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Digital Twin Technology Educational Learning Tools and Kits

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Abstract

Digital twins—virtual replicas of physical systems—are reshaping industry, research, and education through real-time monitoring, simulation, and optimization. Despite rapid growth, digital twin (DT) concepts remain underrepresented in Information Systems (IS) curricula, creating a gap between workforce demand and academic preparation. This paper addresses that gap by aligning DT education with the IS 2010 Curriculum Guidelines for Undergraduate Programs in Information Systems (Topi et al., 2010). We propose a structured framework consisting of three components: (1) student learning outcomes mapped to IS competencies, (2) fundamentals of DT architecture and systems integration, and (3) hands-on labs and projects supported by affordable learning kits. We further analyze challenges educators face—including cost barriers, multidisciplinary complexity, and educator readiness—and suggest strategies for overcoming them. To illustrate practical application, we describe how digital twin (DT) kits were integrated into a project-based course activity, where students designed IoT-based prototypes to explore real-time monitoring and system interaction. We also present a comparative taxonomy of DT platforms analyzing cost, technical skills, use cases, and curricular alignment. By grounding DT education in established IS standards, acknowledging implementation challenges, and offering practical solutions, this study contributes a replicable framework and strategies to prepare students for emerging workforce needs.

Keywords: Digital Twin, Curriculum integration, Educational Technology, Project-based Learning, Learning Kits, Hands-on Learning

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1. INTRODUCTION

Automation and robotics technologies have traditionally been central to manufacturing industries. However, recent advancements have led to the emergence of digital twin systems-virtual representations of physical environments that dynamically respond to real-world data with minimal or no human intervention. Digital twins are now recognized as a pivotal technology in the digital transformation of enterprises, garnering significant interest across both industry and academia (Schalkwyk, 2024) (National Academies of Sciences, Engineering, and Medicine, 2024). Although the concept has existed for several decades, it only recently gained widespread attention (Zhang et al., 2023).

Michael Grieves (2014) is widely credited with formalizing the digital twin concept, defining it as a digital representation of a physical product comprising three interconnected components: the physical entity, its digital counterpart, and the data links between them. This foundational framework established the essential elements of physical space, virtual space, and their continuous connection. Building upon this, subsequent research has expanded the definition to include more complex systems and processes. For example, Tao et al. (2019) proposed a comprehensive framework describing digital twins as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin." This highlights the dynamic, data-driven nature of DTs and their capability for real-time synchronization with their physical counterparts. Digital twins generate real-time simulations that reflect and predict the behavior of physical systems, enabling intelligent monitoring, decision-making, and optimization in changing environments (Ultimate Guides, n.d.). These systems continuously acquire and integrate environmental data, allowing operations to adapt, refine, and evolve autonomously in real time (MIT AeroAstro, 2021).

This paradigm shift is driving significant gains in efficiency, sustainability, and intelligent automation across various sectors, including smart buildings, healthcare, energy management, urban mobility, and campus operations. Digital twins are being deployed for remote monitoring, predictive maintenance, system diagnostics, and resource optimization, transforming how organizations plan, operate, and improve physical infrastructure. Their impact extends to areas such as smart cities, intelligent energy grids, connected campuses, and industrial automation, with the potential for profound socio-economic influence across global markets (Robotics and Autonomous Systems, n.d.).

Industry analysts forecast exponential growth in the digital twin market, projecting its value to surpass $259.32 billion globally by 2032 (The Digital Twin Market, 2025). This expansion will create demand for a large workforce skilled in data analytics, IoT integration, simulation modeling, and systems engineering—fields where current educational pipelines may fall short. To address this emerging skills gap, educational institutions can play a critical role to prepare students by developing interdisciplinary courses, hands-on projects, and simulation-based learning environments. Integrating digital twin technologies into curricula will empower students with the technical expertise and problem-solving abilities necessary to support innovation and workforce development in this rapidly evolving field.

2. DIGITAL TWIN CURRICULUM DESIGN

The rapid growth of digital twin (DT) applications across sectors—ranging from smart infrastructure to healthcare—presents an urgent need to integrate DT concepts into IS education. Designing such curricula requires balancing conceptual knowledge, technical skills, and alignment with recognized IS competencies. The IS 2010 Curriculum Guidelines (Topi et al., 2010) emphasize the integration of systems analysis, data management, organizational context, and emerging technologies. These guidelines provide a foundation for positioning digital twins as part of the IS body of knowledge.

Digital twin technology is inherently multidisciplinary (Jankovskis et al., 2024), drawing from systems modeling, data science, the Internet of Things (IoT), cloud computing, simulation, artificial intelligence, visualization, and cybersecurity. This complexity makes it challenging to design comprehensive education

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and training programs. Many existing courses still address only one element—such as simulation tools, control systems, or analytics—without integrating them into the broader framework of a complete digital twin system (Liu et al., 2021).

To address this gap, a well-designed DT course should be structured around three interdependent components, each supported by literature in IS and engineering education (Jankovskis et al., 2024; Liu et al., 2021).

Student Learning Outcomes (SOs)
Curriculum design for digital twins should hinge on competencies students are expected to demonstrate based on program and industry needs. Key outcomes include:

SO1: Data Integration and Management
- Collecting, cleaning, and synchronizing data across physical and digital platforms.
- Managing real-time IoT data streams and ensuring data quality.
- Applying knowledge of IoT architectures and sensor networks.

SO2: Simulation and Modeling
- Developing virtual representations of physical assets, processes, or systems.
- Using simulation tools (e.g., MATLAB, Simulink, ANSYS) and modeling languages.
- Understanding of system dynamics, predictive analytics, and scenario testing

SO3: Cybersecurity and System Interoperability
- Applying secure data exchange protocols and risk mitigation strategies.
- Integrating DTs across platforms and organizational boundaries.

Demonstrating awareness of interoperability standards (e.g., OPC UA, BIM, ISO 23247).

Fundamentals of Digital Twin and Architecture
This component introduces students to the conceptual model of DTs—physical assets, digital representations, and data links (Grieves, 2014). Instruction emphasizes system architecture, IoT integration, simulation platforms, and visualization environments. Literature highlights the need for multidisciplinary instruction that bridges systems modeling, data science, and cyber-physical integration (Tao et al., 2019; Bastiaan et al., 2019).

A key challenge is determining which competencies to prioritize: systems architecture, real-time data integration, programming and APIs, visualization tools, modeling platforms (e.g., MATLAB, Unity), or ethical and security concerns (Hadfield, 2020). Current trends in instructional design increasingly emphasize cyber-physical systems, heterogeneous platform integration, sensor data acquisition, and diagnostic capabilities. These emphases help ensure that students develop not only technical fluency but also the ability to address interoperability, resilience, and ethical considerations in complex digital ecosystems.

By aligning these outcomes and fundamental competencies with the IS 2010 curriculum areas, digital twin education can be firmly embedded within the IS discipline. For example, SO1 (Data Integration and Management) maps to IS 2010's Data and Information Management and Systems Analysis & Design; SO2 (Simulation and Modeling) connects to Systems Analysis & Design, IT Infrastructure, and IS Project Management; and SO3 (Cybersecurity and Interoperability) aligns with Enterprise Architecture, IS Risk Management, and IT Strategy and Acquisition. Similarly, instruction in DT fundamentals reinforces IS competencies in Human–Computer Interaction (through visualization), IT Infrastructure (through cloud platforms and IoT integration), and Quantitative Analysis (through diagnostics and predictive analytics). This explicit mapping ensures that DT concepts are not treated as add-ons, but as integrated components of IS curricula that prepare students for both current and emerging workforce needs.

Mapping DT Fundamentals to IS 2010 Core Areas
The competencies emphasized in digital twin (DT) fundamentals can be explicitly mapped to the IS 2010 curriculum core areas (Topi et al., 2010), ensuring curricular alignment and pedagogical rigor (see Table 2.1).

This mapping demonstrates that digital twin (DT) education is not an isolated or novel add-on, but rather a natural extension of the IS 2010 curriculum. By explicitly linking DT outcomes and fundamentals to established IS competencies, the proposed framework provides both academic rigor and practical relevance. This ensures that students gain interdisciplinary skills in simulation, data integration, and cybersecurity while still meeting the expectations of accredited IS programs. More importantly, the alignment positions digital twins as a bridge between traditional IS domains and emerging workforce needs in intelligent systems, preparing graduates to contribute meaningfully in industries increasingly shaped by IoT, AI, and cyber-

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physical systems.

3. HANDS-ON LABS AND PROJECTS

Digital twin (DT) learning kits provide affordable and scalable entry points for experiential learning, enabling students to design, monitor, and control virtual replicas of physical systems. Platforms such as Arduino, Raspberry Pi, Unity, MATLAB/Simulink, and Microsoft Azure Digital Twins directly support IS 2010's emphasis on experiential and systems integration learning. By lowering barriers to engagement, these kits make abstract IS concepts tangible and foster project-based learning across disciplines.

Strategies for Incorporating Digital Twins
There are three primary strategies for embedding digital twin concepts into curriculum:

a) **Integrating Digital Twin Topics into Existing Curricula:**
This includes embedding DT-related concepts into established courses like Control Systems, IoT, Artificial Intelligence, Computer Vision, Systems Engineering, Smart Cities, Simulation and Modeling, and Machine Learning.

b) **Incorporating Dedicated Digital Twin Courses into New Curricula:**
This could involve new course offerings such as Introduction to Digital Twins, Cyber-Physical Systems, Real-Time Data Modeling, Digital Twin Platforms and Applications, Ethics and Privacy in Smart Systems, and Digital Infrastructure Design.

c) **Offering Project-Based Learning Opportunities Focused on Digital Twins:**
Hands-on capstone or lab projects that simulate or develop digital twin systems for real-world applications—such as smart buildings, virtual campus monitoring, energy systems, or predictive maintenance—can provide valuable experiential learning.

Table 2.1 Mapping of DT Fundamental Competencies to IS 2010 Curriculum Areas

DT Competency Area	Description	IS 2010 Core Area Alignment
SO1: Data Integration & Management	Collecting, cleaning, and synchronizing IoT data; ensuring quality; integrating across platforms	Data & Information Management; Systems Analysis & Design
SO2: Simulation & Modeling	Creating virtual representations; using MATLAB, Simulink, Unity, ANSYS; predictive analytics	Systems Analysis & Design; IT Infrastructure; IS Project Management
SO3: Cybersecurity & Interoperability	Secure protocols; cross-platform integration; interoperability standards (OPC UA, BIM, ISO 23247)	Enterprise Architecture IS Risk Management; IT Strategy & Acquisition
Fundamentals: System Architecture & IoT	Designing architecture; IoT sensor integration; real-time connectivity	IT Infrastructure; Enterprise Architecture
Fundamentals: Visualization & Interaction	Dashboards, 3D models, AR/VR interaction	Human–Computer Interaction; IT Infrastructure
Cybersecurity & Ethical Considerations	Ensuring secure, interoperable, and responsible DT deployments	IS Risk Management & Security; IT Strategy, Management & Acquisition
Fundamentals: Diagnostics & Analytics	Predictive maintenance, anomaly detection, decision support	Quantitative Analysis; Data & Information Management

Digital Twin Learning Tools

Digital twin (DT) learning tools consist of

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relatively inexpensive and flexible components that allow students to create virtual replicas of physical systems for simulation, monitoring, and control. These educational tools often include breadboards, jumper wires, development boards (like Arduino or Raspberry Pi), a variety of sensors, actuators, and networking modules—combined to represent real-world systems in a virtual environment. These are commonly packaged as do-it-yourself (DIY) or ready-to-run (R2R) educational kits that promote hands-on learning across fields such as IoT, smart systems, and cyber-physical system modeling.

DIY digital twin kits typically come with all the necessary components, software, and instructions to build physical models and connect them to virtual environments (Level 5 Supplies, n.d.). These systems can be extended or customized to simulate complex infrastructure like smart buildings, energy systems, or industrial machines. Many kits are also designed with K-12 STEM education or university-level capstone projects in mind (Dextered, n.d.; James, 2022; Home, n.d.). Some notable platforms and kits supporting digital twin learning include:

a) Arduino-based Smart Home Simulators
b) Raspberry Pi Digital Twin Starter Kits
c) Siemens NX/Mindsphere Academic Tools
d) MATLAB/Simulink Digital Twin Toolboxes
e) Unity with IoT Sensor Integration
f) Microsoft Azure Digital Twins
g) TwinCAT or Factory I/O Learning Simulations
h) Node-RED and MQTT-based IoT Prototyping Kits

These kits usually integrate hardware, software, cloud services, and communication protocols. Hardware components like microcontrollers or microprocessors are programmed through integrated development environments (IDEs) to collect data and interact with real-world systems. Expansion boards or shields can add features such as motion control, displays, wireless communication, and environmental sensing. For instance, an Arduino-based system can include a motor control shield, Wi-Fi shield, and environmental sensor shield to replicate and monitor the physical environment in real time.

As more advanced processing is required, particularly in modeling complex systems or running AI-based simulations, edge computing devices like Jetson Nano or Raspberry Pi 5 can be used to support AI on the edge—enhancing the fidelity and responsiveness of digital twin systems.

Digital twin platforms can be broadly categorized into the following areas:

- **Hardware Platforms:**
  e.g., Arduino, Raspberry Pi, BeagleBone, Jetson Nano, ESP32, Intel Galileo
- **Software Platforms:**
  e.g., Python, C++, MATLAB/Simulink, Unity, Node-RED, Ezblock
- **Cloud Platforms:**
  e.g., Microsoft Azure Digital Twins, AWS IoT TwinMaker, Siemens Mindsphere
- **Network Communication Platforms:**
  e.g., Wi-Fi, Bluetooth, Zigbee, MQTT, CoAP, HTTP
- **Components and Accessories:**
  e.g., sensors, actuators, breakout boards, environmental monitors, cameras, GPS modules

These kits and platforms can simulate a variety of functions relevant to smart environments, such as temperature monitoring, predictive maintenance, room occupancy tracking, real-time data visualization, and energy optimization. Sensors—packaged as ready-to-use modules—can measure environmental parameters like temperature, humidity, light, or motion and feed that data into the digital twin model for visualization and feedback control.

Digital twin kits are particularly suitable for beginners and intermediate learners in engineering, computer science, and systems design. They provide scalable learning opportunities and support cross-disciplinary education. Platforms like Microsoft Azure Digital Twins or Unity-based simulators allow students to create complex, immersive, and connected systems that mirror real-world infrastructure, helping them understand both the physical and digital layers of modern systems. These educational ecosystems not only teach programming and systems thinking but also prepare students for careers in smart manufacturing, intelligent infrastructure, and cyber-physical system integration. As such, digital twin learning tools are essential for building foundational knowledge and hands-on experience in this transformative technology field.

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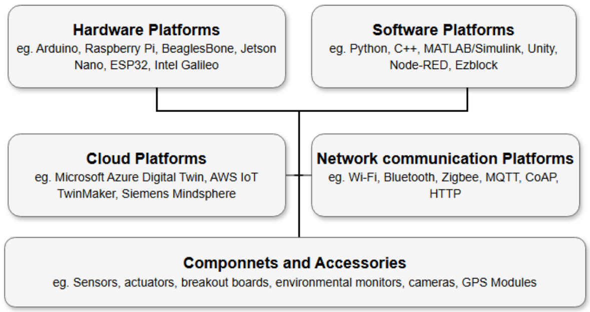

Fig 3.1 Digital Twin Platform Components

To move beyond descriptive listings of available platforms, it is important to critically compare digital twin (DT) learning kits in terms of accessibility, technical requirements, and curricular alignment. Table 3.1 presents a comparative analysis of widely used platforms, including Arduino, Raspberry Pi, MATLAB/Simulink, Unity, Azure Digital Twins, Siemens Mindsphere, and Node-RED. Each platform varies in cost, required skills, and depth of application, but all can be mapped to competencies outlined in the IS 2010 Curriculum Guidelines (Topi et al., 2010).

Table 3.1. Comparative Analysis of Digital Twin Learning Kits and Their Alignment with IS 2010 Curriculum Competencies

Platform / Kit	Approx. Cost	Technical Skills Required	Educational Use Cases	IS 2010 Competencies Supported
Arduino-based Smart Home / IoT Kits	$50–$120	Basic electronics, C/C++ programming	DIY IoT prototypes, simple DT simulations (temperature, lighting, occupancy)	Data & Information Management; Systems Analysis & Design
Raspberry Pi Digital Twin Starter Kits	$80–$150	Python, Linux, IoT networking	Edge computing, sensor integration, real-time monitoring	IT Infrastructure; Data Integration; Systems Architecture
MATLAB/Simulink Digital Twin Toolboxes	Academic license ($50–$100 student; higher institutional)	MATLAB coding, modeling, simulation	Simulation of dynamic systems, predictive analytics, control systems	Systems Analysis & Design; Quantitative Analysis; Modeling & Simulation
Unity + IoT Sensor Integration	Free (student), add-ons vary ($0–$50)	Unity (C#), visualization, IoT data streams	3D visualization of DTs, immersive learning, AR/VR interfaces	IT Infrastructure; Systems Integration; Human-Computer Interaction
Microsoft Azure Digital Twins	Free tier; scales with usage ($0–$50/month for academic)	Cloud computing, APIs, data pipelines	Cloud-scale DT deployments, enterprise integration, IoT hub	Enterprise Architecture; Data Management; IT Infrastructure
Siemens Mindsphere Academic Tools	Institutional license (varies)	Industrial IoT, advanced analytics	Industrial DT scenarios, predictive maintenance	Enterprise Architecture; IT Project Management; Systems Integration
Node-RED + MQTT Prototyping Kits	Free software; hardware <$100	IoT protocols, data routing, event-driven programming	Middleware prototyping, automation flows, plug-and-play DTs	IT Infrastructure; Systems Integration; Emerging Technologies

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For instance, Arduino and Raspberry Pi kits emphasize hands-on IoT integration and data management, supporting foundational IS skills in data handling and systems analysis, while Unity and Azure DT platforms highlight visualization and enterprise-scale integration, reinforcing IS competencies in IT infrastructure, enterprise architecture, and human–computer interaction. By situating these kits within IS curriculum outcomes, educators can make informed decisions about which platforms best match their institutional resources, student preparedness, and program-level goals.

4. BENEFITS AND FUTURE TRENDS

Adopting digital twin (DT) learning tools in education provides numerous benefits for students and institutions while aligning with industry demand for DT expertise. These tools are accessible, scalable, and adaptable across disciplines, supporting learners from K–12 through university-level programs.

Benefits of Digital Twin Learning Tools:

- **Flexibility and Accessibility:** A wide variety of DIY and ready-to-run (R2R) kits are available at multiple price points, making them suitable for different contexts and budget levels.
- **Low Barrier to Entry:** Most kits require limited prior experience, with ample instructional resources.
- **Scaffolded Learning:** Kits are designed for beginners through advanced learners, allowing progressive skill development.
- **Interdisciplinary Engagement:** DT fosters collaboration among students in computer science, engineering, business, and urban planning.
- **Workforce Alignment:** As the DT market expands, graduates gain relevant skills in systems integration, modeling, data analytics, and AI, positioning them for careers in emerging technology fields.

Future Trends in Digital Twin Development

Current and emerging trends in digital twin development are shaping the future of both education and industry. These trends include:

- **IoT and Sensor Integration:** Real-time digital replicas of physical systems through embedded sensing. (Zhang et al., 2023).
- **Edge Computing and AI on the Edge**: Smarter, more responsive DTs that operate close to data sources. (Liu et al., 2021).
- **Cloud-Based DT Platforms:** Scalable environments for collaboration and enterprise integration. (Tao et al., 2019).
- **Simulation-based Decision-making:** Predictive maintenance, energy optimization, and smart infrastructure management. (National Academies, 2024).
- **Immersive Learning and Training:** Augmented and virtual reality (AR/VR) applications for interactive engagement. (Jankovskis et al., 2024).

In coming decades, digital twin systems are expected to play a major role in smart infrastructure and sustainability efforts. These systems will help:

- Optimize energy use and reduce operational costs
- Improve safety and resilience of physical assets
- Support urban planning, walkability, and resource allocation
- Enable real-time diagnostics and remote operations
- Reduce environmental impact through predictive modeling and simulation

Over the coming decades, digital twin systems are expected to play a central role in smart infrastructure and sustainability efforts. They will optimize energy use, reduce costs, improve asset resilience, enhance urban planning, enable real-time diagnostics, and support environmental sustainability (Schalkwyk, 2024).

Workforce development is central to this transformation. Preparing students for DT-related careers requires curricula that combine software engineering, IoT, cloud architecture, data analytics, and systems modeling with domain-specific expertise in civil, electrical, and computer engineering (Liu et al., 2021).

Ultimately, digital twins will become indispensable in both education and industry. The urgent need to develop a workforce capable of designing, deploying, and maintaining DT systems represents an opportunity for educators, researchers, and policymakers to shape the future of learning, innovation, and sustainable development (Zhang et al., 2023; Jankovskis et al., 2024).

5. CHALLENGES OF DIGITAL TWINS

Digital twin (DT) technologies represent one of the most transformative innovations in how we design, monitor, and optimize systems across sectors—from smart campuses and energy systems to industrial automation and healthcare. As such, educators, developers, industry partners, and students face several challenges in

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incorporating DT systems into educational environments. Some of the key challenges in using digital twin kits and platforms in education include:

- **Curriculum Adaptation:**
  Educators face the challenge of rapidly integrating digital twin concepts into existing curricula to keep pace with technological adoption in industry and infrastructure (Hadfield, C., 2020).
- **Multidisciplinary Complexity:**
  Digital twin systems require understanding of multiple subsystems such as real-time data collection, simulation modeling, IoT sensor integration, cloud communication, AI analytics, and visualization. Teaching all of these components within a single course can be difficult.
- **Educator Readiness and Adoption:**
  There may be resistance or hesitancy among educators to adopt and implement emerging technologies due to limited exposure, lack of training, or resource constraints.
- **Industry Collaboration Needs:**
  Educators may need to collaborate with industry partners, platform vendors, or employers to provide students with relevant, real-world digital twin applications and to expose them to career pathways in the DT ecosystem (Hadfield, C., 2020).
- **Overwhelming Variety of Kits and Platforms:**
  With numerous DIY and professional digital twin kits available—ranging from Arduino-based platforms to full cloud-integrated systems—it can be difficult for beginners to select the right tool for their learning objectives and technical level.
- **Cost Barriers:**
  Digital twin kits and associated technologies can range in cost from under $100 to several thousand dollars, making them potentially inaccessible to some students or institutions with limited budgets.
- **Hardware Troubleshooting Challenges:**
  Beginners may struggle with diagnosing and fixing hardware issues, such as faulty sensor readings, poor connectivity, or incorrect wiring—especially when working with modular systems.
- **Software and Hardware Compatibility:**
  Some DT kits and applications may not be universally compatible, which can complicate deployment and learning—particularly when integrating multiple platforms or cloud services.
- **Gap Between Educational Kits and Real-World Systems:**
  While small-scale DT kits help students learn foundational concepts (e.g., simulating building energy usage, monitoring occupancy, etc.), real-world digital twin systems are far more complex, scalable, and security sensitive. Bridging this gap remains a pedagogical challenge.

These challenges underscore the importance of adopting a structured approach to digital twin (DT) education. By explicitly mapping DT competencies to the IS 2010 curriculum, developing scaffolded learning outcomes, and incorporating hands-on kits within a systematic evaluation framework, educators can mitigate many of these barriers. Industry partnerships, targeted faculty development, and careful selection of scalable DT platforms can further bridge the gap between classroom practice and real-world systems. Addressing these challenges is essential not only for advancing DT pedagogy but also for ensuring that students are prepared to contribute effectively in an increasingly digital and interconnected workforce.

6. CONCLUSIONS

This study underscores the urgent need to integrate digital twin (DT) technologies into IS curricula and offers a structured pathway for doing so. We proposed a three-pillar framework—student learning outcomes, DT fundamentals, and hands-on labs—that aligns directly with IS 2010 competencies. A comparative taxonomy of learning kits and platforms further supports curriculum design by helping educators balance affordability, technical skills, and institutional goals.

Our integration of digital twin (DT) kits into a project-based classroom activity demonstrates that low-cost platforms can effectively connect theoretical IS concepts to practical, real-time applications. Students applied DT concepts to small-scale prototypes, strengthening engagement, technical proficiency, and preparedness for workforce challenges. However, challenges remain. Cost barriers, educator readiness, multidisciplinary complexity, and gaps between classroom kits and real-world systems all present obstacles to effective adoption. Addressing these requires deliberate curriculum design, targeted faculty development, and partnerships with industry to ensure relevance and scalability.

Future work should employ design science or

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action research approaches to formally evaluate outcomes and adoption strategies. By grounding DT education in established IS standards, while acknowledging challenges and offering practical solutions, this study contributes both a scholarly foundation and a pragmatic model. Ultimately, integrating digital twins into IS programs is critical to preparing students for careers in an increasingly digital, interconnected workforce.

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