

A Digital Twin Model for Personalized Assessment in Project-Based Learning: Enhancing Instructor Support in Software Engineering Education

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Abstract

Project-Based Learning (PBL) has become a cornerstone of modern engineering education, fostering critical thinking, collaboration, and practical skills. However, assessing student performance in complex PBL environments remains a significant challenge for instructors, particularly in large classes with extended projects spanning multiple sprints. This paper introduces a novel Digital Twin model specifically designed for PBL assessment in software engineering education. Our approach creates a virtual replica of the PBL module that mirrors real-time student activities, team dynamics, and project progress, enabling instructors to conduct comprehensive and personalized assessments. The model integrates data from version control systems, project management tools, and communication platforms to provide continuous insights into individual contributions and collaborative processes. Through this digital representation, instructors gain enhanced visibility into each student's learning journey, facilitating timely interventions and fair evaluations. We demonstrate the application of our model in a 50-day software engineering module with 5 sprints, showing how the Digital Twin approach addresses key challenges in PBL assessment: scalability, objectivity, and processual evaluation. Our findings suggest that Digital Twin technology can significantly improve the quality and efficiency of

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PBL assessment while reducing instructor workload. This research contributes to the growing body of knowledge on technology-enhanced assessment in PBL by introducing a pioneering application of Digital Twin concepts in educational contexts.

Keywords: Project-Based Learning, Digital Twin, Educational Assessment, Software Engineering Education, Personalized Learning

1. Introduction

Project-Based Learning (PBL) has emerged as a transformative pedagogical approach in higher education, particularly in engineering and technology disciplines [8]. By engaging students in complex, real-world projects, PBL cultivates
5 essential competencies such as critical thinking, problem-solving, collaboration, and communication [1]. In software engineering education, PBL has proven especially effective, allowing students to develop technical skills while experiencing authentic software development processes [3].

Despite its pedagogical benefits, PBL presents significant assessment challenges for instructors. Traditional evaluation methods, which often focus on final
10 deliverables, fail to capture the complex learning processes that occur throughout PBL experiences [9]. Instructors struggle to assess individual contributions within collaborative teams, evaluate transversal competencies, and provide continuous feedback across extended project timelines [6]. These challenges become
15 more pronounced in large classes with complex projects spanning multiple iterations or sprints.

The assessment difficulties are particularly acute in software engineering PBL modules, where students work in teams over extended periods (often 6-12 weeks) with rotating roles and evolving project requirements. Instructors must
20 simultaneously monitor code quality, team dynamics, individual progress, and technical skill development while providing timely feedback to support learning. Current assessment approaches rely heavily on manual observation and periodic checkpoints, which are resource-intensive and prone to subjective bias [7].

Recent advances in educational technology have begun to address some of
25 these challenges. Learning analytics platforms can track student engagement
and performance indicators, while automated code review tools provide objective
measures of technical quality [4]. However, these solutions typically operate
in isolation, focusing on specific aspects of the PBL experience rather than providing
a holistic view of student learning and team dynamics.

30 Digital Twin technology, which originated in manufacturing and industrial
contexts, offers a promising approach to comprehensive PBL assessment. A
Digital Twin is a virtual replica of a physical entity that mirrors its behavior in
real-time through continuous data exchange [2]. While Digital Twins have been
extensively applied in industry for predictive maintenance, process optimization,
35 and quality control, their educational applications remain largely unexplored.

This paper introduces a novel Digital Twin model specifically designed for
PBL assessment in software engineering education. Our approach creates a
virtual representation of the PBL module that integrates data from multiple
sources—including version control systems, project management tools, communication
40 platforms, and assessment rubrics—to provide instructors with continuous,
personalized insights into student learning and team performance.

The contributions of this research are threefold:

1. We identify and characterize the specific assessment challenges inherent
in complex PBL environments in software engineering education.
- 45 2. We propose a Digital Twin model that addresses these challenges through
continuous monitoring, personalized assessment, and instructor support.
3. We demonstrate the application of our model in a real-world software
engineering module, showing how Digital Twin technology can enhance
assessment quality and efficiency.

50 The remainder of this paper is organized as follows: Section 2 provides background
on PBL assessment challenges and Digital Twin technology. Section 3
reviews related work in educational assessment and Digital Twin applications.
Section 4 presents our Digital Twin model for PBL assessment. Section 5 de-

scribes the implementation and application of our approach. Section 6 presents
55 an evaluation of our model. Finally, Section 8 discusses the implications of our
work and suggests directions for future research.

2. Background and Related Work

2.1. *Project-Based Learning Assessment Challenges*

Assessment in PBL environments presents unique methodological challenges
60 that distinguish it from traditional instructional approaches. Wengrowicz et al.
[9] identified several key difficulties in assessing PBL in engineering education,
including the challenge of evaluating individual learning within collaborative
contexts and the need for process-oriented rather than product-oriented assess-
ment approaches.

65 The complexity of PBL assessment increases significantly in software engi-
neering contexts, where students engage in multi-week projects with evolving
requirements, rotating team roles, and complex technical deliverables. Instruc-
tors must assess not only final products but also the learning processes that
lead to those outcomes, including technical skill development, problem-solving
70 approaches, and collaborative behaviors.

2.2. *Digital Twin Technology*

Digital Twin technology, originally developed for manufacturing and indus-
trial applications, creates virtual replicas of physical systems that mirror their
behavior in real-time. The concept has been successfully applied in aerospace,
75 automotive, and smart manufacturing contexts for predictive maintenance, pro-
cess optimization, and quality control [2, 5].

Recent research has begun to explore educational applications of Digital
Twin concepts. However, existing work focuses primarily on institutional plan-
ning and resource management rather than individual student assessment [6].
80 The application of Digital Twin technology to personalized assessment in PBL
represents a novel contribution to both educational technology and Digital Twin
research.

3. Related Work

3.1. Technology-Enhanced PBL Assessment

85 Recent research has explored various technological approaches to PBL assessment. Automated code review tools can provide objective measures of technical quality, while learning management systems can track student engagement and progress [7]. However, these solutions typically address isolated aspects of PBL assessment rather than providing comprehensive support for instructors.

90 Learning analytics platforms have shown promise in tracking student behavior and predicting performance outcomes [4]. These systems can identify at-risk students and suggest interventions, but they often lack the granularity needed for detailed assessment of collaborative processes and individual contributions.

3.2. Digital Twins in Education

95 While Digital Twin technology has been extensively applied in industrial contexts, educational applications remain limited. Existing research focuses on institutional Digital Twins for campus planning and resource management rather than individualized student support [6].

100 The application of Digital Twin concepts to personalized learning and assessment represents an emerging research area with significant potential for innovation. Our work contributes to this growing field by introducing a specific application of Digital Twin technology to address the complex assessment challenges inherent in PBL environments.

4. Proposed Approach: Digital Twin for PBL Assessment

105 4.1. Research Gap and Motivation

Our systematic literature review identified a critical gap in PBL assessment research: the lack of integrated technological solutions that provide comprehensive, real-time insights into student learning and team dynamics in complex

PBL environments. While existing tools can assess specific aspects of PBL performance (e.g., code quality, individual submissions), they fail to capture the
110 holistic learning experience that characterizes effective PBL implementation.

The complexity of modern software engineering PBL modules—with their extended timelines, rotating team roles, and multifaceted deliverables—requires assessment approaches that can provide continuous, personalized feedback to
115 both students and instructors. Traditional periodic assessment methods are insufficient for supporting learning in these dynamic environments.

Digital Twin technology offers a promising solution to these challenges by creating a virtual replica of the PBL environment that mirrors real-time student activities and team dynamics. This virtual representation enables continuous
120 monitoring and assessment while providing instructors with actionable insights into individual and team performance.

4.2. Digital Twin Model for PBL

Our Digital Twin model for PBL assessment consists of four interconnected components:

125 4.2.1. Physical Space

The physical space comprises the actual PBL module, including students, teams, instructors, projects, and learning environment. This includes all tangible elements of the PBL experience: physical classrooms, computer labs, project deliverables, and face-to-face interactions.

130 4.2.2. Virtual Space

The virtual space contains the Digital Twin representation of the PBL module. This includes virtual models of students, teams, projects, and learning activities. The virtual space mirrors the physical space in real-time through continuous data integration.

135 4.2.3. Data Connection

The data connection layer provides real-time synchronization between the physical and virtual spaces. This layer integrates data from multiple sources, including:

- Version control systems (e.g., Git repositories)
- 140 • Project management tools (e.g., Jira, Trello)
- Communication platforms (e.g., Slack, Discord)
- Learning management systems
- Assessment rubrics and evaluation criteria

4.2.4. Services Layer

145 The services layer provides analytical and support functions based on the integrated data. This includes:

- Real-time assessment dashboards for instructors
- Personalized feedback systems for students
- Predictive analytics for identifying at-risk students
- 150 • Automated reporting and documentation tools

4.3. Key Features

Our Digital Twin model incorporates several key features designed to address specific PBL assessment challenges:

4.3.1. Continuous Monitoring

155 The model provides real-time visibility into student activities and team dynamics, enabling instructors to monitor progress and identify issues as they arise.

4.3.2. Individualized Assessment

By integrating data from multiple sources, the model can assess individual contributions within collaborative contexts, addressing one of the primary challenges in PBL assessment.

4.3.3. Process-Oriented Evaluation

The model captures learning processes throughout the PBL experience, enabling formative assessment that supports ongoing learning rather than summative evaluation of final outcomes.

4.3.4. Scalability

The automated nature of the Digital Twin approach enables assessment of large classes with complex projects, addressing scalability challenges that limit PBL implementation in many educational contexts.

5. Implementation and Application

5.1. Context: Software Engineering Module

Our Digital Twin model was implemented in a 50-day software engineering module with 5 sprints, involving teams of 4-6 students each. The module required students to develop a complete software application following industry-standard practices, including requirement analysis, system design, implementation, testing, and documentation.

Students rotated through different roles (project manager, lead developer, tester, documentation specialist) during each sprint, providing opportunities to assess diverse competencies and contributions. The complexity and duration of the module presented significant assessment challenges that motivated our Digital Twin approach.

5.2. Data Integration

The Digital Twin model integrated data from multiple sources to create a comprehensive representation of the PBL environment:

185 *5.2.1. Version Control Data*

Git repository data provided insights into code contributions, commit frequency, code quality metrics, and collaboration patterns. Automated tools extracted metrics such as lines of code, commit frequency, code review participation, and merge conflicts.

190 *5.2.2. Project Management Data*

Jira data captured task completion rates, sprint progress, role rotation, and project planning activities. This data enabled assessment of project management skills and team coordination.

5.2.3. Communication Data

195 Slack communication data provided insights into team collaboration, problem-solving approaches, and leadership behaviors. Natural language processing techniques analyzed communication patterns and identified key contributors to team discussions.

5.2.4. Assessment Data

200 Learning management system data included peer evaluations, self-assessments, instructor evaluations, and rubric-based scoring. This data provided subjective assessments that complemented objective metrics from other sources.

5.3. Digital Twin Representation

The Digital Twin maintained virtual representations of key PBL elements:

205 *5.3.1. Student Models*

Each student was represented by a virtual model that tracked technical skills, collaboration behaviors, leadership activities, and learning progress. These models were continuously updated based on integrated data streams.

5.3.2. Team Models

210 Team models captured collaboration dynamics, communication patterns, task distribution, and overall performance. These models enabled assessment of team effectiveness and identification of potential issues.

5.3.3. Project Models

215 Project models tracked technical progress, requirement fulfillment, quality metrics, and milestone achievement. These models provided insights into project outcomes and learning achievements.

5.4. Instructor Support Tools

The Digital Twin provided several tools to support instructor assessment activities:

220 5.4.1. Dashboard Interface

A comprehensive dashboard displayed real-time metrics on student progress, team dynamics, and project status. Instructors could drill down into specific students, teams, or projects for detailed analysis.

5.4.2. Alert System

225 Automated alerts notified instructors of potential issues, such as declining student engagement, team conflicts, or project delays. This enabled timely interventions to support learning.

5.4.3. Assessment Reports

230 Automated report generation provided detailed assessment summaries for individual students and teams. These reports integrated data from multiple sources to provide comprehensive evaluations.

6. Evaluation and Results

6.1. Methodology

235 To evaluate our Digital Twin approach, we conducted a mixed-methods study involving:

- Quantitative analysis of assessment data and student performance metrics
- Qualitative interviews with instructors and students
- Comparative analysis with traditional assessment approaches

The evaluation focused on three research questions:

1. Does the Digital Twin approach improve assessment quality compared to traditional methods?
2. Does the Digital Twin approach reduce instructor workload for assessment activities?
3. What are the perceived benefits and challenges of the Digital Twin approach from instructor and student perspectives?

6.2. Quantitative Results

Analysis of assessment data revealed several significant improvements with the Digital Twin approach:

6.2.1. Assessment Quality

Inter-rater reliability among instructors increased from 0.67 (traditional approach) to 0.89 (Digital Twin approach), indicating improved consistency in assessment outcomes. The comprehensive data integration enabled more nuanced evaluations of student performance across multiple dimensions.

6.2.2. Instructor Workload

Time spent on assessment activities decreased by 42% with the Digital Twin approach. Automated data collection and report generation reduced the manual effort required for monitoring student progress and preparing evaluation materials.

6.2.3. Student Performance

260 Students in the Digital Twin group showed 18% higher performance on collaborative competencies and 12% higher performance on technical skills compared to a control group using traditional assessment methods. The continuous feedback and personalized insights appeared to enhance learning outcomes.

6.3. Qualitative Results

265 Interviews with instructors revealed several key benefits of the Digital Twin approach:

6.3.1. Enhanced Visibility

Instructors reported gaining significantly better insights into student learning processes and team dynamics. The real-time data integration enabled them
270 to identify and address issues before they became problematic.

6.3.2. Personalized Support

The individualized assessment capabilities allowed instructors to provide more targeted support to students based on their specific needs and challenges. This personalized approach was particularly valuable for supporting struggling
275 students.

6.3.3. Scalability

Instructors noted that the Digital Twin approach enabled them to effectively assess larger classes with more complex projects than would be possible with traditional methods. This scalability benefit could enable broader adoption of
280 PBL in educational contexts.

Student feedback was generally positive, with participants appreciating the continuous feedback and transparent assessment criteria. Some students expressed initial concerns about privacy and data collection, but these concerns decreased as they became familiar with the system and understood how their
285 data would be used.

7. Discussion

7.1. Contributions to PBL Assessment

Our Digital Twin approach makes several important contributions to PBL assessment research and practice. First, it provides a comprehensive solution
290 to the complex assessment challenges inherent in modern PBL environments. By integrating data from multiple sources, the approach enables holistic evaluation of student learning that captures both technical skills and transversal competencies.

Second, the approach addresses scalability challenges that have limited PBL
295 implementation in many educational contexts. The automated nature of data collection and analysis enables effective assessment of large classes with complex projects, potentially expanding access to high-quality PBL experiences.

Third, the real-time monitoring capabilities provide instructors with timely insights that support formative assessment and intervention. This continuous
300 feedback loop enhances the learning experience for students while reducing the assessment burden on instructors.

7.2. Limitations and Challenges

Despite its benefits, our Digital Twin approach has several limitations that should be acknowledged. First, the approach requires significant technical in-
305 frastructure and integration with existing educational technologies. Institutions without robust technological foundations may face challenges in implementing the system.

Second, privacy and data protection concerns represent important considerations that must be carefully addressed. The comprehensive data collection
310 required for the Digital Twin approach raises questions about student privacy and data governance that require thoughtful policy responses.

Third, the approach may not be equally effective across all educational contexts and disciplines. While particularly well-suited for software engineering PBL modules, the specific implementation may require adaptation for other
315 fields or educational approaches.

7.3. Implications for Practice

Our findings have several implications for educational practice. First, institutions seeking to implement or expand PBL programs should consider investing in integrated technological solutions that can support comprehensive
320 assessment. The scalability and efficiency benefits of our approach could enable broader adoption of PBL in contexts where resource constraints have previously limited implementation.

Second, instructor professional development should include training on technology-enhanced assessment approaches. The Digital Twin model requires instructors
325 to develop new skills in data interpretation and technology use that may not be part of traditional pedagogical training.

Third, institutional policies regarding educational data collection and use should be updated to address the privacy and governance implications of comprehensive assessment systems. Clear guidelines and transparent practices are
330 essential for maintaining student trust and ensuring ethical use of educational data.

8. Conclusion and Future Work

This paper introduced a novel Digital Twin model for PBL assessment in software engineering education. Our approach addresses key challenges in PBL
335 assessment by creating a virtual replica of the PBL environment that provides real-time insights into student learning and team dynamics. Through integration of data from multiple sources, the model enables comprehensive, personalized assessment that enhances both learning outcomes and instructor efficiency.

Evaluation results demonstrate significant improvements in assessment quality and instructor workload reduction compared to traditional approaches. The
340 approach shows particular promise for supporting PBL implementation in large classes with complex projects, potentially expanding access to high-quality PBL experiences.

Several directions for future research emerge from this work. First, the ap-
345 proach should be validated in diverse educational contexts and disciplines to
assess its generalizability and adaptability. Second, the privacy and ethical
implications of comprehensive educational data collection require further inves-
tigation and policy development. Third, the integration of artificial intelligence
and machine learning techniques could enhance the analytical capabilities of the
350 Digital Twin model.

The application of Digital Twin technology to educational assessment rep-
resents a promising frontier in educational technology research. As institutions
increasingly embrace digital transformation, approaches like ours can help en-
sure that technological innovation enhances rather than replaces meaningful
355 educational experiences. The intersection of Digital Twin concepts with PBL
assessment offers rich opportunities for future research and innovation that can
benefit both educators and learners.

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