Enhancing Computational Thinking through Project-Based Learning: A Structured Framework and Empirical Analysis

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ABSTRACT: *This research investigates the integration of project-based learning with computational thinking to develop an effective instructional framework. The study aimed to: 1) develop a conceptual framework for project-based learning that enhances computational thinking, 2) construct a practical model derived from this framework, and 3) evaluate the post-intervention learning outcomes. The research instruments comprised a structured project-based learning process and a validated assessment tool for computational thinking skills. The results revealed that 83.87% of the participants (n=31) demonstrated proficiency in computational thinking skills after engaging with the learning process, exceeding the established threshold of 80%. The framework exhibited a high degree of reliability (α=0.81), while the assessment tool demonstrated appropriate difficulty indices (p=0.32-0.74) and discrimination indices (r=0.37-0.76). The efficacy of this approach is attributed to its facilitation of iterative development through hands-on problem-solving activities that produce tangible outcomes. This study contributes to educational methodology by providing an empirically-validated framework that systematically develops computational thinking through project-based experiences.*

Keywords: Project-based learning, Computational thinking, Iterative development, Instructional design, Educational framework.

1. Introduction

Contemporary educational paradigms emphasize the importance of learner-centered approaches that cultivate practical competencies and the critical thinking skills necessary for addressing real-world challenges (UNESCO, 2023). Within this context, educational institutions face mounting pressure to develop pedagogical frameworks that effectively bridge theoretical knowledge with practical applications while fostering innovation capabilities (Cuyacot & Cuyacot, 2022). Despite significant advancements in educational technology and methodologies, a persistent gap exists between academic learning outcomes and the complex skill requirements of modern workplaces and social environments (Khlaisang et al., 2023). This gap is particularly evident in the development of computational thinking - a fundamental cognitive skill increasingly recognized as essential for navigating today's technology-driven landscape. Current educational approaches often fail to effectively nurture this critical competency within authentic contexts, creating a significant need for innovative pedagogical frameworks (Shin et al., 2021). Project-based learning (PBL) has emerged as a promising instructional approach that directly addresses this gap through its emphasis on authentic, experiential learning. PBL methodologies engage learners in structured project activities that simulate real-world scenarios, thereby fostering critical thinking, problem-solving capabilities, and the collaborative skills essential for the 21st century workplace (Wannapiroon & Pimdee, 2022). Research indicates that PBL implementations yield significant improvements in learner motivation, knowledge retention, and practical skill development across diverse educational contexts (Yang et al., 2024). Concurrently, computational thinking has been recognized as a fundamental cognitive framework that enhances systematic problem-solving abilities which are applicable across disciplines. However, research examining the systematic integration of computational thinking within PBL frameworks remains limited, particularly regarding empirically-validated models for implementation across different educational levels (Ashraf et al., 2025). This research gap is particularly significant given the growing emphasis on digital literacy and technological competence in contemporary education systems (Qassrawi, 2023). The present study addresses this research gap by developing and empirically- validating a structured framework that integrates computational thinking principles within PBL methodologies. By establishing clear parameters for such an integration, and assessing its impact on learning outcomes, this research contributes to the advancement of educational practices that effectively prepare learners for the complex challenges of contemporary society and workplace environments (Istiningsih et al., 2024).

2. Research Objectives and Hypotheses

This study aimed to accomplish the following objectives:

1. To develop a conceptual framework for a PBL process aimed at enhancing computational thinking.
2. To construct a model of the PBL process to foster computational thinking.
3. To examine the outcomes of employing PBL processes for promoting computational thinking, focusing on post-learning achievement.

Hypotheses

More than 80% of learners who participate in the PBL process will achieve the established proficiency threshold in computational thinking.

3. Literature Review

3.1 Project-Based Learning

Project-based learning (PBL) represents a transformative pedagogical framework in which educators play a pivotal role in fostering learner engagement and cultivating an active, participatory educational environment. Rooted in John Dewey's seminal philosophy of "Learning by Doing", PBL emphasizes the importance of experiential learning, integrating real-world applications in such a way as to enhance students' acquisition of essential skills and knowledge (Efstratia, 2014; Chronicles, 2023). This instructional methodology has evolved significantly since its inception, with its foundation in the progressive education movement of the late 19th and early 20th centuries. Educational pioneers such as Dewey championed experiential and inquiry-driven approaches, recognizing their potential to deepen learners' conceptual understanding, critical thinking, and problem-solving abilities (Shin et al., 2021). PBL prioritizes active and experiential learning, emphasizing the execution of structured, project-based activities. This approach is instrumental in developing critical competencies, including problem-solving, collaboration, and effective communication, all of which are essential in contemporary educational contexts (Ozkan, 2023; Koednet & Phaudjantuk, 2021). Widely acknowledged for its efficacy, PBL engages students by connecting academic concepts to real-world challenges, promoting a deeper understanding of subject matter (Arochman et al., 2024). In today's technology-driven society, PBL has emerged as a pivotal framework in modern education systems, particularly when integrated with computational thinking, a critical skill set for navigating and innovating within technologically-advanced environments (Wanglang & Chatwattana, 2023).

PBL has demonstrated particular effectiveness in vocational and technical education, especially within the Thai context, where it fosters meaningful, hands-on learning experiences. Research highlights a structured five-step process for implementing PBL in vocational settings: preparation, topic selection, creation and testing, presentation, and evaluation (Nilsook et al., 2021). This model aims to equip students with the skills necessary to design innovative projects and inventions, while simultaneously fostering attributes critical to 21st century education and professional landscapes. These include presentation skills, effective communication, interpersonal collaboration, critical thinking, creativity, and problem-solving (Plailek et al., 2023). The implementation of PBL in vocational education aligns with expert recommendations advocating for the alignment of teacher and student roles in order to ensure cohesive and effective learning experiences. This process not only provides a framework for managing vocational education curricula but also addresses the dynamic demands of modern educational and professional contexts by nurturing lifelong learning, adaptability, and innovation (Wannapiroon et al., 2022).

3.2 Computational Thinking

Computational thinking (CT) represents a systematic approach to problem-solving derived from principles of computer science but applicable across disciplines. It involves breaking down complex problems, recognizing patterns, abstracting essential information, and developing algorithmic solutions. This cognitive framework enhances analytical capabilities and supports methodical approaches to addressing challenges in both academic and real-world contexts (Muhammad et al., 2023). The theoretical foundation of CT is grounded in four fundamental components that collectively form its cognitive architecture:

1. Decomposition: The systematic breakdown of complex problems into smaller, manageable constituent elements, akin to the modularization of large-scale projects into discrete, actionable tasks.
2. Pattern Recognition: The identification and analysis of recurring structures and similarities within problem spaces, facilitating the transfer and adaptation of problem-solving strategies across diverse contexts and domains.
3. Abstraction: The cognitive ability to isolate and prioritize essential information while filtering out extraneous details, analogous to constructing conceptual models that emphasize critical relationships while excluding irrelevant elements.
4. Algorithm Design: The development of systematic, repeatable procedures for problem resolution, characterized by a precise sequencing and logical progression of steps that ensure consistency and reliability in achieving desired outcomes (Dia et al., 2024; Rahmawati et al., 2024).

The implementation of CT demonstrates significant utility in everyday contexts, enhancing problem-solving efficacy across diverse domains. This framework supports systematic approaches to time management, project planning, and decision-making processes, extending its relevance beyond computational contexts. It offers a structured methodology for addressing challenges in both professional and personal spheres, making it a versatile tool for contemporary problem-solving (Prahmana et al., 2024; Koednet et al., 2021). The cultivation of CT competencies has become a critical imperative for modern society, extending beyond its traditional association with computer science and information technology. This cognitive framework enhances analytical capabilities and fosters systematic problem-solving skills, both of which are essential for navigating the complexities of the contemporary digital landscape. Integrating CT principles into educational curricula and professional development programs is vital for equipping individuals with these critical cognitive skills (Ugur & Çakiroglu, 2024). In conclusion, CT represents a sophisticated cognitive framework that provides a systematic and robust methodology for problem-solving in the digital age. Its principles continue to evolve, offering valuable tools for addressing complex challenges across diverse domains. The ongoing development and refinement of CT competencies remain indispensable for effective problem-solving, innovation, and decision-making in contemporary contexts shaped by rapid technological and societal advances (Yang et al., 2025).

3.3 Integration of PBL and Computational Thinking

Recent studies have begun to explore the potential synergies between PBL and CT. Shin et al. (2021) demonstrated that structured PBL activities can serve as effective vehicles for developing CT skills when appropriately designed. Their research highlighted that projects requiring systematic problem decomposition, pattern analysis, and algorithmic thinking resulted in measurable improvements in students' CT capabilities. However, a significant gap exists in the literature regarding structured frameworks that systematically integrate PBL and CT across different educational contexts. While previous research has established the individual merits of each approach, comprehensive models that explicitly delineate how PBL processes can be aligned with CT development remain underdeveloped (Zapata-Cáceres et al., 2024). This study addresses this gap by developing and validating such an integrated framework.

4. Research Framework

This research establishes a conceptual framework that systematically integrates PBL with CT to create a cohesive instructional model. The framework positions CT as the intended learning outcome, while PBL serves as the methodological approach to achieving this outcome. Figure 1 presents the conceptual framework of the research.

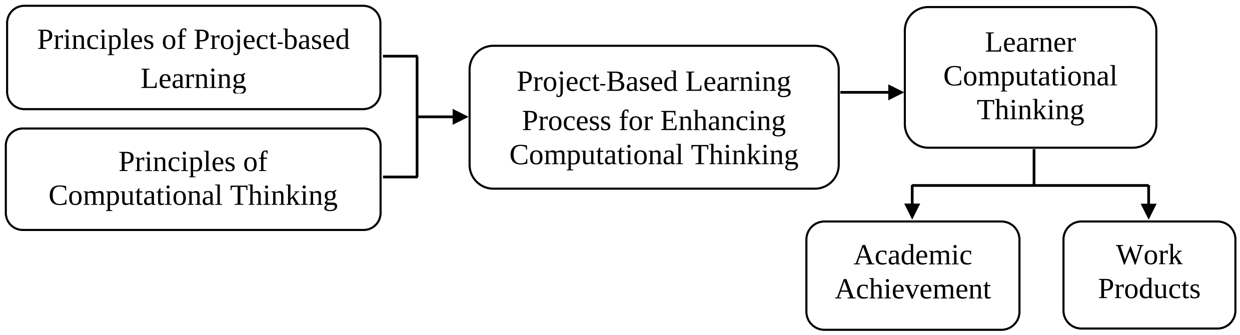

Figure 1: Research Conceptual Framework

The framework illustrates how the principles of PBL and CT are synthesized to form an integrated pedagogical process. This process is designed to facilitate the development of CT skills in learners, which is evaluated through two distinct outcomes: academic achievement (as measured by assessment instruments) and tangible work products created during the learning process.

5. Methodology

5.1 Research Design and Participants

This study employed a mixed-methods research design, incorporating both qualitative approaches for framework development and quantitative methods for outcome assessment. The integrated learning process was implemented with the support of 31 vocational education students enrolled in a Programming Principles course at Samut Songkhram Polytechnic College, Thailand. All participants were in their second year of study and had basic programming knowledge but limited exposure to systematic computational thinking instruction.

5.2 Research Instruments

The study utilized two primary research instruments:

1. PBL Process Framework: A structured instructional framework designed to integrate CT principles within PBL activities. This framework was developed through a synthesis of relevant literature and validated by a panel of five experts in educational technology and computer science. The implementation spanned 10 weeks with 3 hours of instruction per week, structured around programming projects that systematically incorporated CT components.
2. CT Assessment Tool: A validated 20-item assessment instrument designed to measure CT proficiency across the four dimensions of decomposition, pattern recognition, abstraction, and algorithmic thinking. The instrument underwent content validation by five subject matter experts (IOC = 0.82) and was piloted with 30 students not participating in the main study to establish reliability (KR-20 = 0.81) prior to implementation.

5.3 Data Collection and Analysis

The research methodology was structured into three sequential phases:

Phase 1: Literature Review and Framework Development

An extensive study and synthesis of academic literature related to PBL and CT was conducted to establish the conceptual framework. This involved a systematic review of articles published between 2014 and 2025.

Phase 2: Development and Validation of the Learning Process

A PBL process tailored to promote CT was developed based on the conceptual framework established in Phase 1. The developed framework was validated by a panel of experts using a structured evaluation form with a 5-point Likert scale across nine dimensions of pedagogical effectiveness. The framework was refined based on expert feedback prior to implementation.

Phase 3: Implementation and Evaluation of Learning Outcomes

The effectiveness of the developed learning process was assessed through implementation with the participant group. Pre-assessment and post-assessment of computational thinking skills were conducted, and student project outputs were evaluated using a standardized rubric. Statistical analyses included the use of descriptive statistics, reliability analysis (KR-20), item analysis (difficulty and discrimination indices), and hypothesis testing against the 80% achievement criterion.

6. Results

6.1 Synthesis of the Project-Based Learning Process for Computational Thinking

The study synthesized PBL processes from multiple theoretical sources (Efstratia, 2014; Kerdpol, 2015; Nilsook et al., 2021; Kamiri, 2023; Yuyu Wahyudin, 2023) to develop a comprehensive five-step process: 1) Preparation, 2) Defining and Selecting Topics, 3) Planning and Project Operations, 4) Implementation and Project Evaluation, and 5) Presentation.

Table 1: Project-Based Learning Process

Project-Based Learning Process	(Efstratia, (2014	(Kerdpol, (2015	(Nilsook et al., 2021)	(Kamiri, (2023	(Yuyu Wahyudin, (2023
1. Preparation	✓	✓	✓	✓	✓
2. Define and Selecting Topics	✓	✓	✓	✓	✓
3. Writing the Outline of the Project	✓	✓	✓	✓	✓
4. Plan and Project Operations	✓	✓	✓	✓	✓
5. Implementation and Project Evaluation	✓	✓	✓	✓	✓
6. Presentation	✓	✓	✓	✓	✓

Similarly, computational thinking was synthesized from the relevant literature (Li et al., 2020; Repenning et al., 2023; Dia et al., 2024; Rahmawati et al., 2024; Zapata-Cáceres et al., 2024) into four key components: 1) Decomposition, 2) Pattern Recognition, 3) Abstraction, and 4) Algorithm Design.

Table 2: Computational Thinking

Computational Thinking	(Li et al., 2020)	(Repenning et al., 2023)	(Dia et al., 2024)	(Rahmawati et al., 2024)	(Zapata-Cáceres et al., (2024
1. Decomposition	✓	✓	✓	✓	✓
2. Pattern Recognition	✓	✓	✓	✓	✓
3. Abstraction	✓	✓	✓	✓	✓
4. Algorithm Design	✓	✓	✓	✓	✓

The integration of these elements resulted in the development of an aligned framework that maps specific PBL stages to CT components, as shown in Table 3.

Table 3: Alignment of Project-Based Learning Process with Computational Thinking Components

Project-Based Learning Process	Teaching and Learning Process Description	Computational Thinking Component
1. Preparation	Setting the groundwork by establishing objectives, providing foundational knowledge, and preparing resources to support student engagement.	1. Decomposition
2. Define and Select Topics	Identifying and selecting topics that align with interests and learning goals, emphasizing relevance and contextualization.	2. Pattern Recognition
3. Plan and Project Operations	Developing structured project plans with specific objectives, timelines, and methodologies to foster organizational skills.	3. Abstraction
4. Implementation and Evaluation	Conducting project activities while continuously evaluating progress, reflecting on effectiveness, and making adjustments.	4. Algorithm Design
5. Presentation	Presenting completed projects to stakeholders, promoting communication skills and critical reflection.	Integration of all Computational Thinking components

6.2 The Integrated Framework Model

Based on the synthesis and alignment described above, as illustrated in Figure 2, a comprehensive model of the PBL process to promote CT was developed.

Figure 2: The Project-Based Learning Process to Promote Computational Thinking Model

The model illustrates the integration of the five stages of the PBL approach (Preparation, Definition, Planning, Implementation, and Presentation) with the four components of CT (Decomposition, Pattern Recognition, Abstraction, and Algorithm Design). Each stage of the PBL process was designed to emphasize and develop specific CT competencies, creating a comprehensive and synergistic educational framework. The model was validated by a panel of five experts in educational technology and computer science, yielding a mean suitability rating of 4.52 (SD = 0.31) on a 5-point scale, indicating high appropriateness for implementation in vocational education settings.

6.3 Assessment of Learning Outcomes

The post-implementation assessment of CT skills revealed significant development on the part of the participants. The quality analysis of the assessment instrument demonstrated appropriate psychometric properties, with a difficulty index (p) ranging from 0.32 to 0.74 (indicating moderate difficulty) and a discrimination index (r) ranging from 0.37 to 0.76 (indicating good differentiation capability). The overall reliability coefficient (KR-20) was 0.81, demonstrating high internal consistency. In terms of achievement outcomes, 26 out of the 31 learners (83.87%) demonstrated proficiency in CT in terms of the established criteria, exceeding the hypothesized threshold of 80%. The mean score on the 20-item post-assessment was 16.2 points (81%), a significant improvement from the pre-assessment mean of 9.86 points (49.30%). Qualitative analysis of student project outputs further supported these findings, with 28 out of the 31 participants (90.32%) producing work products that exhibited clear evidence of CT across all four dimensions. The most notable improvements were observed in the areas of abstraction (mean improvement of 48.60%) and algorithmic thinking (mean improvement of 45.20%).

7. Discussion and Conclusion

The findings of this study demonstrate the effectiveness of integrating PBL with CT to enhance learning outcomes. The significantly high percentage of learners who achieved proficiency (83.87%) validates the efficacy of the developed framework and supports the hypothesis that structured PBL can effectively foster CT skills. The integrated framework developed in this study addresses a critical gap in educational methodology by providing a systematic approach to developing CT through authentic project experiences. Unlike previous approaches that treat CT as an isolated skill set, this framework embeds it within meaningful project contexts, thereby enhancing its relevance and applicability to real-world scenarios. The alignment between the PBL stages and the CT components proved particularly effective, creating natural synergies that enhanced the development of both skill sets simultaneously. For example, the "Define and Select Topics" stage naturally facilitated pattern recognition skills as students identified similarities and differences across potential project areas, while the "Planning and Project Operations" stage developed abstraction skills through the creation of conceptual models and frameworks. The high reliability coefficient (0.81) of the assessment tool provides strong evidence for the consistency and dependability of the measurement approach, while the appropriate difficulty and discrimination indices indicate that the instrument effectively differentiated between varying levels of CT proficiency. These findings align with previous research by Shin et al. (2021), who found that structured project activities can serve as effective vehicles for CT development. However, our study extends beyond previous work by providing a comprehensive and validated framework that explicitly delineates how PBL processes can be systematically aligned with CT development.

This research has developed and validated a structured framework that integrates PBL with CT in such a way as to enhance educational outcomes. The framework comprises five PBL stages (Preparation, Definition, Planning, Implementation, and Presentation) aligned with four CT components (Decomposition, Pattern Recognition, Abstraction, and Algorithm Design). The assessment results demonstrated that 83.87% of the participants achieved proficiency in CT skills after engaging with the integrated learning process, exceeding the established threshold of 80%. The assessment tool exhibited appropriate psychometric properties, with a reliability coefficient of 0.81 and suitable difficulty and discrimination indices. The effectiveness of this approach is attributed to its facilitation of iterative development through hands-on, problem-solving activities that produce tangible outcomes. By embedding CT within authentic project contexts, the framework enhances the relevance and applicability of these skills to real-world scenarios. This study contributes to educational methodology by providing an empirically validated framework that systematically develops CT through project-based experiences. The framework offers educators a structured approach to integrating these complementary methodologies, potentially enhancing the development of critical 21st-century skills among learners.

Future research should explore the application of this framework across different educational levels and subject domains, as well as investigate its long-term impact on learners' CT development and transfer to other contexts.

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