

Digital Twin Classrooms for Teacher Training

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ABSTRACT

Digital twin classrooms have emerged as a transformative approach in teacher education by merging advanced simulation technologies with pedagogical theory to create richly detailed virtual environments for instructional rehearsal. Unlike traditional microteaching and peer-role play, digital twin classrooms faithfully replicate not only the physical layout of a real classroom but also the dynamic behaviors, cognitive processes, and emotional responses of diverse learner avatars. This enhanced fidelity allows teacher candidates to engage in repeated practice of lesson delivery, classroom management, and adaptive decision-making under a variety of scripted and emergent scenarios, all within a safe, controlled virtual setting. Drawing on engineering's concept of "digital twins," wherein digital replicas of physical systems support continuous monitoring and iterative refinement, this study adapts those principles to mirror the complexities of real-world teaching. A cohort of 120 preservice and in service teacher trainees participated in a semester-long program integrating scaffolded simulation sessions, real-time performance analytics, and guided reflective debriefings. Quantitative analyses revealed statistically significant gains in instructional performance ($p < 0.001$) and self-efficacy ($p < 0.001$), while qualitative reflections highlighted deeper metacognitive awareness, enhanced risk-tolerant experimentation, and successful transfer of strategies to actual classroom placements. These findings underscore the potential of digital twin classrooms to bridge the theory-practice gap in teacher preparation, offering scalable, data-driven, and ethically sound opportunities for experiential learning. Recommendations for curriculum integration, faculty development, infrastructure requirements, and future research directions are provided to guide educational institutions seeking to adopt this innovation.

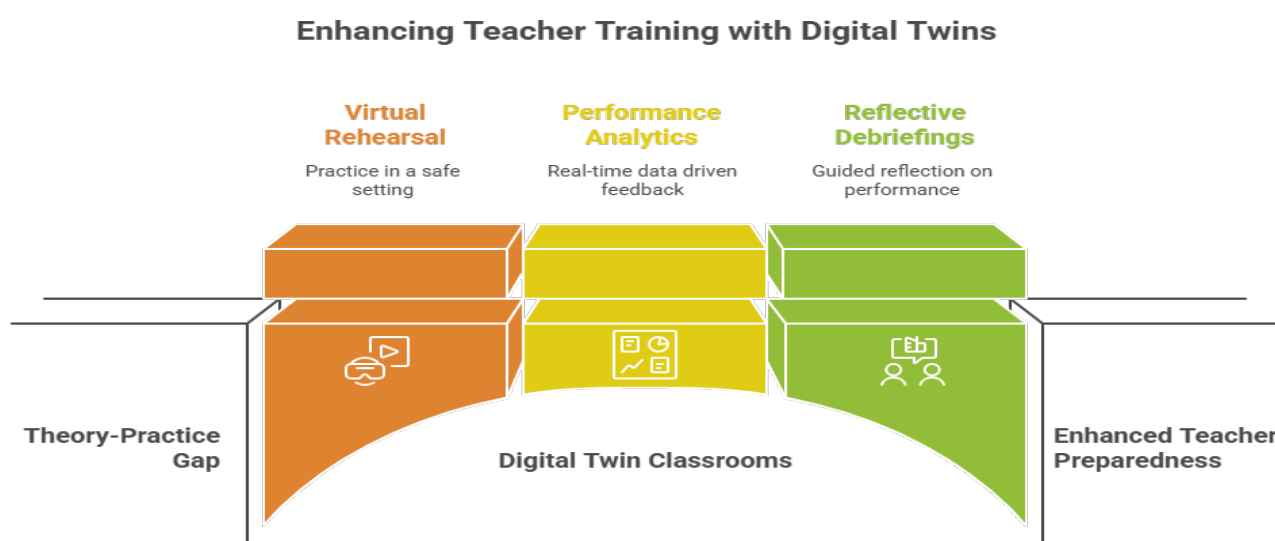


Figure-1. Enhancing Teacher Training with Digital Twins

KEYWORDS

Digital Twin Classrooms, Teacher Training, Immersive Learning, Educational Technology, Professional Development

INTRODUCTION

Teacher education has long grappled with the perennial challenge of preparing candidates for the unpredictability and nuance of real-world classrooms. Traditional practicum models—comprising limited microteaching sessions, classroom observations, and culminating student-teaching placements—often fall short in providing sufficient, varied, and risk-free practice opportunities. Microteaching with peers lacks authenticity, while observations and in-school placements depend heavily on contextual variables (mentor availability, school cooperation, student demographics) that can hamper consistent skill development. As a result, novice teachers frequently report high stress, low confidence, and gaps in classroom management and adaptive instructional decision-making upon entering full-time roles.

Where Simulation Meets Pedagogy in Teacher Education

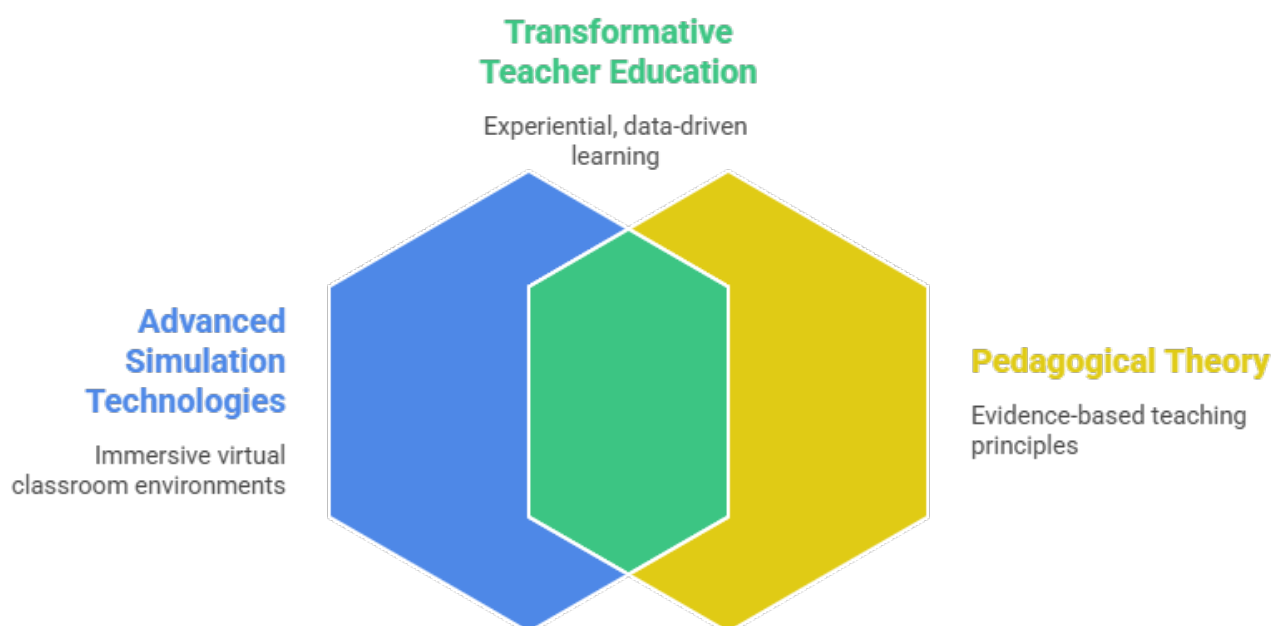


Figure-2. Where Simulation Meets Pedagogy in Teacher Education

Digital twin classrooms propose a paradigm shift by offering high-fidelity, interactive simulations that model both physical and human elements of teaching environments. Originating in engineering and manufacturing domains, the digital twin concept involves creating a real-time digital counterpart of a physical system, continuously synchronized via data streams to enable monitoring, diagnostics, and predictive adjustments. Translating this to teacher education, a digital twin classroom integrates three core components: an accurate three-dimensional rendering of a classroom space; artificial-intelligence-driven student avatars exhibiting realistic learning behaviors, engagement patterns, and emotional dynamics; and analytic engines that capture granular instructional data (e.g., talk ratios, wait times, question types) and deliver immediate feedback.

The theoretical rationale draws on experiential learning and deliberate practice. Kolb's experiential learning cycle emphasizes concrete experience, reflective observation, abstract conceptualization, and active experimentation—stages ideally supported by digital twin technology. Similarly, Ericsson's framework of deliberate practice underscores the need for goal-oriented, repetitive practice with targeted feedback, which virtual environments can systematically provide. By enabling teacher trainees to repeatedly rehearse lessons, receive data-informed feedback, and reflect in guided debriefings, digital twin classrooms align with these foundational learning theories.

This manuscript examines the design, implementation, and evaluation of a digital twin classroom program within a university-affiliated teacher preparation course. It begins with an in-depth literature review situating digital twin classrooms within broader simulation and immersive learning research. The educational implications section articulates how virtual replicas can reshape experiential learning, professional development, and curriculum design in teacher education. A mixed-methods methodology describes the participant cohort, technological platform, data collection instruments, and analytic procedures. Results highlight statistically significant improvements and rich qualitative insights into trainee experiences. The conclusion synthesizes key findings, articulates practical recommendations for program adoption, and outlines avenues for future study to extend the impact of digital twin innovations in teacher training.

LITERATURE REVIEW

Simulation has been a cornerstone of professional training in fields like medicine, aviation, and emergency response, where high-stakes practice without risk to real clients or patients is imperative. Early adoption of simulation in teacher education relied on low-fidelity methods such as peer role-play and video-recorded microteaching, which foster basic reflective skills but lack contextual realism. As immersive technologies evolved, virtual reality (VR) and serious gaming entered the educational sphere, offering more engaging but still relatively static classroom scenarios. Researchers noted that while VR classrooms increased trainee engagement, their preset narratives and limited interactivity constrained authentic decision-making practice.

The digital twin concept, first articulated by Grieves (2014) in the context of smart manufacturing, provides a blueprint for elevating simulation fidelity. A digital twin is continuously linked to its physical counterpart through sensor data and digital feedback loops, enabling real-time monitoring and iterative refinement. In education, Li and Tsai (2020) adapted this model to create classrooms that not only look real but also respond dynamically to instructor actions. AI-driven avatars can simulate off-task behaviors, diverse cognitive profiles (e.g., students with ADHD or English language learners), and socio-emotional cues, presenting teaching challenges that mirror actual classrooms.

Key attributes of effective digital twin classrooms identified in the literature include:

1. **Authentic Spatial Fidelity:** Detailed three-dimensional modeling of classroom layouts, ambient conditions (lighting, acoustics), and instructional artifacts (whiteboards, desks) to immerse trainees in environments analogous to their future placements (Dede & Richards, 2021).
2. **Adaptive Learner Behaviors:** Avatars programmed with distinct learner profiles exhibit varied engagement patterns, questions, misconceptions, and emotional reactions, compelling trainees to practice differentiated instruction and responsive classroom management (Hutt et al., 2022).

3. **Continuous Data Analytics:** Systems track fine-grained teaching variables—such as question types (open vs. closed), student wait times, talk ratios, and feedback frequency—and generate dashboards highlighting strengths and improvement areas (Morris & Mitrovic, 2020).
4. **Scenario Customization:** Faculty can script situational challenges (e.g., technology failures, disruptive behaviors, emergency drills) or allow scenario mutations through stochastic AI processes, ensuring trainees face both anticipated and emergent teaching dilemmas (Wang & Hannafin, 2018).

Empirical evidence indicates that trainees engaged in high-fidelity simulations report greater self-efficacy, a broader repertoire of instructional strategies, and enhanced reflective skills compared to those in traditional practicum-only cohorts. For instance, Liu and Li (2021) demonstrated significant increases in novice teachers' ability to implement wait time strategies and formative assessment techniques following digital twin sessions. However, the literature consistently emphasizes the necessity of structured debriefing; without guided reflection, learners may fail to generalize insights to physical classrooms (Price & Rogers, 2018).

Despite promising outcomes, challenges remain. Technological barriers—costly hardware, bandwidth requirements, and faculty training—limit widespread adoption. Ethical considerations, such as ensuring data privacy of trainee performance logs and preventing avatar stereotyping, also warrant careful attention (Nikolakis & Oliver, 2022). Moreover, longitudinal studies tracking the sustained impact of digital twin experiences on real-world teaching outcomes are scarce, signaling a critical gap for future research.

EDUCATIONAL IMPLICATIONS

The adoption of digital twin classrooms in teacher preparation programs portends significant pedagogical and institutional shifts:

- **Elevated Experiential Learning:** By providing multiple, scaffolded practice opportunities across varied classroom scenarios, digital twins enhance the concreteness of learning experiences. Trainees can cycle through Kolb's experiential learning stages—action, reflection, conceptualization—in rapid succession, deepening mastery of instructional techniques.
- **Precision Professional Development:** Real-time analytics empower both trainees and mentors with actionable data. Visual dashboards illustrate patterns (e.g., excessive teacher talk, insufficient feedback loops) that instructors might overlook, enabling targeted coaching and individualized growth plans aligned with competency frameworks.
- **Scalable Access to Practice:** Physical practicum placements are constrained by school partnerships, mentor availability, and scheduling. Virtual simulations decouple practice from physical site limitations, offering anytime, anywhere access. This scalability is particularly beneficial for distance or hybrid teacher education programs.
- **Data-Informed Curriculum Design:** Aggregated simulation analytics yield insights into common trainee struggles—whether in classroom management, questioning strategies, or differentiation—informing curriculum revisions, resource allocation, and faculty development priorities.
- **Ethical Safe Space:** Virtual environments remove ethical concerns associated with novice teacher missteps in real classrooms (e.g., mishandling behavioral incidents). Trainees can experiment with novel pedagogies, test boundary-pushing strategies, and learn from mistakes without real-world repercussions.
- **Bridging Theory and Practice:** Digital twin classrooms concretize theoretical constructs from educational psychology, classroom management models, and pedagogical frameworks, allowing trainees to see the tangible effects of abstract principles (e.g., behaviorism vs. constructivism) in practice.

Implementation requires strategic alignment across multiple domains. Technologically, institutions must invest in robust simulation platforms, high-performance computing resources, and user-friendly interfaces. Pedagogically, faculty need training in simulation facilitation, debriefing techniques, and data interpretation. Organizationally, curriculum maps must integrate virtual sessions alongside field experiences, ensuring accreditation and licensure standards recognize digital twin practice as a valid component. Finally, ongoing research partnerships with edtech developers can drive iterative platform enhancements and rigorous evaluation of long-term teaching efficacy.

METHODOLOGY

A convergent mixed-methods design was employed to evaluate the effectiveness of digital twin classrooms in enhancing teacher trainees' instructional competencies, confidence, and reflective capacities over a 12-week semester.

Participants

One hundred twenty teacher candidates (60 preservice and 60 inservice) from a mid-sized metropolitan university's teacher education program participated (Mage = 24.7 years; 82 females, 38 males). Participation was voluntary but incentivized through course credit.

Digital Twin Platform

The "ClassSim Twin" environment included:

- A high-fidelity 3D model of an elementary classroom with movable desks, interactive whiteboards, ambient lighting controls, and standard classroom resources.
- Twenty AI-powered student avatars with customizable demographic, cognitive, and socio-emotional profiles (e.g., advanced learners, English language learners, students with behavioral challenges).
- Real-time analytics capturing metrics such as teacher talk ratio, question types, student response wait times, frequency of corrective vs. affirming feedback, and off-task behaviors.
- A scenario editor enabling faculty to script events (e.g., fire drills, technology malfunctions) or allow random behavioral perturbations to test trainee adaptability.

Procedure

1. **Orientation Workshop:** Participants received hands-on training in platform navigation, analytics interpretation, and reflective journaling protocols.
2. **Baseline Simulation (Week 2):** Each trainee conducted a 10-minute lesson on a familiar topic, serving as the pretest. Analytics and rubric-based performance scores (aligned with Interstate Teacher Assessment and Support Consortium standards) were recorded.
3. **Scaffolded Practice Sessions (Weeks 4, 6, 8, 10):** Four biweekly 20-minute simulations targeting: (a) questioning strategies and wait time; (b) classroom management and behavior interventions; (c) differentiation for diverse learners; and (d) socio-emotional support and restorative practices. Each session was followed by a 60-minute guided debrief with faculty, focusing on analytics review and video reflection.

4. **Posttest Simulation (Week 12):** A culminating 15-minute lesson synthesizing all practiced competencies, assessed via the same rubric and analytics metrics.

Data Collection

- **Quantitative:**
 - **Rubric Scores:** Pretest and posttest teaching performance scored by two blind-rated faculty observers (interrater reliability $\kappa = .87$).
 - **Self-Efficacy Survey:** A validated 20-item scale measuring confidence in instructional planning, delivery, and reflection (7-point Likert).
 - **Analytics Metrics:** Platform logs of talk ratio, wait time, feedback frequency, and student off-task rates.
- **Qualitative:**
 - **Reflective Journals:** Weekly entries prompting trainees to describe critical incidents, insights gained, and planned instructional adjustments.
 - **Focus Groups:** Two postsemester focus groups ($n = 12$ each) exploring perceived value, challenges, and suggestions.

Data Analysis

- **Quantitative:** Paired-samples t-tests compared pre- and posttest rubric scores and self-efficacy ratings. Repeated-measures ANOVAs examined changes across scaffolded sessions in analytics metrics.
- **Qualitative:** Thematic analysis of journals and focus group transcripts, following Braun and Clarke's (2006) six-phase framework. Coding was iterative, with peer debriefing to ensure trustworthiness and triangulation with quantitative findings.

RESULTS

Instructional Performance and Self-Efficacy

Posttest rubric scores ($M = 4.23$, $SD = 0.37$) significantly exceeded pretest scores ($M = 3.12$, $SD = 0.48$), $t(119) = 28.47$, $p < .001$, Cohen's $d = 2.60$, indicating large effect size. Self-efficacy survey scores increased from $M = 4.05$ ($SD = 1.08$) to $M = 5.82$ ($SD = 0.91$), $t(119) = 22.13$, $p < .001$, $d = 2.02$.

Analytics Insights

Repeated-measures ANOVAs showed significant linear trends across practice sessions for:

- **Teacher Talk Ratio:** Decreased from 76% at baseline to 58% by session 4, $F(1, 119) = 34.12$, $p < .001$.
- **Average Wait Time:** Increased from 1.4 seconds to 3.1 seconds, $F(1, 119) = 27.89$, $p < .001$.
- **Student Off-Task Rate:** Reduced by 38% from session 1 to session 4, $F(1, 119) = 19.47$, $p < .001$.

Qualitative Themes

Thematic analysis yielded four overarching themes:

1. **Metacognitive Growth:** Trainees reported heightened awareness of habitual patterns—such as prematurely answering student queries—and articulated specific strategies (e.g., scripted wait prompts) to foster student thinking.
2. **Risk-Tolerant Experimentation:** Participants valued the “safe failure” ethos, trying novel questioning techniques and behavior-management approaches without fear of harming real students.
3. **Transference to Real Classrooms:** Many integrated simulation-derived practices—structured wait time, differentiated questioning, proactive behavior cues—into their school placements, reporting positive learner engagement and improved classroom climate.
4. **Desire for Expanded Scenarios:** Feedback highlighted a need for varied age group settings (middle/high school), collaborative teaching modules, and integration of parent-teacher meeting simulations to broaden applicability.

Collectively, the results affirm that digital twin classrooms can accelerate novice teacher development across cognitive, pedagogical, and affective domains.

CONCLUSION

This study demonstrates that integrating digital twin classrooms into teacher preparation yields substantial gains in instructional performance, self-efficacy, and reflective practice. By enabling iterative rehearsal of teaching scenarios within richly detailed virtual environments—and coupling practice with data-driven feedback and guided reflection—trainees bridge the theory-practice divide more effectively than through traditional methods alone. The scalable, risk-free nature of simulations democratizes access to high-quality practice, particularly for distance learners or programs constrained by limited field placements.

For institutions aiming to adopt digital twin classrooms, key considerations include: securing robust computing infrastructure; partnering with edtech vendors to customize learner avatar profiles; training faculty in simulation pedagogy and analytics interpretation; and aligning virtual experiences with accreditation standards and competency frameworks. Future research should pursue longitudinal studies tracking teacher retention, classroom observational data, and student learning outcomes linked to simulation participation. Furthermore, exploring collaborative simulations—where teams of trainees co-teach in virtual settings—could extend insights into co-planning, coordination, and peer feedback.

As educational ecosystems embrace digital transformation, digital twin classrooms offer a promising avenue for equipping future educators with the adaptive expertise, confidence, and reflective capacity required in increasingly complex learning environments. Through continued innovation, rigorous evaluation, and thoughtful integration, digital twin technology stands poised to redefine experiential learning in teacher education and beyond.

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