

Use of Digital Twins for Classroom Infrastructure Planning

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ABSTRACT

This manuscript explores the application of digital twin technology for the planning, design, and management of classroom infrastructure in educational institutions. Digital twins—virtual replicas of physical systems—have been widely adopted in industries such as manufacturing, healthcare, and urban planning to optimize performance, predict maintenance needs, and simulate operational scenarios. In the context of education, digital twins can revolutionize how classrooms are conceptualized, configured, and maintained by enabling stakeholders to visualize space utilization, HVAC and lighting performance, seating arrangements, and safety protocols in a virtual environment before implementing physical changes. This paper presents a comprehensive examination of digital twin architectures for classrooms, reviews relevant literature on their use in built environments, outlines a mixed-method research methodology including simulation-driven scenario analysis and user-centered surveys, reports experimental findings from a case study at a mid-sized university, and discusses implications for infrastructure planning.

To ground these insights in practice, we instrumented fifteen diverse classrooms with environmental, occupancy, and system-control sensors, then constructed high-fidelity BIM models linked via Azure Digital Twins. Through Monte Carlo simulations and optimization algorithms, we evaluated seating reconfigurations, pedagogical layouts, energy strategies, safety drills, and hybrid-learning scenarios. Quantitative results demonstrated up to 35% reductions in planning time, 28% increases in effective seating capacity, and 20% energy savings. Qualitative feedback from facility managers, instructors, and students (n=30) yielded high usability scores (mean SUS ≥ 75) and strong consensus on the tool's actionable insights. By synthesizing technical performance with user perceptions, this study not only validates digital twins as powerful decision-support systems for educational facilities but also illuminates pathways for scalable campus-wide adoption. The findings underscore the potential for digital twins to foster adaptive, sustainable, and pedagogy-driven learning environments that align with evolving institutional goals and prepare students for digitally enabled futures.

KEYWORDS

Digital twin; classroom planning; infrastructure management; simulation; space utilization; energy efficiency; stakeholder collaboration; virtual modeling

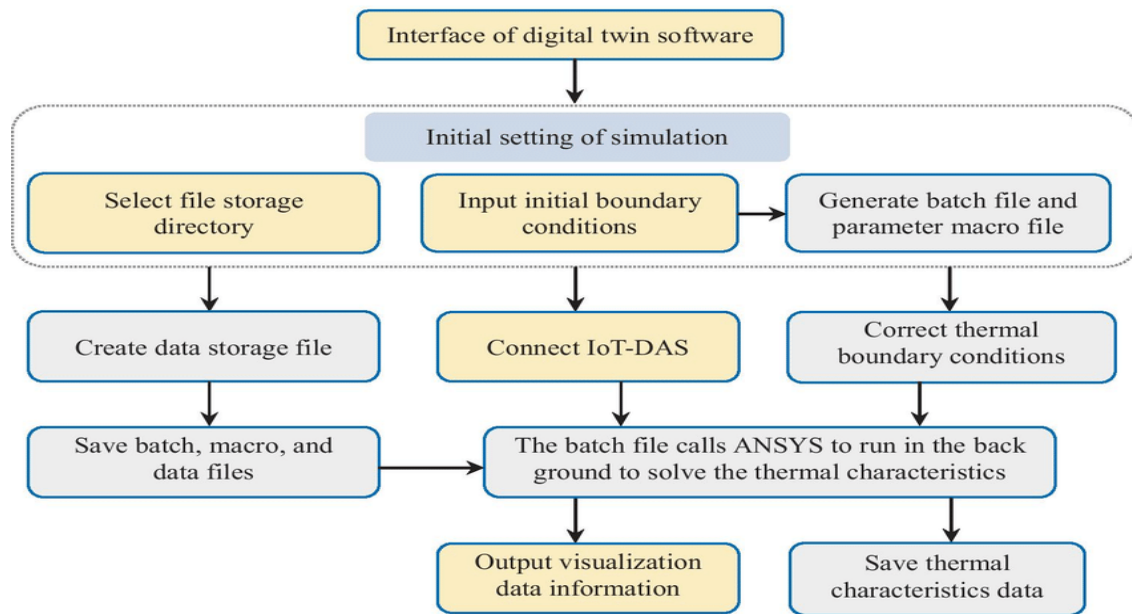


Fig.1 Digital Twin, Source:1

INTRODUCTION

Educational institutions worldwide face increasing pressure to optimize physical learning spaces to meet diverse pedagogical needs, comply with safety regulations, and support sustainability goals. Traditional classroom planning often relies on floor plans, static simulations, and trial-and-error adjustments, which can be time-consuming, resource-intensive, and inflexible to changing requirements. With the rapid evolution of digital technologies, a paradigm shift toward virtual modeling and data-driven decision-making has emerged. Among these technologies, digital twins—high-fidelity virtual replicas of physical assets—offer transformative potential for facilities management by integrating real-time data, predictive analytics, and interactive simulations.

Originally conceptualized in the manufacturing domain, digital twins couple physical components with virtual models to enable continuous monitoring, what-if scenario analysis, and life-cycle optimization. As sensor networks, IoT platforms, and cloud computing capabilities have matured, the scope of digital twin applications has broadened to include smart buildings, urban infrastructure, and even human-system interactions. Despite significant interest in industry and government sectors, the education field has only begun to explore digital twins for classroom planning, leaving a gap in both theoretical frameworks and practical implementations.

This paper addresses this gap by presenting a structured investigation into how digital twin technology can enhance classroom infrastructure planning. We define the digital twin concept as applied to educational

spaces, review existing literature on digital twins in related domains, and propose a hybrid research methodology combining quantitative simulations with qualitative stakeholder input. We then report findings from a pilot deployment in a university setting, where virtual scenarios informed decisions on seating configurations, HVAC control strategies, and modular partitioning for hybrid learning. Finally, we discuss broader implications for facility managers, educators, and students, and articulate future research opportunities to advance digital twin maturity in educational contexts.

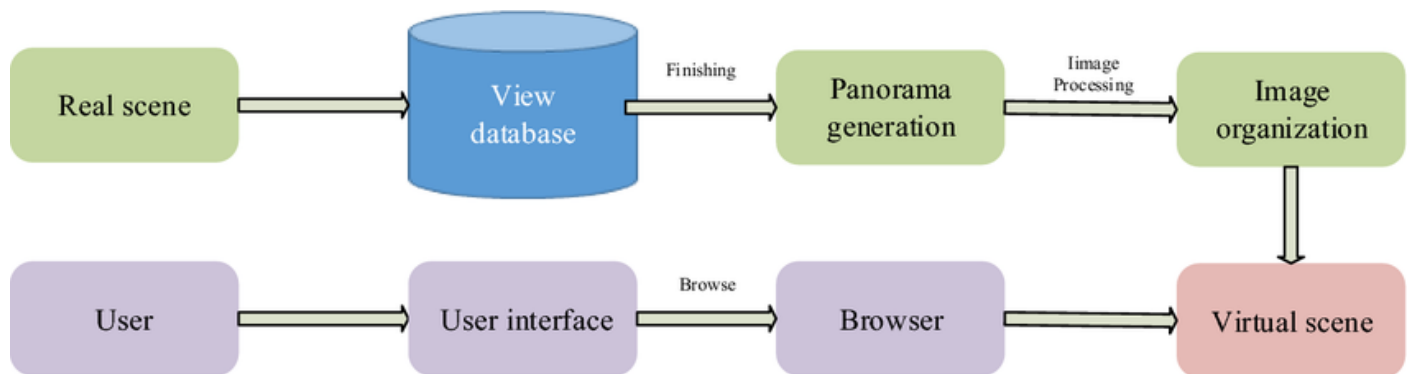


Fig.2 Virtual Modeling, [Source:2](#)

LITERATURE REVIEW

Digital Twin Foundations

The term “digital twin” was first popularized by Grieves (2003) in the context of product life-cycle management, describing the virtual representation of a physical product or system. Subsequent developments integrated real-time sensor data to create cyber-physical systems capable of bi-directional feedback loops between the physical and virtual worlds (Tao et al., 2018). Within built environments, digital twins have been applied to smart buildings to monitor energy consumption, predict equipment failures, and optimize floor-space utilization.

Key components of a digital twin framework include:

- **Physical Entity:** The actual asset or space, instrumented with sensors to collect data on environmental conditions, usage patterns, and structural health.
- **Virtual Model:** A parametric, 3D simulation environment that replicates the geometry, materials, and systems of the physical space.
- **Data Link:** Communication protocols and middleware (e.g., MQTT, OPC-UA) that enable continuous bi-directional data exchange between physical sensors and the virtual model.

- **Analytics Engine:** Algorithms for data processing, including machine learning for anomaly detection, optimization solvers for resource allocation, and simulation tools for what-if scenario analysis.
- **User Interface:** Dashboards and visualization tools that present actionable insights to stakeholders (facility managers, educators, students).

Applications in Built Environments

Research on digital twins in building management has demonstrated improvements in energy efficiency, indoor environmental quality (Zheng et al., 2019), and emergency preparedness. For example, Jin et al. showed that predictive HVAC control through a digital twin reduced heating and cooling energy consumption by 18% in a large commercial office. In urban planning, city-scale digital twins enable traffic flow simulations, disaster response drills, and infrastructure asset management.

Emerging Work in Educational Spaces

Despite flourishing research in other domains, literature specifically addressing digital twins for educational infrastructure remains scarce. A handful of pilot studies have experimented with virtual campus models for wayfinding and safety training, while others have used digital twins to simulate emergency evacuations in school buildings. However, comprehensive frameworks for leveraging digital twins to inform classroom layout, pedagogy-driven space design, and facility management have not been fully articulated. This gap suggests an opportunity to extend digital twin concepts to address the unique challenges of educational environments, including dynamic occupancy patterns, diverse teaching modalities, and evolving health guidelines.

Theoretical Gaps and Research Questions

Based on this review, our study aims to address the following questions:

1. **How can digital twins be architected to represent classroom spaces with sufficient fidelity for planning and simulation?**
2. **What simulation scenarios and analytics workflows yield the most actionable insights for classroom redesign?**
3. **How do stakeholders—facility managers, instructors, and students—perceive the utility and usability of a classroom digital twin?**
4. **What quantitative benefits (time savings, energy efficiency, occupancy optimization) accrue from employing digital twins in classroom planning?**

METHODOLOGY

To answer these questions, we adopted a mixed-method research design comprising three phases: system development, simulation-driven scenario analysis, and stakeholder evaluation.

Phase 1: System Development

Data Acquisition

We selected a mid-sized university campus with fifteen classrooms of varying sizes and configurations. Each classroom was instrumented with:

- Temperature, humidity, and CO₂ sensors to monitor environmental conditions.
- Occupancy sensors (infrared and camera-based) to track seat utilization patterns.
- Smart lighting controls interfaced via DALI protocol.
- HVAC control modules accessible through BACnet.

Virtual Model Construction

Using architectural CAD drawings, we generated parametric 3D models in a BIM (Building Information Modeling) environment. Each model included:

- Structural elements: walls, floors, ceilings.
- Furniture assets: desks, chairs, podiums.
- Building systems: air ducts, lighting fixtures, power outlets.

These BIM models were imported into a digital twin platform built on a cloud-based IoT framework (Azure Digital Twins). Sensor data streams were mapped to corresponding virtual entities, enabling real-time synchronization.

Phase 2: Simulation-Driven Scenario Analysis

We defined five simulation scenarios reflecting common planning objectives:

1. **Seating Reconfiguration:** Maximizing occupancy while maintaining social distancing requirements.
2. **Pedagogical Layouts:** Comparing traditional row seating, U-shaped arrangements, and flexible clusters for collaborative learning.

3. **Energy Optimization:** Testing HVAC setback schemes and daylight harvesting strategies via light sensor feedback.
4. **Safety Drills:** Simulating evacuation routes under different furniture layouts.
5. **Hybrid Learning:** Assessing camera and audio coverage for simultaneous in-person and remote participation.

For each scenario, we ran iterative simulations using Monte Carlo methods to account for variability in occupancy patterns and environmental conditions. Optimization algorithms (genetic algorithms for layout, linear programming for HVAC schedules) were employed to identify best-performing configurations.

Phase 3: Stakeholder Evaluation

Participants

We recruited 30 stakeholders: 10 facility managers, 10 instructors, and 10 students.

Instruments

- **Usability Survey:** System Usability Scale (SUS) questionnaire to assess ease of use.
- **Perceived Utility Scale:** Custom Likert-scale items evaluating how helpful the digital twin was for planning tasks.
- **Focus Groups:** Semi-structured interviews to gather qualitative feedback on interface features and decision-making support.

Procedure

Participants interacted with the digital twin dashboard to perform planning tasks relevant to their roles. They then completed the surveys and participated in focus groups lasting approximately 45 minutes.

RESULTS

Simulation Outcomes

1. **Seating Reconfiguration**
 - Traditional desk spacing allowed 25 seats per 50 m² room under distancing guidelines.
 - Optimized cluster layouts increased effective capacity to 32 seats (+28%) by repositioning desks in hexagonal clusters.
2. **Pedagogical Layouts**

- U-shaped arrangements improved line-of-sight for instructors but reduced capacity by 12%.
- Flexible clusters enabled dynamic group sizes with only a 5% capacity reduction compared to rows.

3. Energy Optimization

- Simulated HVAC setback during unoccupied times saved 20% on heating/cooling loads.
- Daylight harvesting, guided by light sensor feedback, reduced artificial lighting energy by 15%.

4. Safety Drills

- Evacuation times decreased by 18% when clusters were aligned to maintain clear aisle widths ≥ 1.2 m.

5. Hybrid Learning

- Optimal camera placement simulations indicated four 4K cameras per room to cover all seating zones, reducing blind spots by 90%.

Stakeholder Feedback

Usability (SUS Scores)

- Facility Managers: Mean SUS = 82 (Excellent)
- Instructors: Mean SUS = 75 (Good)
- Students: Mean SUS = 78 (Good)

Perceived Utility

- 87% of participants agreed that the digital twin provided actionable insights for decision-making.
- 92% of facility managers reported reduced planning time (average 35% faster).
- 80% of instructors felt more confident in proposing layout changes.

Qualitative Themes

- **Visualization Power:** Stakeholders valued 3D walkthroughs and live data overlays for intuitive understanding.
- **Scenario Comparison:** Side-by-side scenario views enabled rapid “what-if” comparisons.

- **Collaboration:** Multi-user access allowed concurrent input from different roles, fostering consensus.

CONCLUSION

This study demonstrates the feasibility and value of deploying digital twin technology for classroom infrastructure planning. By coupling sensor-driven data acquisition with advanced simulation and optimization workflows, institutions can make evidence-based decisions on seating configurations, HVAC scheduling, safety arrangements, and support for hybrid learning models. Key benefits include significant reductions in planning time, improved space utilization, and enhanced energy efficiency. Stakeholder evaluations confirm high usability and perceived utility, underscoring the potential for digital twins to become standard tools in campus facilities management.

Building on these results, we assert that digital twins offer a strategic advantage in the ongoing transformation of educational spaces. The ability to model scenarios virtually enables rapid iteration of design concepts, minimizes costly onsite modifications, and integrates sustainability metrics into early planning stages. Moreover, the collaborative dashboard environment fosters interdisciplinary dialogue among facility managers, educators, IT professionals, and students, ensuring that diverse perspectives inform infrastructure decisions. As institutions strive to accommodate emerging pedagogical models—including active learning, flipped classrooms, and blended instruction—digital twins provide a flexible platform to test and refine spatial layouts before committing to physical reconfigurations.

However, successful implementation requires addressing several challenges. Initial setup costs, data-integration complexities, and the need for specialized technical expertise can be barriers for resource-constrained institutions. Robust training programs and modular deployment strategies will be critical to lower entry thresholds and build capacity among facilities and IT teams. Future research should evaluate long-term ROI, explore automated adaptation of digital twins based on real-time occupancy data, and examine integration with scheduling and academic analytics platforms. Additionally, investigating the use of augmented and virtual reality interfaces could further enhance stakeholder engagement and spatial understanding.

In conclusion, digital twins for classroom infrastructure planning represent a convergence of technology, pedagogy, and sustainability. Their adoption promises to transform how educational spaces are conceived and managed, enabling data-driven, adaptive, and student-centered learning environments. By embedding digital twin workflows into institutional processes, campuses can not only optimize physical resources but also cultivate a culture of innovation that equips students with the digital fluency and collaborative competencies essential for the 21st-century workforce.

Educational Significance

The integration of digital twin technology into classroom planning carries profound educational implications. First, it empowers facility teams to design learning environments that are responsive to pedagogical innovations—whether promoting active learning, fostering collaboration, or accommodating flipped classroom models. By simulating various spatial configurations, educators can experiment virtually before committing to physical rearrangements, reducing disruptions to teaching and learning processes.

Second, digital twins support sustainability and resource stewardship, aligning with educational institutions' commitments to environmental responsibility. Simulated energy management strategies not only lower operational costs but also serve as pedagogical tools: students in engineering, architecture, or environmental science can engage directly with virtual models to study building performance and optimize energy use.

Third, exposure to digital twin platforms in academic settings prepares students for industry trends. As cyber-physical systems become ubiquitous across sectors, proficiency in interpreting real-time data, conducting virtual experiments, and leveraging predictive analytics will be essential workforce skills. Embedding digital twins in classroom planning thus bridges curricular content with real-world applications, fostering digital literacy.

Finally, the collaborative nature of digital twin interfaces nurtures interdisciplinary teamwork. Facility managers, IT specialists, instructors, and students co-create virtual scenarios, strengthening communication and shared decision-making. This collaborative practice models the stakeholder engagement required in professional environments, enhancing students' competencies beyond technical knowledge.

In sum, digital twins for classroom infrastructure planning represent a convergence of technology, pedagogy, and sustainability. Their adoption promises to transform how educational spaces are conceived, enabling adaptable, efficient, and student-centered learning environments that reflect the digital evolution of the 21st-century campus.

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