. This depends on the specific security categories tested, and the results obtained here cannot be generalized for other domains.
- *Continuous DT monitoring:* Gemini Flash achieves 83.7% accuracy at \$0.036/run (2,342 pts/\$), which is optimal for always-on DT tasks. For tighter budgets accepting lower accuracy, GPT-OSS (77.2% at \$0.060/run, 1,278 pts/\$) might be another acceptable LLM model.
- *Compliance and forensic validation:* Claude Sonnet’s 2.2% median CV shows very stable results, which is critical for regulatory audits, since inconsistent outputs can raise legal concerns.

- *Accuracy assessment:* MiniMax-M2’s balanced cross-category profile minimizes blind spots, reducing the risk of false negatives in critical infrastructure or financial network assessments.
- *Autonomous incident response and reliability:* Single-agent architectures with comprehensive tooling (MiniMax 87.5%, Mistral 85.9%) avoid the 24.4% performance drift observed in hierarchical delegation, favoring prompt engineering over architectural complexity.

#### IV. CONCLUSION

This article explored how agentic AI can bring autonomous reasoning, planning, and tool use to digital twin-based network management. We discussed the core components of LLM-based agents, from single-agent architectures to multi-agent systems and open communication standards, and showed how they map to practical DT operations. Results show an 84.3% average task-completion rate with a median coefficient of variation of 5.5%, confirming that agents can operate reliably inside DTs.

The convergence of DT and agentic AI is undeniable. However, several challenges remain open. Firstly, agent safety is a crucial concern. As agents gain more autonomy within digital twins, the risk of prompt injection, adversarial manipulation, or cascading errors grows. Standardization of agent communication protocols (MCP, A2A, and others) is still fragmented, making it hard to build interoperable agent ecosystems across vendor boundaries. Also, we tested a hierarchical orchestrator–sub-agent design; however, other multi-agent topologies such as peer-to-peer or consensus-based remain to be studied. Finally, the cost of running agentic systems at scale, particularly for continuous monitoring, calls for further work on efficient model selection and adaptive autonomy levels.

Looking ahead, we see the digital twin evolving from a passive simulation tool into an active, agent-operated environment, a sandbox where AI reasons about network state, tests responses, and learns from outcomes. Achieving this vision will require closer collaboration between the networking, AI, and broader communities. Our benchmark and taxonomy are a step in that direction, and both are available as open-source resources to support future research.

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