WHITE PAPER: DIGITAL TWINS FOR DATA CENTERS

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Revision History

Revision	Version	Date	Comments
1.0	1.0	December 2025	Initial Submission
1.0	1.1	June 2026	Edits following review comments from OCP reviews.
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Executive Summary

The challenges of scale, complexity, and workload changes for today's data centers demand an evolution from static management to intelligent, adaptive design and operations . The Digital Twin (DT) is a transformative technology evolution driving this shift. A continuously synchronized, virtual replica of a physical counterpart, able to simulate the behavior of the counterpart; the DT enables predictive optimization and monitoring across the data center's lifecycle.

The Open Compute Project (OCP), is a collaborative community driven project dedicated to designing and sharing open data center technologies. It has begun a strategic initiative around DTs to accelerate industry adoption and help overcome some confusion around definitions, capabilities and implementation standards. This white paper establishes a clear, unified definition agreed by stakeholders across the data center ecosystem and presents a comprehensive maturity model to guide operators and decision makers. We discuss the impact DTs are having across the data center lifecycle with example use cases where DT unlock benefits including: reductions in Total Cost of Ownership (TCO), maximizing resource utilization, enhanced resilience against failures and the achievement of critical sustainability goals. Finally, we outline the key technical challenges, specifically the need for greater standardization and interoperability, that must be addressed to realize the vision of fully autonomous, lights-out data center operations promised by DTs..

Definitions

Aggregation: An integration strategy that involves copying data to gather it into a centralized location.

Model-Based System engineering (MBSE): MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. The initiative was established in 2007 to realize the MBSE Vision of the "future of systems engineering is model based" to scale systems engineering by replacing document-oriented practices with models (INCOSE definition).

Systems Modeling Language (SysML): SysML is a general-purpose modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities (OMG definition). It's commonly applied in systems engineering for domains like aerospace, automotive, defense, robotics, medical devices, etc.

Digital Thread: Is the interconnected flow of data across a system lifecycle, from design and construction to operation and decommissioning.

Artificial Intelligence Data Center (AIDC): A data center purpose-built or optimized for artificial intelligence workloads (large-scale model training and inference); sometimes called an "AI factory". Compared to conventional data centers, AIDCs are characterized by extensive deployments of accelerators (GPUs or other AI silicon) and much higher power and heat density per rack, requiring advanced cooling approaches and high-bandwidth, low-latency interconnect fabrics. AIDCs place greater emphasis on precise thermal management, power delivery, and capacity planning.

List of Abbreviations

AIDC - Artificial Intelligence Data Center

BIM - Building Information Modeling

DC - Data Center

DCIM - Data Center Infrastructure Management

DT - Digital Twin

DTI - Digital Twin Instance

DTP - Digital Twin Prototype

IOT - Internet Of Things

OEM - Original Equipment Manufacturer

PUE - Power Usage Effectiveness

WUE - Water Usage Effectiveness

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Tables & Figures

Compliance with Open Compute Project Tenets

As a white paper rather than a hardware or software contribution, this document advances the OCP tenets primarily through knowledge sharing, definition clarity and describing a common framework rather than through a deployable artifact. The following describes how it aligns with each tenet.

Openness

This whitepaper was developed collaboratively under the OCP Digital Twin Initiative, with authors and contributors drawn from multiple organizations across the data center ecosystem. It is published under a Creative Commons Attribution-ShareAlike 4.0 License, allowing any third party to freely use, adapt, build upon and redistribute its content. Rather than promoting a single proprietary approach , the paper deliberately surveys open and industry standards and presents a vendor-neutral definition and maturity model intended to be extended and redefined by the wider community. The framework is designed as a starting point and feedback, revision and contribution from other OCP projects, as well as external stakeholders is encouraged.

Efficiency

The subject of this whitepaper is a driver of efficiency itself, and this document makes the efficiency case explicit and measurable. It details how digital twins (DTs) reduce both capital and operational expenditure through right-sizing of infrastructure, predictive maintenance and continuous operational optimization. These gains are grounded in concrete examples with case studies provided by contributors.

Impact

This whitepaper targets a recognized source of friction in the market: widespread confusion over what constitutes a DT for data centers. This has slowed adoption and complicated procurement. By establishing a clear, stakeholder-agreed definition and a forward looking maturity model that operators can use to benchmark capability and plan, the paper lowers the barrier to adoption and aims to increase value for adopters. The intended audience of the whitepaper is one of operators, DT tool makers and decision makers worldwide. The framework is positioned to inform future OCP work, both in the Digital Twin Strategic Initiative and in alignment with other OCP specifications like the OCP Ready™ Data center Specification.

Scale

The maturity hierarchy is explicitly designed as an additive, incremental model. Operators are not required or expected to adopt fully autonomous systems at the outset. The sub-system examples allow the framework to be applied selectively, one domain at a time, rather than as an all-or-nothing deployment. We also provide guidance on adoption so that the concepts can be implemented at any scale.

Sustainability

Sustainability is a central theme of the whitepaper, we describe how DTs support greener data centers across their lifecycle . We connect the various ways that data centers DTs can aid in efficiency and sustainability with recognized frameworks such as the GHG Protocol and the EU Taxonomy for Sustainable Activities. The white paper also highlights how DTs can aid in operational levers to aid sustainability like load shifting or waste heat recovery. The whitepaper frames DTs as an enabler of transparency in environmental impact and continuous decarbonization that serves the goal of this tenet.

Introduction

The concept of the digital twin (DT) for data centers is gaining momentum, promising transformative advancements in how facilities are designed, managed, and optimized. However, there is significant confusion in the market about what constitutes a true DT. Many existing solutions fall short of delivering the comprehensive capabilities required to fully replicate and manage a physical data center virtually. This lack of clarity has created challenges for data center professionals and organizations seeking to adopt and leverage DT technology effectively.

Recognizing this gap, the Open Compute Project (OCP) developed this white paper to establish a clear framework for defining the DT for data centers. By providing standardized definitions and outlining key functionalities, this framework aims to help the industry better understand what a DT is—and what it can achieve—while fostering collaboration and innovation around this emerging technology.

At its core, the DT for data centers is a behavioral representation of a physical facility, capturing its structure, operations, and dynamic changes over time, with visualization ranging from abstract, non-spatial representations to detailed 3D views as needed. It integrates multiple layers of descriptive information and provides a complete representation of all components in the data center, enabling detailed inventory tracking and bill-of-materials generation. Beyond its appearance, the DT behaves like its real-world counterpart through physics-based simulations, modeling airflow, temperature changes, and other critical behaviors.

The DT continuously synchronizes with its physical counterpart, usually via real-time data streams, ensuring that any changes (e.g. IT configuration updates or workload variations) are captured instantly. Looking ahead, AI-driven inferencing capabilities will enable DTs to actively optimize their physical counterparts in real time, responding dynamically to operational changes to enhance performance and efficiency.

This white paper explores the definition, use cases, and transformative potential of DTs for data centers while addressing industry-wide confusion about their scope and capabilities. It is specifically developed for data center operators, DT tool makers, and industry decision-makers. By establishing a shared understanding of this technology, OCP aims to empower operators to unlock smarter resource management, predictive maintenance, and adaptive optimization—ushering in a new era of intelligent data center design and operations.

1. What is a Digital Twin?

DTs are not exclusive to the data center industry; they have been widely adopted in sectors such as automotive, aerospace, oil and gas, and manufacturing. They are used to support design validation, process optimization, and lifecycle management. Similar applications are emerging in the data center industry, where DTs are being explored to improve design, support operations, and inform sustainability.

There are many competing definitions for what constitutes a DT that focus on differing aspects of their use case, technology implementations and position in a system's lifecycle (van der Valk et al. #) For our purposes we define a DT as:

> *A **Digital Twin (DT)** is a dynamic, behavioral virtual replica of a physical system or object; either existing in the real world or intended for future creation. This virtual representation is dynamically synchronized with its physical counterpart through continuous data exchange. A DT captures not only the physical attributes of its counterpart but also its behaviors, interactions and operational context.*

When a DT is created prior to the physical counterpart it is often referred to as a **Digital Twin Prototype (DTP)** or a Design Twin. These can be used to analyze in-context behavior of a system and inform the design and construction process. An operational DT or a **Digital Twin Instance (DTI)** is linked with its counterpart and is used to inform operational decisions, improve efficiency and manage change. Together, through the life cycle of a system there is a **Digital Thread** representing the traceable, continuous flow of data and information that links a DTP (in design), DTI (In operation) and the eventual decommissioning of the system.

Digital Twins in the Data Center

The concept of a DT is similar but distinct from existing data center technologies like Building Information Modeling (BIM) and Data Center Infrastructure Management (DCIM), though it leverages them. Data centers already utilize these technologies: BIM provides 3D models and DCIM supplies real-time operational data. The DT expands on this foundational data collection by adding functional, logical, system-level (1D) and physics-based simulation moving beyond monitoring to predictions and optimization.

Data center DTs are distinguished by their emphasis on real-time operational optimization, energy efficiency, and risk management—driven by the unique needs and complexity of data center environments. Compared to other industries, these DTs are tailored to continuous uptime, precise thermal management, and proactive capacity planning under high-density, mission-critical conditions.

Problems solved by digital twins in data centers

DTs in data centers address a distinct set of operational, environmental, and business-critical problems. By virtually replicating the data center's systems, DTs help mitigate risks, optimize resource use, and prevent costly disruptions.

Some of the main problems addressed by DTs are:

- **Unplanned Downtime and Service Interruptions**: DTs enable real-time monitoring, predictive maintenance, and simulation of failure scenarios, allowing operators to anticipate and swiftly address faults before they escalate into outages.
- **Poor Energy Efficiency**: By simulating thermal flows, cooling systems and energy consumption, DTs help operators optimize cooling strategies, reduce power usage, and achieve significant cost savings while supporting sustainability and ESG goals. Outside of internal efficiency gains, DTs can also help model more advanced energy strategies such as waste heat recovery and dynamic grid interactivity.
- **Inefficient Capacity and Space Planning**: DTs model rack layouts, power distribution, and cooling supporting better space utilization and enabling seamless capacity expansions to meet growth in demand without overspending on infrastructure.
- **Difficulty Managing System Complexity**: The increasing complexity of data centers and the integration of different engineering disciplines (power, cooling, network) makes siloed management ineffective. DTs offer a unified overview, based on digital models, of all systems and subsystems, thus improving the design (interface definition, failure impact, system sizing) and the efficiency of these different systems when they interact during operation.
- **Slow Incident Response and Root Cause Analysis**: Through continuous documentation and real-time simulation, DTs enable rapid reconstruction of incidents, aiding faster diagnostics and corrective action.

- **Compliance and Audit Challenges**: DTs support regulatory compliance (GDPR, ISO 27001, SOC 2) by automating infrastructure documentation and tracking configuration changes across the entire lifecycle.
- **Innovation acceleration**: new concepts and solutions can be thoroughly simulated and tested with minimal risk, enabling faster innovation cycles.
- **Security Threats**: Integrated real-time monitoring with AI-enhanced analytics allows detection of unusual behavior, supporting cybersecurity and physical security management.

Digital Twin Capability and Maturity

DT implementations are not uniform; the DT eco-system presents a broad spectrum of capabilities, features and maturity levels. A single, initial deployment or tool is generally insufficient to deliver the full range of benefits or achieve the highest levels of optimization and automation promised by the technology.

Capabilities span from DTs that provide pure visualization (integrating data collection with 3D models for situational awareness) to advanced predictive models that leverage sophisticated physics-based simulations and artificial intelligence (AI) for autonomous optimization. In section 4, we provide an OCP maturity hierarchy that offers a framework for evaluating existing DT capabilities in use in an organization. It is important to note that while there is a correlation between capabilities and maturity in DTs, these are not necessarily required to reach a certain level of maturity. It often depends on the use case and organizational readiness as to which capabilities of a DT contribute to its maturity.

2. Use Cases in the Data Center Lifecycle

The true value of a DT lies in its application across the lifecycle of the data center. Historically, the data center process from planning and design to construction, commissioning, and operations has been fragmented. DTs can act as a single continuous source of truth that bridges these traditional silos. This section details the critical use cases for DTs, demonstrating how they bring value and improve operations. Indeed, there are several types of DT, each suited to specific use cases. Some may require 3D capabilities, while others do not. Some may demand real-time operation, while others do not. There are also different types and levels of DT with varying levels of maturity. Throughout this section we also provide more concrete example case studies, detailing deployed DTs with real-world impact.

Understanding the Data Center Lifecycle

The data center lifecycle spans from initial planning through to eventual decommissioning, encompassing design, construction, operation, and ongoing evaluation; key stages are detailed in Table 1. It's a dynamic, iterative process that demands continuous optimization to align with shifting business goals and technological innovations. The average lifespan of a data center, including its core infrastructure, is generally 10 to 20 years. However, individual components within a data center, like IT equipment, will have shorter lifespans and require more frequent upgrades. DTs serve as a crucial, continuous thread through this lifecycle, providing a virtual replica for design optimization, deployment simulation and operational monitoring to ensure continuous performance improvement.

Digital Twins and the Data Center Lifecycle: A Smarter Way to Build and Operate

A DT is a virtual replica of a data center (DC), either planned or currently in operation, which validates that the DC is designed as specified and that simulates how the facility will perform throughout its lifecycle. These models offer powerful capabilities for optimizing design, predicting system behavior, and identifying risks before a single server is installed.

Stage	Purpose
Planning	Define the data center's purpose, capacity, and location. This stage includes risk analysis, cost forecasting, and identifying opportunities for scalability and efficiency.
Design	Translate business and capacity requirements into detailed architectural, engineering, and operational plans specifying power, cooling, IT infrastructure, security, and scalability requirements, resulting in site-specific schematics, drawings, and specifications for construction and future operations.
Build	Construct the facility and install all critical systems. Integration and commissioning ensure the data center is fully operational and aligned with design specifications.
Operate	Run and maintain the data center to support business activities. This includes performance monitoring, maintenance, energy management, and incident response.
Assess	Evaluate performance metrics, identify inefficiencies, and plan upgrades. This phase ensures the data center remains reliable, efficient, and ready for future demands.

Table 1: Key Stages in Data Center Lifecycle

While still maturing in the DC industry, DT technology is already transforming how organizations approach data center planning, design, construction, and operation, helping deliver more efficient, scalable, and sustainable outcomes from day one.

Design phase: Design right first time

The purpose of the data center design phase is to ensure optimal performance, reliability, energy efficiency, and scalability by creating an infrastructure that meets current and future operational needs while minimizing costs and environmental impact. Some of the capabilities of DTs include: Definition, optimization & validation of Data center / AI factory architectures, when changes for improvement are low-cost.

Using a DTP during the data center design phase enables owners and design teams to evaluate proposed designs to select the best alternative based on criteria (e.g. performance, cost, speed of deployment). Model-based system engineering (MBSE) enables model-based design of a robust and coherent architecture. This involves decomposing the system into subsystems, their interaction, and their progressive integration. Simulations of mechanical systems and thermal effects related to anticipated IT deployment help detect hot spots and pressure imbalances caused by airflow or liquid coolant distribution. It also reveals uneven cooling plant loading due to placement and sizing, allowing optimization of rack placement and IT distribution for better use of cooling resources. The DT captures system performance across deployment stages and future scenarios to understand the impact of uneven load throughout the data hall.

Critical systems must operate continuously, even during failures. Detailed DTs support transient analysis of IT heat dissipation and cooling behavior, extending insights into failure modes. Power network modeling helps stress test distribution and fail-over scenarios to ensure resilience.

Adapting designs based on these findings optimizes resource use, thermal conditions, and operational resilience. Understanding cooling and electrical plant capabilities in various scenarios enables right-sizing, avoiding over-provisioning and high capital costs, while also managing operating expenses. Detailed power use

Case Study: Digital Twin accelerates Construction Process

Challenge	With growing demand for data centers, a global hyperscale company was planning to improve time to build data centers. The company decided to move away from traditional approach to follow Engineering, Procurement, Construction process to modular product centric approach. Product design improvement alone was not sufficient to gain desired efficiency.
Digital Twin	This hyperscale used the digital twins of their data center to define the model-based process, including the resources required for construction. This model was then used for simulating the installation process (construction activities). Digital models representing work packages for installation including sequence of operations, bill of material, resource requirement, documents were prepared. Process documentation was prepared with 3D Model Based Work Instructions which are leveraged by construction sites.
Outcome	Modeling and Simulation of pre-fabricated modules integration and installation process helped optimizing the process, resource utilization as well as reducing risk of safety issues. Capitalization of knowledge and knowhow helped to standardize process across projects and improve on-site construction activities efficiency.

Case Study 1: DT accelerates construction process data lets designers evaluate energy efficiency of hardware arrangements and control strategies to minimize costs and carbon emissions.

When evaluating system efficiency financially or resource-wise, considering model boundaries is vital. Analyzing sub-systems provides valuable insight but can miss effects on the wider system. A full-system DT, including interfaces with the environment and power supplies, is necessary for fully integrated performance understanding.

Here are some examples of use cases:

- Estimate the PUE and WUE during the phase of selecting the most suitable technologies, taking into account the requirements
- A physical 3D model of the complete data center architecture that allows, for example, defining a nomenclature of cables and their respective lengths, with appropriate fiber type, connector types, multi-fiber connectors' polarity and port mapping, and all necessary specifications for structured cabling.
- Simulations of cooling, power, network and IT systems before implementation
- Generation of work instructions for installation

Sustainability Assessment and Future-Proofing

DTs also aid in creating greener, more sustainable data centers. The simulation-based optimization strategies naturally lead to more sustainable practices in data center management. These can be at the design phase where DTP simulations can help with:

- Building orientation for solar exposure
- Envelope design for passive cooling
- Integration of water harvesting and renewable energy sources

Combined with **BIM and building performance simulations (BPS)**, these tools can project total energy consumption and environmental impact before construction even begins.

Under operation, DTs enable flexible load shifting at two levels: within a facility, matching cooling and power consumption to real-time conditions such as external temperature or on-site renewable generation; and across facilities, shifting compute workloads between regional data centers to follow the availability of renewable energy on the grid. This proactive management, informed by the DT insight and simulations, helps ensure continuous decarbonization efforts and can future-proof against evolving environmental regulations and conditions.

Life Cycle Assessment (LCA)

LCA is a powerful and essential sustainability tool that evaluates the environmental impacts of the selection of material and building processes across its entire life cycle. Using this method during the design phase allows the right materials and processes to be chosen when modifications are still possible and least expensive, enabling a meaningful reduction in the carbon footprint of a data center before construction begins. DTs significantly enhance the LCA process by providing a dynamic, simulation-based environment in which material selections and design decisions can be evaluated against their environmental impact. Where traditional LCA is often a static, point in time analysis, a Digital Twin Prototype (DTP) allows designers to run multiple scenarios, and assess the trade-offs of each; transforming LCA from auditing tool into a design tool.

As the data center moves into operation, the DT can continue to support LCA by maintaining accurate and up to date records of physical assets, through hardware refresh cycles, infrastructure upgrades and energy source changes. Enabling assessment of the continuing impacts on the environment rather than relying on a one-off assessment. In turn this supports continuous decarbonization requirements from investors and regulatory frameworks like the GHG protocol and EU Taxonomy for Sustainable Activities.

Recovery and Risk Mitigation

From power outages to cyberattacks, a DT allows you to simulate and stress-test various failure scenarios.

- Identifies vulnerabilities before they impact operations
- Strengthens disaster recovery strategies

Case Study: Physics-Aware AIDC Equipment Selection

Research team in Nanyang Technological University (NTU) created a GenAI and PhyAI dual-agent collaboration framework where GenAI interprets natural language prompts to generate tokenized AIDC digital twins. PUE was optimized to 1.25 from 1.35.

Challenge	The goal is to select proper equipment that meets user-defined objectives at the AIDC design stage. The purpose is to demonstrate the effectiveness of introducing GenAI and physical simulation for equipment selection. The selection criteria should incorporate several key factors, including computing performance, energy efficiency, and adherence to facility layout standards. The generated design should include the optimal combination of facilities and their spatial relationships.
Digital Twin	Users will input prompts such as: "I would like to design an AIDC in a tropical region with a computing performance of 50-petaFLOPS and energy-efficient design. Please assist in selecting appropriate facilities and generating a data hall layout to achieve this goal." In response, the GenAI will produce semantic configurations that define facility relationships and properties for physical simulation.
Outcome	Started with an initial set of randomly sampled candidates and 5 iterations, the top five candidates are feedback to the LLM. By introducing the LLM, the design is initialized with better performance, and the PUE is optimized to 1.25.

Case Study 2: Physics-aware AIDC equipment selection

- Enhances overall resilience through proactive scenario modeling

Construction: Building with Confidence

DTs help construction teams by modeling and anticipating construction phases, thus identifying all potential inefficiencies before the concrete is poured. This approach also makes it possible to take into account the necessary resources, whether human or material. This helps, for example, ensure that the right equipment (e.g., crane) is available at the right time.

Thus, if a delivery delay occurs, modeling and simulating assembly sequences makes it possible to find alternatives to avoid stalling the construction site.

Commissioning: Detect defects before the physical commissioning

Since DTs are not just a 3D representation, but also include functional behavior. Using this functionality allows us to anticipate, through simulations, certain tests that are to be carried out during physical commissioning, and thus avoid the late discovery of malfunctions or design errors that can delay the data center's commissioning.

Operational Optimization: From Monitoring to Automation

Once operational, a data center can integrate its DT with **DCIM** (Data Center Infrastructure Management) systems to monitor live data in real time. This combination allows operators to:

- Visualize airflow and cooling demands
- Simulate the impact of hardware changes before implementation
- Run “what-if” scenarios to prevent failures and downtime

Over time, machine learning can refine these models based on historical performance data, helping systems self-adjust for optimal cooling and energy usage.

Automation and AI-Driven Optimization

DTs enable the foundation for implementing advanced automation and AI-driven optimization strategies in data centers.

By integrating machine learning algorithms with real-time data collection and simulation capabilities, the system can move beyond simple pre-programmed actions to achieve true predictive and adaptive control. These could include:

- **Predictive Maintenance**: By analyzing performance trends captured in the DT, it can predict equipment failures before they occur and automatically generate work orders or adapt by triggering system shifts to standby components.

- **Automated Resource Scaling**: By using the DT to simulate the impact of future IT loads and automatically scale resources like cooling and power before the load hits, preventing any performance degradation or thermal issues.
- **Self-Correction and Healing**: A DT could detect anomalies (like a hot spot forming) and automatically test and trial corrective actions within the virtual DT first before applying the most optimal, validated solution to the physical systems, ensuring minimal disruption.
- **Continuous Optimization**: By continuously running scenarios within the DT small optimizations can be found that might otherwise be overlooked, enabling current infrastructure and hardware to be used more effectively. Collectively these can lead to significant, sustained improvements in key metrics like PUE and energy efficiency.
- **Reduced Scaling Cost**: By simulating projected workload growth and its impact on infrastructure systems (power, cooling, space), the DT can generate accurate Bills of Materials (BOMs) for scaling, avoiding costly over-procurement.

Real-Time Monitoring and Operational Visibility

DTs provide a unified, 360-degree view that seamlessly integrates data across all critical layers: individual servers , power distribution networks, cooling infrastructure, and surrounding environmental factors. This comprehensive integration enables operators to have much greater insight and control, and transform reactive management into proactive optimization.

With this holistic operational visibility, operators gain the ability to:

- **Quickly detect anomalies:** Beyond simple alerts, the DT can use real-time sensor data and machine learning to pinpoint the location of anomalies and analyze the root cause.
- **Simulate operational scenarios to identify the most efficient configuration:** Operators can use the DT to stress-test changes to the real-world system virtually. Before making any physical adjustments, they can simulate the operational impact to identify optimally efficient configurations.

- **Automate system adjustments for optimal energy and resource use:** Using the DT's simulation models, systems can be programmed for self-correction. The DT can automatically execute closed-loop control to adjust infrastructure for continual optimization of energy and resource utilization.
- **Eliminate inefficiencies and reduce operational bottlenecks:** Visualizing metrics against historical baselines and expected performance, exposes hidden bottlenecks like mismatched power provisioning, isolated capacity or underutilized cooling. This enables data-driven decision making.

Predictive Maintenance and Downtime Prevention

By leveraging machine learning, a DT can transform maintenance strategies by anticipating equipment issues before failures occur. This moves beyond rigid, time-based schedules; maintenance is instead scheduled based on actual usage and current equipment conditions. This predictive maintenance approach allows operators to anticipate equipment issues and intervene precisely before failures occur. As a result, the risk of unscheduled downtime is significantly reduced, and the smarter upkeep ensures that the operational life of expensive data center equipment is maximized, extending its lifespan.

Regulatory Compliance and Security

DTs offer a powerful mechanism for maintaining continuous regulatory compliance and strengthening the overall security procedures of the data center. By providing a comprehensive suitable record of the infrastructure, any changes, and its performance, the DT ensures adherence to the industry and government standards:

- **ISO 27001 (Information Security Management):** By mapping physical security controls, access points and logging procedures to the DT, operators can continuously prove the effectiveness of their information Security Management System.
- **General Data Protection Regulation (GDPR):** While primarily an IT function, the DT can help ensure compliance regarding data sovereignty and physical location by accurately tracking and visualizing where data is stored and processed with the physical infrastructure.

Case Study: Digital Twin enables circular hardware refresh

A fintech company used a digital twin powered by Interact to simulate infrastructure upgrades resulting in a 2.5x efficiency gain and approximately £1.68M in savings.

Challenge	With CPU performance gains slowing, the company's conventional 3 to 5 year server refresh cycle no longer delivered meaningful efficiency improvements. This posed a significant challenge for their transaction-heavy workloads, which rely heavily on sustained CPU performance. A full migration to the public cloud was infeasible due to regulatory requirements and cost constraints; the company adopted a hybrid model built on a private cloud.
Digital Twin	A digital twin was developed to simulate the company's production workload on alternative server configurations. This enabled accurate forecasting of application performance and power usage; reducing both financial and operational risk. Internal testing validated the model's accuracy. The analysis produced two options: a new, energy-optimised configuration, and a refurbished, cost-optimised one.
Outcome	The company selected the cost-optimised refurbished option. It delivered 3.5x CPU performance and 4x RAM capacity for the same cost. The digital twin-led decision saved approximately £1.68 million compared to a cloud-only approach, it also avoided 27 Tonnes of CO_2e scope 3 emissions and resulted in an IT estate that was 2.5x more efficient per server.

Case Study 3: DT enables circular hardware refresh

- **Uptime Institute Tier Guidelines:** The DT can help verify resilience objectives (Tier III, Tier IV) by simulating failure modes, failover sequences and maintenance actions to confirm that the infrastructure maintains the required level of redundancy and availability.

It can also enhance cybersecurity by extending its modeling and simulation capabilities to potential security threats and identifying vulnerabilities in advance. By modeling the impact of a breach or attack on the IT or Operational Technology systems, or simulating a sudden system shutdown or denial-of-service attack; the DT can help test response procedures and identify vulnerabilities in a safe, virtual environment.

Looking Ahead: The Path to Lights-Out Data Centers

As the industry shifts toward **remote and autonomous operations**, DTs will be essential for enabling **"lights-out"** data centers—those requiring minimal on-site human presence.

With real-time visibility, predictive modeling, and automation, DTs reduce operational risk, streamline maintenance, and support long-term sustainability goals.

DTs are redefining how data centers are designed, built, and run. By combining real-world physics with real-time data and simulation, they give organizations the tools to future-proof their infrastructure while optimizing efficiency and sustainability at every stage of the lifecycle.

In today's fast-paced, data-intensive landscape, data-driven decision-making has become mission-critical—not just a competitive advantage, but a necessity. For enterprise organizations and colocation providers alike, improving efficiency, resilience, and scalability hinges on the ability to turn data into action.

Maximize ROI with a Digital Twin

From reducing energy consumption and maintenance costs to avoiding expensive downtime, the benefits of DT technology are measurable and significant. In short, a DT isn't just a model—it's a strategy for building smarter, more sustainable, and more resilient data centers. The result? Lower operating costs, reduced manual intervention, and improved uptime.

3. Technical Challenges and Barriers to Adoption

The development and continued adoption of DTs in data centers, faces significant technical challenges and barriers to adoption that extend across multiple domains. Successfully resolving these issues is crucial for realizing the potential of DTs to improve data center performance, efficiency and sustainability. This section explores the primary limitations and barriers, beginning with a lack of conceptual frameworks and semantic standards necessary for unified implementations. We then examine the inherent difficulties in implementing comprehensive and accurate simulations and the essential requirements for robust data management and validation. Finally, we address critical non-technical factors, including organizational and operational challenges, as well as the risks related to security and scalability. It is important to note that the challenges detailed here are not exhaustive, but represent the most prevalent obstacles currently facing the industry. Addressing these multi-faceted issues through industry collaboration, standardization and focused innovation, will enable the rapid transformation purported by DTs.

Conceptual and Semantic Challenges

One of the main challenges to the further adoption of DTs in data centers is the lack of shared conceptual frameworks and semantic standards. The term DT itself can have varied interpretations across disciplines and industries which in turn can lead to inconsistent implementations and expectations. Data center DTs lack widely accepted machine-readable ontologies and interfaces that can uniformly describe the physical assets, telemetry streams, operational states and behaviors of systems in a data center. Without this common language, implementation and integration remains a significant challenge.

There are several standards or industry standards that could be utilized or built upon, these are detailed in table 2. Each caters to specific modeling or communication needs

SysML is used for defining system requirements, modeling system structure (components and relationships), modeling behaviors (activities, state changes, interactions). This standardized modeling language enables :

- Helps manage system complexity
- Enables consistency across engineering disciplines
- Supports traceability from requirements → design → verification

- Improves communication among teams
- Reduces risk of design errors

USD focuses on 3D scene composition representing the spatial layout of a system or place while FMI focuses on simulation and model exchange enabling co-simulation across multiple domains and simulation environments. While some of these standards are relatively mature, no single standard has yet emerged as the definitive framework for DTs especially in data centers, resulting in fragmented toolchains and interoperability challenges.

Closely tied to USD is the notion of "SimReady" assets. These are generally phy sical components that are provisioned with metadata, interfaces, and telemetry schemas necessary for modeling and control of their behavior. In practice, many data center assets lack this preparedness, requiring manual effort to instrument and model them before they can be meaningfully incorporated into a DT. Establishing industry-wide conventions for SimReady components would greatly streamline DT deployment and reduce integration errors.

Furthermore, the data center ecosystem encompasses a wide variety of stakeholders including facilities managers, IT operations, sustainability officers, and hardware vendors. Each group brings unique perspectives, priorities, and data requirements, which complicates the creation of unified models, workflows and DTs. Addressing these diverse stakeholder needs within a consistent conceptual framework is essential to ensure a DT's relevance and usability across organizational silos.

Standard / Industry standard	Primary Focus	Scope/Domain	Relevance
SysML	Design and describe behavior of complex systems OMG standard	Systems engineering	Helps manage system complexity. Enables consistency across engineering disciplines. Supports traceability from requirements → design → verification. Improves communication among teams Reduces risk of design errors.
STEP (ISO 10303)	Standard for the Exchange of Product model data ISO International standard	Engineering / CAD / PLM	It's a Neutral, Vendor-Independent Format Supports More Than Just Geometry. Industry Standard Across Sectors.
Universal Scene Description (USD)	3D scene composition and visualization	Graphics, Simulation, VR/AR	Enables detailed spatial modeling of assets and environments, and can encapsulate multiple layers of information. Useful for visualizing layouts.
Functional Mock-up Interface (FMI)	Model exchange and co-simulation Modelica Association	Multi-domain simulation	Facilitates integration of heterogeneous simulation models for co-simulation workflows.
Thing Description (TD)	Semantic description of IoT devices	IoT and sensor networks	Provides standardized metadata and interfaces for IoT devices, aids interoperability and device discovery.
Digital Twin Definition Language (DTDL)	Semantic modeling of DTs	DT modeling, IoT	Defines formal models of DTs including components, telemetry, and commands; supports integration and control of complex systems.

Table 2: A selection of relevant Standards and Interfaces for DTs

Simulation Specific Challenges

Implementing an effective and comprehensive monolithic simulation DT of a data center is infeasible. Simulation engines and tools are often specialized to model specific domains or processes. Co-simulation allows simulators from different domains to be combined, passing information between themselves during simulation. Multiple simulations, each responsible for modeling distinct domains with their own boundary conditions, work in concert together to model the whole system controlled by an overarching orchestration system. The primary benefit of this approach is that it allows the coupling of existing models and simulation engines to generate more realistic and dynamic results by breaking down the boundary condition barriers of individual simulations. However, coordination and communication between each of the simulations is crucial, typically the simulation will advance and then have an integration step where data is exchanged. Common challenges include:

- **synchronization**: Ensuring different simulators advance their time steps in a coordinated manner especially when they operate at different speeds and model different granularities.
- **Causality**: When models provide feedback to each other, preventing logical inconsistencies is crucial. Algorithmic feedback loops can exist within the orchestrated co-simulation and these can span across multiple models and can lead to unstable or divergent simulation behavior. Additionally, ensuring correct causality during integration steps can be difficult if the time period of the phenomenon being modeled is smaller than the timestep.
- **Continuous and discrete simulations**: Data centers inherently combine both continuous simulations and discrete simulations. Continuous simulations are those whose states change continuously over time (e.g. power flow, thermal dynamics, airflow). Discrete simulations model events where states change at specific points in time (e.g. workload deployed, hardware power ON/OFF). Combining these two requires careful synchronization.
- **Timestep Management**: Determining optimal timestep for continuous simulations is crucial. Too small results in increased computation, while too large can compromise accuracy.
- **Rollback:** Many discrete simulations are optimistic and proceed ahead until they encounter events. If events arrive out of order, then a rollback mechanism is required to correct for any causality violations. These can propagate through a system and be both computationally and memory expensive.

Data Management and Validation

The quality of the insights and utility of a DT are fundamentally linked to the quality, integrity and management of the data it consumes and produces. The level of detail for a DT is a critical challenge. When the goal is to model everything with the DT, then there is a significant risk of scope creep leading to higher complexity and unwieldy systems that are often more expensive and fail to deliver the promised results. Conversely, having too little detail in the DT results in less insights and again the risk of failing to deliver.

The value of a DT depends on its accuracy and ability to reflect the real-world assets it is twining. In all DTs the need to keep pace with changes in the physical asset through synchronization is key. But the cadence of the synchronization depends on the timeliness of the system. Often there is a push for real-time DTs, but if the synchronization mechanisms aren't capable of millisecond updates or if changes to the system are rare this can be unnecessary. As long as the DT is capable of synchronizing at the pace the business needs, then that is sufficient. Additionally, an often overlooked aspect of simulation DTs is validation. The predictive accuracy of the simulation is almost as important as the real-world data. Therefore, validating the accuracy of the simulation is crucial to ensure it recreates similar results to those being measured in the physical data center. This requires a robust calibration of sensors and a comprehensive integration check during the initial phases of use of the DT.

Organizational and Operational Challenges

Integration of a DT into a data center involves much more than just the technical deployment; it can fundamentally impact organizational structures, operational processes and potentially requires a shift in thinking. One critical barrier is stakeholder alignment and siloed organizations. Data centers involve diverse teams, each with unique requirements and priorities, which complicates the creation of a unified DT that serves everyone. Overcoming these organizational differences and establishing common goals and workflows is essential for a DT's cross-functional utility. Furthermore, there may be a significant challenge in a talent and expertise gap, as deploying and maintaining a high-fidelity DT requires specialized, interdisciplinary skills. Beyond human capital, another barrier is the justification of cost and return on investment (ROI), as substantial investment in a DT platform must be clearly linked to measurable, long-term operational value. Another potential concern is the integration of legacy systems. Many existing data centers rely on older, often disparate and proprietary systems for monitoring and control, most notably Data Center Infrastructure Management

(DCIM) and Building Management Systems (BMS). Integrating DT platforms with these legacy systems is complex, potentially requiring custom interfaces and middleware for data flow. Beyond a technical challenge, these changes challenge the *single source of truth* traditionally provided by these systems, forcing teams to decide whether these legacy systems act as primary data sources or are superseded by a DT. This can also lead to process change and therefore cultural resistance to the new operational procedures and tools necessitated by DTs.

Security

Given the level of connectivity required for a datacenter DT, it can significantly expand the cyber-physical attack surface and introduce new and complex security risks. The DT is an aggregation point for massive amounts of sensitive, frequent data from facility and IT systems, creating a highly valuable, centralized target for adversaries. A core concern is data integrity and manipulation, an altered or falsified feed of telemetry data would easily lead to incorrect predictions and erroneous, potentially damaging control decisions in the physical counterpart. This risk is amplified in systems with bi-directional communication where a DT can issue commands to physical control systems; if compromised, the DT provides a vector for an attacker to directly damage systems. Established standards such as IEC 62443 and NIST SP 800-82 provide frameworks to govern cyber-physical security in industrial control system environments. Any organization deploying DTs with control system integration should apply these from the outset.

Scalability

The growth of data centers present significant scalability challenges for DT implementation; primary through computational intensity. Data center DTs that incorporate high-fidelity physical simulation, e.g. Computational Fluid Dynamics (CFD) for airflow, are inherently compute-intensive. As the size and granularity of the model increases, so does the computational workload; especially when models are running for real-time or faster-than-real-time scenario testing. Increasing the demand for massive parallel processing resources that are already stretched in data centers under artificial intelligence workloads. This is closely related to data volume and velocity challenges too.

4. Paths to Adopting Digital Twins

Navigating the transition to fully integrated DT can be a complex and daunting task. While the promise of increased efficiency, enhanced reliability and reduced operational costs is compelling, the path from manual operations to autonomous systems is not always clear. To provide a clear roadmap and practical guidance, this section outlines a phased approach to DT adoption.

We define a five-level hierarchy of DT maturity, inspired by other models in this field (Yong-Woon 2020), we include a baseline level 0 to represent no DT and capability levels range from basic monitoring systems to fully autonomous control. This framework serves as a benchmark for evaluating an organization's or tool's current capabilities and provides a roadmap for future development. We then provide some concrete examples across key data center sub-systems to illustrate how these maturity levels apply in both operational and design contexts. Finally, we explore key enabling features and advanced capabilities that can accelerate adoption and enhance a DT's value proposition. By providing a clear, actionable guide, we aim to empower data center operators to strategically invest in this technology and realize its full benefits.

Initial strategic considerations

The pursuit of a DT for a data center must be grounded in the clear understanding that it is a solution, not a goal in itself. The fundamental strategic consideration is to first, identify significant pain points and overarching business goals they inhibit. This could be excessive energy, consumption, frequent unplanned downtime, lost capacity or high operational expenditure. This clarity is essential for aligning any DT investment with measurable returns. The next critical step involves identifying key stakeholders, including facilities, IT, finance and engineering teams to establish a consensus on the difference between the current state and desired state. This analysis can help to identify and prioritize high-value use cases, offering the greatest immediate impact.

The viability of the entire initiative relies on technical and organizational readiness. The feasibility of any DT implementation hinges on data availability and existing infrastructure. Without timely, accurate data from other systems like a Building Management System (BMS), DCIM or IT hardware, a DT is inert. Therefore, careful planning is needed around data availability and handling gaps as well as the infrastructure required to run the simulation models. Finally, an often overlooked factor is organizational enthusiasm; given the cross silo nature of

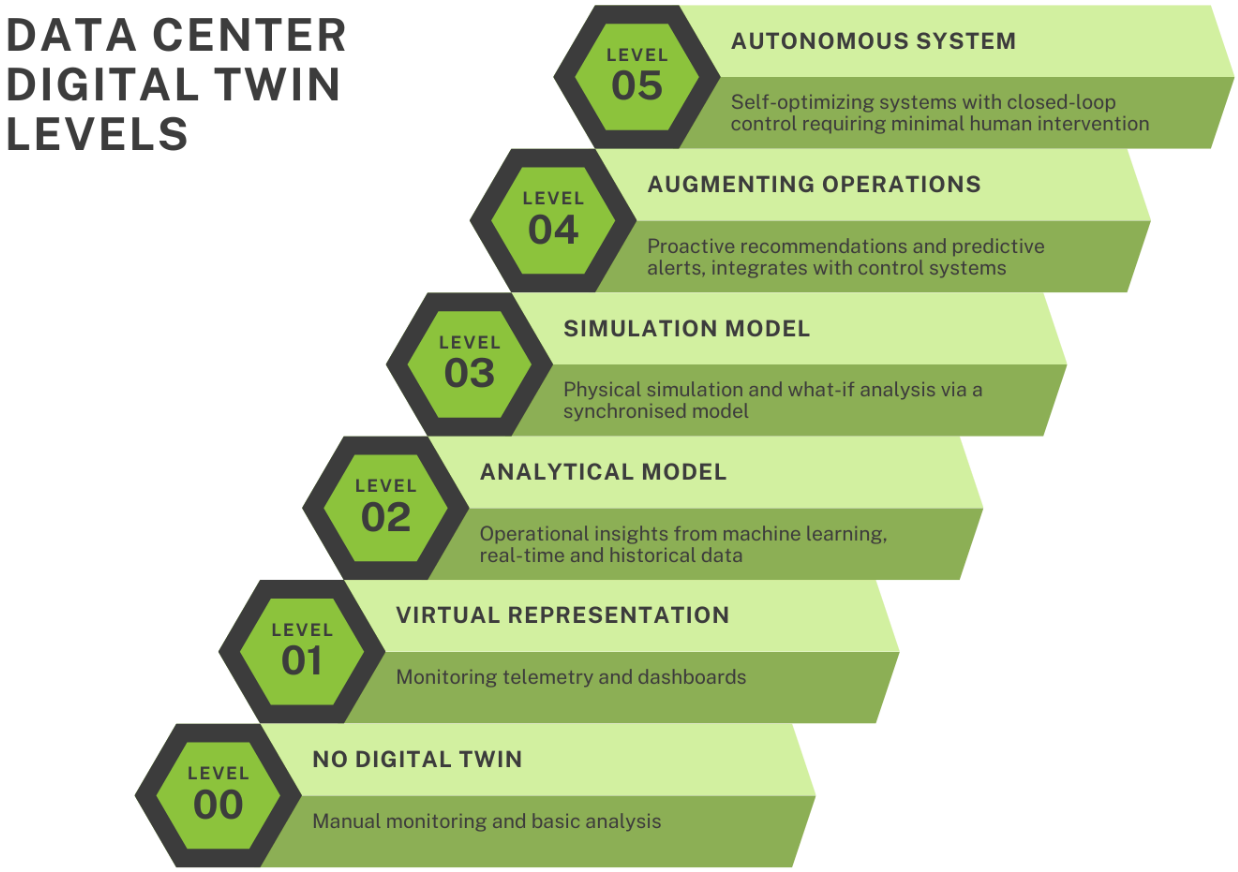

Figure 1: Data Center DT Maturity Levels

DTs, broad support and training are necessary to realize the full potential of a DT and avoid it becoming a niche, underutilized tool.

Digital Twin Maturity

The maturity and capabilities of a DT can vary greatly across implementations, suppliers and data centers. While some may rely on basic monitoring tools, others harness predictive analysis and simulation for operational insights.

To navigate this competitive landscape and provide a guide to data center operators in the transition towards DT automation we propose a five-level hierarchy that categorizes DT maturity based on their capabilities. The five-levels we have defined range from legacy manual operations without any DT capability (level 0) through to an optimistic future of autonomous, self optimizing systems (level 5). Each level represents a significant leap in DT functionality and additional value over previous levels to the data center operator.

By defining this five-level hierarchy, we aim to not only describe the evolution of DTs but also offer practical guidance for data center operators. Our intention in creating this hierarchy is to provide:

- Benchmarking/Stratification: Help organizations evaluate their current level of DT adoption and the capabilities of existing tools
- A Development Roadmap: Offer a clear path for progressing toward fully autonomous operations.
- Industry standardization: Establish a common language for DT development and deployment.

Maturity level examples

To provide some practical guidance, we've given examples of different maturity levels, broken down by data center sub-systems. This allows operators to see the level hierarchy applies to their day-to-day operations and identify opportunities for improvement in each area. Table 3 outlines how these levels would manifest in a few key data center sub-systems.

Maturity Level	Level 1	Level 2	Level 3	Level 4	Level 5
Cooling System	Dashboards displaying temperature and airflow data.	Real-time analysis of cooling usage to aid in identifying inefficiencies.	Simulating the thermal and airflow impact of new or replacement hardware deployments, hot-spot prediction.	DT advises raising cooling set-point so save energy based on weather and real-time loads.	The system autonomously adjusts cooling output and fans to maintain optimal temperature and minimize energy overall.
Power Distribution	A schematic shows the current status of the power network.	Machine learning models predict power consumption based on historical usage.	DT simulates the impact of UPS failure or additional load.	Proactive alerts based on probabilities of circuit overload, suggests load shifting strategies.	The system asynchronously reroutes power and balances load to prevent failure.
Asset Management	2D/3D model shows physical location or all assets in racks.	Analyzes asset utilization over time to identify idle equipment.	Simulates the impact of new server equipment on power and thermal loads and job performance.	Provides predictive alerts for hardware failure and proactively recommends hardware replacements when more efficient models become cost-effective.	Autonomously migrates and rebalances workloads for optimal performance.

Table 3: Maturity level examples by sub-system

Enabler and Advanced Capabilities

While the 5 levels provide a clear progression path for a single system, certain enabling features in a DT can significantly increase the value proposition of a tool or product. These are often independent of a specific maturity level and not necessarily part of a linear progression but rather a cross-cutting capability that can be integrated at various stages to enhance a DT's functionality and value.

Co-simulation and Model Interchange

One of the most powerful of these cross-cutting enablers is co-simulation (discussed in section 3), which involves orchestrating multiple specialized models together to get a holistic view of a system. For example, a thermal model of a data center room could be co-simulated with an electrical model of the power distribution network and loads. This allows the operators to analyze the interdependencies between sub-systems. For example, understanding how both power and cooling loads interplay as workload demand increases in our data center room example could lead to identifying stranded capacity or hot-spots.

The ability to easily exchange these models, often through standard formats like Functional Mock-up Interface (FMI) or Universal Scene Description (USD), is critical for achieving this level of interoperability and integrating models from different vendors or development teams. While this capability might be a requirement for some truly autonomous level 5 DTs, it is not strictly tied to any single maturity level. Even a level 2 DT performing inference-based machine learning could significantly benefit from contextual data provided by a co-simulation or historical telemetry, unlocking greater value than its based capabilities would otherwise allow.

Data Integration and Interoperability

DTs rely on data, and their benefits are directly tied to the ability to integrate data from diverse sources. The insights derived from a DT are only as good as the data feeding it. Much like co-simulation and model interchange, the ability for a DT to ingest data from multiple sources for better context, and do so using standard data representations, is a crucial enabler.

This extends beyond real-time sensor telemetry to include maintenance records, work orders, building management systems (BMS) and IT asset management (ITAM) systems. Robust data integration is a prerequisite for advancing DT maturity, especially since autonomous systems (level 5) would require access to control systems before being able to act. The ability for different systems to communicate seamlessly, providing interoperability, is a fundamental requirement for unlocking the most significant benefits from DTs.

3D visualization

High-fidelity 3D visualization is another key enabler. While DTs are defined by their internal virtual representations, mimicking real-world systems and objects in data models. Providing a more advanced visualization that is data-rich and interactive can transform how a DT is used. Basic charts and graphs might be able to show a prediction or identify a problem, but a 3D visualization could show the exact physical location or a problem, allowing technicians to easily find and address it. This feature, while optional, provides increased situational awareness when examining the output from any DT, as well as aids in training and can facilitate better communication between teams.

5. Conclusions & Future Work

The emergence of the DT represents a fundamental, transformative shift in the operational paradigm for data centers. By establishing a clear framework and standardized definition, the Open Compute Project (OCP) aims to overcome existing market confusion and accelerate the adoption of this critical technology. The DT is defined as a behavioral l replica that continuously synchronizes with its physical counterpart via real-time data, enabling robust simulation and optimization.

Benefits and Opportunities

DTs offer measurable and significant value across the entire data center lifecycle.

- **Planning and Design:** They enable a smarter start by allowing engineers to optimize the overall data center architecture, performance, reliability, energy efficiency and scalability by creating an infrastructure that meets current and future operational needs while minimizing costs and environmental impact.
- **Operational Excellence:** In the operational phase, they provide unified visibility across all systems, facilitate predictive maintenance and drive autonomous optimization of cooling and workload distribution.
- **Sustainability and Resilience:** DTs are key enablers for creating greener data centers, supporting compliance, reducing energy consumption, and enhancing overall resilience.

Ultimately, this strategy delivers a strong Return on Investment (ROI) through lower operating costs, reduced manual intervention, and maximized uptime, setting the essential groundwork for future "lights-out" data centers.

Technical Challenges and Barriers

Despite the vast potential, the adoption of DTs is constrained by significant technical and organizational hurdles. These challenges include:

- **Standardization:** A crucial barrier is the lack of common conceptual frameworks and semantic standards necessary for unified implementation across diverse systems and vendors.
- **Simulation and Data:** Challenges exist in ensuring the accuracy and validation of physics-based simulations, managing the scalability of computation, and maintaining the integrity and timeliness of massive, sensitive data streams required for synchronization.

Future Work and Paths to Adoption

To successfully guide the industry forward, this white paper introduced a five-level DT maturity hierarchy. This framework provides a practical roadmap for operators to benchmark their current capabilities and plan a phased progression toward fully autonomous systems.

The next and most crucial steps for the OCP and the broader industry involve focusing on key enabling capabilities to overcome the present barriers:

- **Interoperability and Standardization:** Future work must address the standardization of model exchange and co-simulation formats to enable seamless integration of models from diverse vendors and development teams.
- **Alignment with OCP Ready™ Specification:** Continued effort is needed to align the DT capabilities with the OCP Ready Datacenter Specification to ensure a cohesive and open ecosystem.

By championing these standards and fostering continued collaboration, the OCP will empower operators to unlock the full potential of DT technology, continuing the growth in intelligent, adaptive datacenter design and operations.

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