

Impact of Digital Twin and AI Control on Cooling Efficiency and Setup Time in Data Centers

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Abstract - Highly energy-intensive facilities like data centers have accounted for their substantial proportion of total energy consumption by their cooling systems and project setup complexity. In conventional cooling design and control methods, dependency on static assumptions and rule-based operations have resulted in energy inefficiencies, extended setup and commissioning periods and limited adaptability to dynamic IT loads. As highlighted in recent studies, digital twin technology and AI-based control systems have addressed the above-mentioned challenges through predictive modeling, lifecycle integration, and adaptive optimization.

By integrating digital twin technology and AI-based cooling control, this paper explores how it impacts cooling efficiency and setup time in data centers. Data center lifecycle stages like planning, design, construction, commissioning and operations, involve many professionals through which responses have been collected for a quantitative survey, as a part of methodology adopted for this paper. In current industry practices, data continuity, predictive capability and lifecycle integration are some of the significant limitations that have been revealed through findings. Early-stage decision making can be enhanced, design rework can be reduced, virtual commissioning can be supported and operational readiness can be improved through digital twin enabled environments as indicated in survey results with strong industry consensus. Furthermore, the limitations of reactive control strategies have been addressed by AI-based cooling control systems which enabled predictive and adaptive optimization of cooling performance.

The paper concludes that in modern data centers, to reduce setup time, to improve cooling energy efficiency and to enhance operational reliability, the application of integrated digital twin and AI technologies provide a comprehensive lifecycle approach.

Keywords - Data Center, Digital Twin; Artificial Intelligence (AI); Reinforcement Learning (RL); Machine Learning (ML); Cooling Efficiency; Commissioning Time.

I. INTRODUCTION

In modern infrastructure, among the largest energy consumers are the Data centers, driven further by AI's immense workload due to their explosive growth. 30-40% of total power consumption can be accounted for by cooling alone (Uptime Institute, 2023; ASHRAE, 2025). Depending on static layouts and rule-based control, traditional data center cooling design often leads to longer commissioning time and inefficiency.

Significant potential has been shown for improvement in efficiency and adaptability through recent advances in digital

twin technology (virtual replicas of physical systems) and AI-based control methods. Engineers, before construction, test configurations and during operation, optimize cooling systems through digital twins which help in simulating thermal and airflow behaviour in real time. Based on continuous feedback with the help of AI algorithms, especially through reinforcement learning (RL) and physics-informed machine learning (PIML), HVAC and airflow systems can be dynamically controlled (Chi Zhou et al., 2024).

From the design stage to the operational stage of data center projects, the research aims to evaluate the combined effect of integration of digital twin and AI-based control on cooling energy savings and setup (commissioning) time reduction.

Due to the extensive expansion of AI workloads, cloud services and digital infrastructure, the demand for high performance data centers is growing rapidly. These facilities, from being among the largest energy consumers globally, are essential for computation and storage. Nearly 2% of total global electricity is used by global data centers which consume approximately 460 TWh of electricity annually as reported by International Energy Agency, 2024 and it is forecasted that if efficiency measures are not adopted, this demand will be projected to double by 2030 (International Energy Agency, 2024).

To maintain the optimal thermal environment for servers, a significant portion of this consumption (around 30-40%) is attributed to cooling systems (Uptime Institute, 2023; ASHRAE, 2025). Energy waste, uneven temperature distribution and extended setup times have become a by-product of traditional air-conditioning and rule-based HVAC systems. To create adaptive and data-driven infrastructure, researchers have proposed the integration of digital twin technology and AI-based control systems to solve the above issues.

Real-time sensor data is continuously updated through digital twin which provides a virtual replica of the data center. Even before the construction begins, Engineers use digital twins to simulate and test airflow, thermal zones and cooling performance which helps in drastically reducing post-build commissioning. Cooling energy consumption can be lessened by up to 12-15% with the help of a physics-informed digital twin which predicts thermal behavior with higher accuracy as per researchers (Shi et al., 2021).

Cooling parameters such as airflow, fan speed and chilled-water flow are dynamically adjusted by AI control algorithms, especially through reinforcement learning (RL). Energy Efficiency has been improved by 10-20% and thermal variation has been stabilized within $\pm 1^\circ\text{C}$ as per studies (Chi Zhou et al., 2024; Siemens AG, 2022). Also, studies have shown that traditional PID (Proportional-Integral-Derivative) controllers can be outperformed by AI-based systems. Similar studies have reported that data centers' commissioning time can be reduced by 15-25% by integrating design simulations and sensor layout optimization in the early phase of construction, extending the benefits in setup time as well (Lu et al., 2020; Khajavi et al., 2019).

The research explores how data centers can be created which are smarter, faster and more sustainable by combining digital twins and AI control with the inclination towards achieving global goals of carbon neutrality and intelligent infrastructure.

II. LITERATURE REVIEW

A. Overview of Data Center Energy Consumption

Due to their continuous operation and high-density IT infrastructure, Data centers are among the most energy-intensive facilities. A significant portion of this energy demand arises, to maintain safe operating temperatures by cooling systems. It has become difficult to manage thermal performance as computational workloads and rack densities have increased tremendously lately. It has indicated through studies that total data center energy consumption has been accounted for 30-50% for cooling systems (International Energy Agency, 2024).

In data centers, for evaluation of energy efficiency, Power Usage Effectiveness (PUE) is used. It was noted that earlier facilities had PUE values greater than 2.0 but lately, in modern data centers, they aim to achieve PUE values closer to 1.2 through improved design and operational practices (McKinsey & Company, 2024). However, it becomes difficult to maintain consistently low PUE due to dynamic IT loads and limitations of traditional cooling methods.

B. Conventional Cooling Design and Control Practices

Conventional cooling systems are typically designed based on assumptions which are static and control strategies which are rule-based, which also includes common configurations like hot and cold aisle layouts, raised floor air distribution, and fixed air temperature setpoints for CRAC and CRAH units (Uptime Institute, 2023). On the basis of estimation made during early design stages about peak loads, these systems are planned which rarely adapt dynamically during operations.

However, reliability ensured through these methods, several limitations still exist. It has been noted that excessive energy consumption has been a result of over-provisioning of cooling capacity, while inefficiencies in airflow and localized hotspots have been a result of uneven server workloads. Additionally, manual monitoring and static controls are conventional and therefore they lack cooling systems' ability to respond effectively to real-time environmental changes (Siemens AG, 2022).

C. Digital Twin Technology in the Built Environment

In various industries like manufacturing, infrastructure and smart buildings, digital twin technology has become an inevitable and powerful tool for modeling, simulation and performance optimization. A physical asset or system, when represented digitally and dynamically, which continuously gets upgraded using real-time data from various sensors and monitoring systems, is defined as Digital Twin (Khajavi et al., 2019).

Digital twin has the ability to make decisions with respect to the context of the built environment on the basis of data center lifecycle by integrating design models, operational data and simulation capabilities. Studies have shown that digital twin has allowed stakeholders to test scenarios virtually, even before implementing them in the physical environment, which has improved design accuracy, reduced rework and enhanced operational performance (Khajavi et al., 2019, Tao et al., 2019).

D. Application of Digital Twins in Data Centers

Lately, Digital twin technology's application for thermal analysis, capacity planning, energy optimization and fault detection in data centers, has gained huge attention as per findings by researchers. Simulation of airflow patterns, temperature distribution and cooling system performance under various operating conditions is done by Digital Twin by integrating computational fluid dynamics (CFD) models with real-time sensor data (Zhai & Chen, 2005; Shi et al., 2021).

It has been shown through literature that the application of digital twins can significantly reduce uncertainty during design and commissioning stage. Digital twin has allowed engineers to validate cooling layouts, identify potential hotspots and optimize equipment through virtual commissioning before physical construction. As a result, it allowed project setup time to reduce substantially and to lower commissioning risks. Additionally, it allowed continuous monitoring, predictive analysis during operations, supporting proactive maintenance and system optimization (Roberto Saracco, 2019; Tao et al., 2019).

E. Artificial Intelligence in Data Center Cooling

Unlike traditional rule-based controls, AI-driven approaches in data center operations lead to handling the complexity and dynamic nature of cooling systems by predicting system behaviour and optimizing control actions which happen from learning from historical and real-time data (Chi Zhou et al., 2024).

Machine learning (ML) techniques, when applied, can help in forecasting temperature variations, predicting cooling demand and detecting anomalies, which otherwise would have made the whole execution process difficult. When interacting with the environment, by optimal actions of reinforcement learning (RL), in particular, it has been promising and has shown to be optimizing cooling control strategies. It has been indicated by research that AI-based cooling control can significantly reduce energy consumption while also maintaining thermal safety limits (Evans & Gao, 2016; Siemens AG, 2022).

F. Integration of Digital Twin and AI Control

Recent literature emphasized that greater benefits can be achieved if digital twin and AI control are used together, than either technology used alone. While AI algorithms serve as adaptive decision-making engines, digital twins provide a high-fidelity simulation environment. This integration helps in reducing operational risks by allowing AI models to evaluate control strategies within the virtual environment (Lu et al., 2020).

Studies demonstrate that to enhance cooling efficiency, to improve system stability and to support autonomous operation, this closed-loop feedback system will help. While AI-driven insights refine the digital twin's predictive accuracy, the digital twin continuously updates the AI model with real world data. Real-time optimization and long-term performance improvement can be enabled through this synergy (Evans & Gao, 2016; McKinsey & Company, 2024).

G. Impact on Setup and Commissioning Time

Several researchers have highlighted that the setup time and commissioning durations for data center projects can be reduced through the intervention of digital twins. Traditional commissioning processes are time-consuming and prone to error as they heavily rely on physical testing and iterative adjustments. Most issues can be identified and resolved during the design stage by means of virtual commissioning using digital twins (Lu et al., 2020).

The literature reports that depending on the project complexity, the commissioning time can be reduced by up to 30-40% by early-stage simulation and validation. Operational readiness can be accelerated by faster commissioning, additionally reducing project costs and improving return on investment (McKinsey & Company, 2024).

H. Case Studies

Modern data centers consume between 1-3% of global electricity, with cooling systems accounting for 35-45% of total facility energy demand (International Energy Agency, 2024; Uptime Institute, 2023). Typical power usage effectiveness (PUE) values range from 1.5 to 1.7 for enterprise facilities as traditional data center design and operation rely on static BIM models, isolated CFD simulations and rule-based cooling control (Uptime Institute, 2023; ASHRAE, 2021). Recent literature identifies that through continuous, data-driven optimization, critical advancement through digital twin and AI integration, it is capable of reducing design uncertainty, commissioning duration and operational energy consumption (Siemens AG, 2022).

1) *NVIDIA Israel-1 Supercomputer: Impact of Virtual-first Construction:* Using a high-fidelity digital twin, this project adopted a virtual-first construction methodology. To simulate the entire data center environment before physical construction, NVIDIA utilized Omniverse and NVIDIA Air platforms. To perform pre-construction validation and performance testing, the methodology integrated MEP systems, network topology, rack density, and airflow simulations within a unified digital environment. Early identification of design

conflicts and optimization of infrastructure layout has been enabled by digital twins. As a result, cooling oversized margins were reduced by 10-15%, and construction and commissioning schedules reduced by ~15-20% (McKinsey & Company, 2024).

2) *Foxconn Guadalajara Facility: Measured Energy Reduction via AI-trained Digital Twins:* Foxconn integrated CFD simulations, equipment layout modeling, and robotic operations by implementing a digital twin environment combining NVIDIA Omniverse with Siemens Xcelerator. Before real-world deployment, AI models were trained within the virtual environment, allowing optimization of airflow and cooling strategies prior to physical implementation. Only 5-10% energy efficiency improvements can be achieved typically by traditional optimization approaches. ~30% reduction in total facility energy consumption, and more than 20% reduction in localized thermal hotspots, are the operational performance data which revealed significant efficiency improvements. Post-deployment PUE values have been approaching 1.30, and results showed that airflow uniformity has been improved (Siemens AG, 2022).

3) *BMO and Siemens: AI-based Cooling Optimization with documented ROI:* To implement White Space Cooling Optimization (WSCO), an AI-driven system based on machine learning algorithms, the Bank of Montreal collaborated with Siemens. Continuous monitoring of heat loads and environmental conditions were involved in the methodology, which enabled predictive adjustments to cooling infrastructure in real time. Implementation of the AI-based optimization system resulted in 55% reduction in total energy consumption, and over 40% reduction in cooling energy usage. Results also showed that return on investment was achieved within 24 months. The findings have highlighted PUE improvements exceeding 0.20, compared to less than 0.05 improvements in traditional rule-based systems (Siemens AG, 2022).

4) *Compass Data Centers and Vertiv: Modular Deployment and Commissioning Efficiency:* To implement Vertiv SmartRun, an integrated system combined with AI-enabled cooling control and digital monitoring, Compass Data Centers partnered with Vertiv. To support scalable expansion, the methodology focused on prefabricated modular deployment with intelligent performance monitoring. Operational outcomes demonstrated improvements in deployment and scalability, 30-40% reduction in commissioning time which reduced from 20-24 weeks to 13-16 weeks. During modular expansion, results showed that PUE optimization sustained. It has been highlighted from the findings that redesign and recommissioning requirements during capacity upgrades have been reduced (Siemens AG, 2022).

I. Discussion of Findings

Across all literature case studies, digital twin and AI integration consistently delivers PUE reductions of 12-25%, cooling energy savings of 30-55%, commissioning time reductions of up to 40%. In comparison to traditional static design and rule-based operation, these improvements far exceed the incremental gains achieved. The literature clearly

indicates that digital twin and AI technologies enable a paradigm shift from reactive, over-provisioned data centers to predictive, adaptive and energy-optimized infrastructure (Siemens AG, 2022; McKinsey & Company, 2024; ASHRAE, 2021).

III. RESEARCH METHODOLOGY

J. Research Design and

In this research, a quantitative survey-based methodology has been adopted to evaluate cooling efficiency and setup time in data centers, to review the impact of digital twin and AI control. Primary data has been collected through a structured and technical questionnaire which was answered by professionals directly involved in various stages of data centers' lifecycle which includes planning, design, construction, commissioning and operations. From recognizing and analyzing the expectations from future digital twin and AI-driven solutions, the questionnaire aimed to identify and understand the limitations of current tools by capturing opinions and experiences from industry-wide practices.

On the basis of survey responses, across the data center's lifecycle, it was evaluated how decision-making, efficiency and project delivery can be influenced by digital technologies.

K. Respondent Profile and Industry Representation

Responses in the survey have been collected from professionals with various experience levels, roles and companies in the data center ecosystem. A mature and informed respondent base has been formed as a majority of respondents reported more than 6 years of experience in the construction and infrastructure sector. Roles represented in the survey included design engineers, MEP and HVAC engineers, project managers, operations and facility managers, consultants and digital solutions specialists.

Respondents were involved across multiple lifecycle stages in terms of project exposure like planning and design, construction and execution, commissioning, and operations and maintenance. Additionally, it was reflected through responses that their engagement was across medium (10-30MW), large (30-60MW), and hyperscale (>60MW) data centers, ensuring that the findings are applicable across different project scales.

L. Data Collection and Input Parameters

1) Setup Time Analysis Across Project Stages:

a) *Concept and Planning Stage:* Highlight Survey results indicate that during early-stage planning, spreadsheets, 2D CAD drawings and BIM-based conceptual models are the most commonly used. However, particularly scenario comparison, manual data updates and poor linkage with later design stages have been identified as significant limitations in these tools by more than 60% of the respondents. It has been expected that future tools will enable faster feasibility analysis, real-time cost and schedule estimation and early identification of construction risks, which emerged as a strong trend shown from the respondents' responses. This highlights a clear gap between current planning practices and the capabilities offered by digital twin-based planning environments (Roberto Saracco,

2019).

b) *Detailed Design Stage:* Revit/BIM platforms, Navisworks for clash detection and CFD software are widely used during the design phase. Despite this, by a significant portion of respondents in the survey, it has been revealed that the integration between architectural, structural and MEP models has been rated as moderate to low. Late-stage design changes, incomplete multidisciplinary coordination and limited ability to evaluate execution impact are the key challenges reported during the design freeze stage. The need for real-time multidisciplinary coordination and automated clash and risk detection has been expressed by more than 70% of the respondents, indicating strong industry demand for digital twin-enabled design environments that go beyond static BIM coordination (Tao et al., 2019).

2) *Construction and Execution Phase Findings:* A mixed digital maturity was observed by the respondents in the construction stage section. A substantial proportion of respondents still rely on paper-based drawings or hybrid workflows, despite the usage of tools like Primavera/MS Project and 4D BIM simulations. Responses clustered around low to moderate effectiveness when asked to rate the effectiveness of current tools in managing design changes during execution. Lack of real-time design updates, poor coordination between trades and manual progress tracking were identified as the most critical gaps impacting setup time. It has been indicated by over 65% of the respondents that along with the virtual testing of construction sequences, live synchronization between site activities and design models, would significantly improve construction-phase efficiency (Tao et al., 2019; Lu et al., 2020).

3) *Commissioning and Handover Challenges:* Survey findings show that static documents, spreadsheets and PDF-based O&M (Operation & Maintenance) manuals are predominantly used for commissioning data. Challenges due to incomplete or outdated handover information are frequently faced by facility teams and have rated these challenges in majority as moderate to high. Live system performance data, clear linkage between design intent and installed assets and improved usability for operations teams are strongly favoured by respondents for future handover systems. These results indicate that delays in operational readiness can be reduced by reinforcing the value of digital twins in enabling virtual commissioning and data-rich handover (Khajavi et al., 2019).

4) Cooling Efficiency: Current Practices vs Future Expectations:

a) *Design and Predictive Accuracy:* CFD (Computational Fluid Dynamics) tools, vendor proprietary software and experience-based assumptions are currently driving the cooling system design. However, a disconnect between design intent and operational reality has been indicated as confidence in these tools accurately predicting real operational performance was largely rated as moderate (Uptime Institute, 2023; International Energy Agency, 2024).

b) *Cooling Operations and Adaptability*: It was indicated through the survey that operational monitoring primarily relies on BMS (Building Management System) and DCIM (Data Center Infrastructure Management) platforms, yet many respondents rated adaptability to changes in IT load and rack density as low to moderate. Reactive control strategies, siloed design and operations data, and manual decision-making processes are included as key limitations. More than 70% of respondents identified a direct consequence of these limitations that is energy inefficiency (McKinsey & Company, 2024; Chi Zhou et al., 2024).

c) *Expectations from Digital Twin and AI Control*: Respondents expressed strong confidence in future cooling systems that provide continuous optimization using live data, predictive hotspot identification, virtual testing of cooling scenarios and automated control recommendations. A majority of respondents indicated that when particularly validated against digital twin simulations, they would trust AI-recommended cooling actions (Lu et al., 2020).

5) *Technology Adoption Drivers and Barriers*: Reduction in setup and commissioning time, improved cooling energy efficiency, lower lifecycle cost and reduced operational risk are some of the key drivers in influencing adoption of digital twin and AI platforms. However, the need for structured adoption of frameworks has been underscored as respondents identified barriers such as ROI uncertainty, skill requirements, system integration challenges and organizational resistance (International Energy Agency, 2024; Khajavi et al., 2019).

6) *Case Studies*: An organized literature review methodology has been employed for the paper, analyzing peer-reviewed journals, industry white papers and documented case studies related to digital twin and AI applications in Data Centers. Sources were accessed for empirical evidence, quantitative performance metrics, and relevance to cooling efficiency, commissioning time and operational optimization.

M. Discussion of Findings

The survey results clearly demonstrate that limitations in efficiency, predictability and integration are significantly faced by the current data center cooling systems and project delivery practices. The potential of digital twin and AI-based systems to improve cooling efficiency and reduce setup time across all project stages, has been strongly supported by quantitative trends from the questionnaire (Lu et al., 2020; Siemens AG, 2022).

IV. RESULTS AND DISCUSSIONS

N. Overview of Results Interpretation

In relation to the research objectives, the survey findings were interpreted and supported by evidence from previous studies. The project setup time and cooling performance has been examined and analyzed how it influences the existing practices in data center development. It also considers how the limitations of conventional approaches have been addressed by digital twin and AI-based control technologies. To evaluate the

relevance of observed survey trends, for improving modern data center projects, they were compared with theoretical concepts and empirical research (Tao et al., 2019; McKinsey & Company, 2024).

O. Analysis of Setup Time Across Data Center Project Phases

1) *Concept and Planning Phase*: Survey results show that in predicting realistic timelines and identifying potential risks, tools like spreadsheets, 2D CAD drawings and basic BIM models, which are still widely used during early project stages, have limited capabilities. To represent complex system relationships in the construction industry, static planning methods often fail, which may lead to delays. The findings have shown that one can overcome these limitations by the application of digital twin-based planning environments which enables dynamic simulations and early risk identification (Lu et al., 2020; Khajavi et al., 2019).

2) *Detailed Design Phase*: It has been reported that during the design stage, limited coordination happens between architectural, structural, and MEP disciplines due to moderate adoption of BIM, Navisworks and CFD tools. Digital twins with real-time synchronization can improve design coordination, which helps reduce design conflicts and rework during execution (Zhai & Chen, 2005).

P. Construction and Execution Phase Performance

It has been noted that as many teams still rely on manual documentations, the efficiency of managing design changes gets reduced, therefore highlighting through the survey, the gap between planned digital workflows and actual construction practices in the industry. It has been brought into notice that through digital twin-enabled environments, linking site activities with virtual models by using IoT sensors for real-time data synchronization. This allows early detection of conflicts and improved project productivity (Khajavi et al., 2019).

Q. Commissioning and Handover Challenges

During commissioning and handover stages, fragmented documentation and outdated records become constant difficulties, therefore the support from digital twin to maintain updated system information is vital. By virtual commissioning, it improves traceability and enables smoother transitions to operations (Roberto Saracco, 2019).

R. Cooling Efficiency: Design Accuracy vs Operational Reality

Survey responses indicate that while differences often occur between predicted and actual performance, moderate confidence can be put in current cooling design tools. Prediction accuracy can be improved and continuous cooling optimization can be achieved by integrational real-time operational data extracted from IoT sensors with simulation models with the help of digital twin (Siemens AG, 2022).

S. Operational Adaptability and Control Limitations

Due to dependency on fixed rule-based controls, existing cooling systems are energy inefficient. AI-based control systems make predictions based on historical and real-time

data, and improve adaptability to optimize cooling operations and energy use (Chi Zhou et al., 2024).

T. Industry Readiness for Digital Twin and AI Adoption

The survey highlighted that industry shows strong interest in adopting digital twin and AI technologies due to their potential to lessen setup time and improve efficiency, but some challenges still remain barriers like integration with legacy systems, skill shortages, and uncertain return on investment (Khajavi et al., 2019).

U. Case Studies

When digital twin is adopted with AI technology, the literature review reveals that data centers have consistent, quantifiable performance improvements in comparison to traditional approaches. Across multiple case studies, when these technologies have been implemented, they improve PUE values from 1.50-1.70 to 1.25-1.35 which allows PUE reductions ranging from 12% to 25% (Evans & Gao, 2016; Siemens AG, 2022; Uptime Institute, 2023). Cooling systems, through predictive and adaptive AI optimization, show 30-55% energy savings, which traditionally consume 35-45% of total facility energy (International Energy Agency, 2024; Chi Zhou et al., 2024; Wei et al., 2017).

Furthermore, digital twin technology supported virtual commissioning represents a 30-40% reduction in commissioning durations as conventional timelines reduce from 20-24 weeks to 12-16 weeks (Lu et al., 2020; Khajavi et al., 2019). In contrast, through manual tuning, typically marginal efficiency gains yielded 5-10% by traditional rule-based cooling systems and static design tools (ASHRAE, 2021; Uptime Institute, 2023). These findings indicate that Digital twin and AI integration validate their effectiveness as transformative technologies rather than incremental enhancements in data center design and operation by substantially delivering higher and more consistent performance benefits.

V. Inferences

These conclusions from the literature review strongly corroborate with the survey findings. Measurable improvements in cooling efficiency and setup time are offered by digital twin and AI-based control systems which has been confirmed both by the empirical data and prior research. The results extend existing knowledge by demonstrating that benefits span the entire project lifecycle and are not limited to operations alone (Roberto Saracco, 2019; McKinsey & Company, 2024).

V. CONCLUSION AND RECOMMENDATIONS

W. Research Findings

Current industry practices, limitations of conventional tools and the potential of digital twin and AI technologies across the data center project lifecycle, are investigated through this study. The findings indicate that existing approaches are largely fragmented and reactive in nature for planning, design, construction, commissioning, and operations stage (Lu et al., 2020; McKinsey & Company, 2024).

Static tools such as spreadsheets and 2D drawings lack predictive capability and integration with downstream project phases, whose heavy dependency in early-stage planning and feasibility analysis are revealed through survey results. Late-stage design changes and extended setup time are the results of BIM and coordination tools' limited interoperability and static nature during the detailed design stage (Lu et al., 2020).

In the construction and execution phase, a major contributor has been identified for inefficiencies and rework that is insufficient real-time synchronization between site activities and design information (Khajavi et al., 2019). Operational difficulties and delayed stabilization are some of the prominent challenges which are due to reliance on static documentation during commissioning and handover processes.

Researchers have recognized a notable gap between design-stage predictions and true operational performance in terms of cooling efficiency. Conventional cooling control systems were considered highly reactive and significantly insufficient to adapt dynamic IT loads, which resulted in energy inefficiencies (Siemens AG, 2022; International Energy Agency, 2024).

The findings collectively demonstrate that by enabling lifecycle integration, predictive analysis and continuous optimization, digital twin and AI-based control systems offer substantial improvements.

X. Conclusions

Based on the analysis and discussion, the following interpretations can be drawn. To manage the complexity and dynamic nature of modern data center facilities, conventional data center project delivery methods are insufficient, particularly in relation to cooling system performance and setup time. By providing a dynamic, data-driven representation of the data center, digital twin technology significantly enhances decision-making across various stages like planning, design, construction, commissioning, and operations (Tao et al., 2019; Lu et al., 2020). By enabling predictive and adaptive control strategies, integration of AI-based control systems improves cooling efficiency that outperform traditional rule-based systems. Setup and commissioning time has been reduced, rework has been minimized and operational readiness has been accelerated by enabling virtual commissioning through digital twins. Both project delivery performance and long-term operational efficiency in data centers are improved by a critical enabler, lifecycle data continuity. Industry readiness for adoption of technology is high, although successful implementation requires addressing organizational, technical, and economic barriers (International Energy Agency, 2024; McKinsey & Company, 2024).

It has been confirmed from literature review that digital twin and AI integration significantly outperforms traditional design and operational methodologies of data centers. Documented case studies have enough evidence that indicates PUE reductions of 12-25%, lowering typical values from 1.50-1.70 to 1.25-1.35 (Evans & Gao, 2016; Uptime Institute, 2023). Cooling energy consumption is reduced by 30-55% through AI-driven predictive optimization which conventionally accounts for 35-45% of total facility energy (International Energy

Agency, 2024; Chi Zhou et al., 2024). Additionally, digital twin-enabled virtual commissioning achieves up to 40%-time savings by reducing commissioning timelines from 20-24 weeks to 12-16 weeks (Lu et al., 2020; Khajavi et al., 2019).

Y. Recommendations

Based on the conclusions, the following recommendations are proposed for data center owners, designers, contractors, and operators. To enable scenario analysis, risk identification and informed decision-making, adopt digital twin-based planning frameworks during the concept and feasibility stages. By integrating real-time data, simulation capabilities and lifecycle connectivity, extend BIM workflows into full digital twin environments. To enable predictive optimization of cooling performance and reduce energy consumption, implement AI-driven cooling control systems. The findings highlighted that virtual commissioning techniques validate system performance prior to physical commissioning, thereby reducing setup time and operational risk. Integrated digital platforms should be established for seamless information flow across design, construction, commissioning, and operations (International Energy Agency, 2024; McKinsey & Company, 2024). Investment should be made in workforce training and capability development to ensure effective utilization of advanced digital technologies.

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