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Establishing a Seamless Integrated Project-Based Learning Framework Mediated by an Evidence-Based Project-Based Learning System

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Abstract: This empirical study establishes a seamless integrated project-based learning framework mediated by an evidence-based project-based learning system. Combining theoretical model construction and practical application, this research aims to bridge gaps in learning objectives, processes, resources, and assessments. The model employs conceptual clusters, problem chains, and evidence-driven task design to foster the development of interdisciplinary competency. A 40 h case study, centered on the "Interior Space Design of Teachers' Apartments" project, demonstrated quantifiable improvements; students' design proposal scores increased by 45.5%, problem-solving efficiency improved by 62.5%, and team collaboration scores rose from 60 to 85. Additionally, innovative applications per design surged from 2–3 to 6–8, while student engagement time doubled. These results validate the effectiveness of the seamless integrated project-based learning framework in enhancing interdisciplinary knowledge integration, core competencies, and intrinsic motivation, providing a data-supported framework for technology-enhanced educational reform.

Keywords: seamless learning; project-based learning; model construction; effectiveness test; EPBL

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1. Introduction

Against the backdrop of the country's strong promotion of the construction of a powerful education system, the pursuit of more effective and engaging learning models is an inevitable requirement for implementing national education policies and cultivating well-rounded talents. With the implementation of the education digitalization strategy and the increasing emphasis on the cultivation of students' comprehensive qualities, traditional learning methods can no longer meet the demands of education development in the new era. Seamless learning and project-based learning align with the direction of national education policies, bringing new opportunities for educational development. Seamless learning breaks the boundaries of different learning contexts, meeting the requirements for constructing a ubiquitous learning environment and helping to achieve the educational vision of "learning anywhere, anytime". Project-based learning, which focuses on enhancing students' practical skills and fostering critical thinking through hands-on projects, is well aligned with the national policy emphasizing practical education and innovation. This study effectively combines the strengths of both approaches, creating a cohesive and integrated project-based learning model utilizing the EPBL platform. This innovative educational method aims to contribute significantly to the promotion of educational equity, ensuring that all students have access to quality learning opportunities that prepare them for the challenges of the modern world.

2. Research Review

2.1. Seamless Learning

On a literal level, seamless means occurring with smooth continuity. In 1996, George Kuh introduced the concept of seamless learning in the field of higher education reform, aiming to connect independent learning experiences in and out of the classroom, both academic and non-academic, as well as on-campus and off-campus into a cohesive whole, achieving the completeness and continuity of the learning experience [1]. With the continuous advancement of technology, in 2006, Chen Dehuai and other scholars systematically discussed the concept and framework of seamless learning based on mobile learning, emphasizing the role of mobile technology in facilitating seamless transitions in learning, positing that students can quickly learn in different contexts through personalized mobile devices [2]. Technology enriches the connotation and extension of seamless learning, gradually encompassing the integration of formal and informal learning, personal and social learning, as well as the fusion of the real world and the virtual world, along with seamless connections in various aspects such as learning resources, learning activities, and learning terminals [3].

The theoretical foundations of seamless learning include communicative learning, situative learning, and knowledge construction. Communicative learning theory posits that learning occurs as a cognitive process in a social environment, where the connectivity provided by mobile technology offers learners more opportunities for interaction, thereby promoting the learning process [4]. Situative learning theory emphasizes the close relationship between learning and specific contexts; seamless learning creates rich learning environments that enable learners to better understand and apply knowledge [5]. Knowledge construction theory focuses on the creation and advancement of knowledge by learners through collaboration; seamless learning encourages learners to communicate and collaborate in different contexts, jointly constructing knowledge systems [6].

Mobile technology is a crucial supporting technology for seamless learning, enabling learners to access learning resources anytime and anywhere across different contexts, achieving seamless transitions in learning. For instance, the application of technologies such as positioning systems and sensors enhances the precision of situational awareness in learning, supporting personalized learning [7]. Alongside the development of intelligent technologies such as artificial intelligence, big data, and virtual reality, more enriched application scenarios and means of support for seamless learning are provided [8]. The advancement of technology supports the transformation of learning methods, with seamless learning emphasizing personalized, diversified, and contextualized approaches to learning, offering learners a richer learning experience through the integration of multiple technological means [9].

In the integration of technology and learning, it is necessary to pay attention to educational ethical issues, such as data privacy protection and the fairness of technology application, ensuring that the use of technology aligns with the essence and purpose of education [10]. Seamless learning involves multiple disciplines, including pedagogy, psychology, computer science, and sociology. Interdisciplinary research aids in a deeper understanding of the essence and laws of seamless learning, providing more scientific theoretical support for practical application [11]. Cross-disciplinary application among various fields brings new development opportunities for seamless learning [12].

2.2. Probject Based Learning

Project-based learning, as an innovative and impactful educational model, is increasingly recognized for its significance in the field of education. The origins of project-based learning can be traced back to the early 20th century, when Kilpatrick integrated the theories of Dewey and Thorndike to creatively propose the prototype of project-based learning. Subsequently, it was first promoted in Europe and the United States, gradually attracting widespread attention in the global education community. With the continuous evolution of educational concepts, it has become one of the core teaching methods for cultivating students' comprehensive qualities and key competencies.

From the perspective of theoretical research, constructivist theory plays a crucial role in project-based learning. Marra et al. point out that constructivism emphasizes the active construction of knowledge systems by students through interaction with their environment. The authentic problem situations created by project-based learning provide a platform for such knowledge construction, enabling students to deepen their understanding and mastery of knowledge through the practice of problem-solving [13]. Contextual learning theory is equally indispensable; as Xia Xuemei describes, this theory posits that learning is closely tied to specific contexts. Project-based learning effectively enhances the effectiveness and transferability of learning by simulating or introducing real-life scenarios, allowing students to apply knowledge in context.

In the area of research on the key points of implementation, project design and selection are the cornerstones of successful project-based learning. Xia Xuemei suggests that high-quality projects should possess key elements such as challenge, authenticity, and feasibility [14]. For example, in a science education project, a project can be designed around the real issue of environmental pollution control, prompting students to comprehensively apply knowledge from multidisciplinary fields such as chemistry and biology. It is also essential to clarify the project's objectives, tasks, implementation processes, and evaluation criteria to ensure the orderly advancement and effective assessment of the project. In terms of teaching process management, the transformation of the teacher's role in project-based learning is crucial. Conway and Little argue that teachers need to shift from traditional knowledge transmitters to guides and facilitators of learning [15,16]. During project implementation, teachers should organize students to engage in collaborative group learning, reasonably guide students to independently explore and solve problems, and provide timely and precise support and guidance based on student needs. Additionally, using diverse evaluation methods to comprehensively assess students' learning outcomes, such as employing formative assessment to focus on students' performance during the learning process, combined with summative assessment to evaluate the quality of project completion.

Regarding the impact of project-based learning on students' abilities, research by Islamiati et al. indicates that project-based learning significantly promotes the enhancement of students' critical and innovative thinking [17]. Taking mathematics project-based learning as an example, students are required to conduct in-depth analysis, comprehensively consider various solutions, and critically reflect on the results when solving real-world mathematical problems, effectively exercising their thinking abilities [17]. In terms of developing cooperation and communication skills, research by Yolanda Dhea Afelia et al. found that the group collaboration aspect of project-based learning strongly drives the development of students' cooperation and communication abilities. In group projects, students need to closely collaborate and fully exchange ideas with their peers to complete tasks together, thereby enhancing their teamwork and communication skills [18].

In the field of application research, project-based learning is widely applied in subject teaching. In science education, as mentioned by Marra et al. [13], conducting project-based learning activities such as ecosystem research enables students to integrate knowledge from biology, geography, and other fields, deeply understanding scientific concepts and principles while cultivating a spirit of scientific inquiry and practical abilities. In mathematics education, project-based learning can utilize projects such as mathematical applications in architectural design, allowing students to apply mathematical knowledge to solve problems in real contexts, thereby improving their mathematical application skills and logical thinking abilities. Furthermore, in interdisciplinary learning, project-based learning breaks down subject boundaries, promoting the integration and application of knowledge. For instance, in sustainability projects, students are required to synthesize knowledge from environmental science, economics, sociology, and other disciplines to analyze and solve complex real-world problems, thereby fostering interdisciplinary thinking and integrated application abilities.

2.3. Problem Statement

The evidence-based project-based learning system (E-PBL system) integrates outstanding project-based learning programs and cases from both domestic and international sources. It generates project-based learning solutions through various methods, including automatic recommendation and manual selection, based on curriculum standards across disciplines, subject knowledge graphs, and learner capability development models. Additionally, it supports online learning for learners and collects data throughout the entire learning process for intelligent assessment, thereby continuously promoting the development of learners' problem-solving abilities, innovation capabilities, and other comprehensive qualities. This study combines the trends of seamless learning and project-based learning, proposing a theoretical model for seamlessly integrated project-based learning design, and conducts design practice for related courses on the E-PBL platform to explore more possibilities for project-based learning development supported by technology, with the aim of providing valuable references for the advancement of project-based learning.

3. Key Features of Seamless Integrated Project-Based Learning

Project-based learning, as a method that can stimulate students' interest and initiative in learning while cultivating their comprehensive abilities, often faces limitations in learning time, space, and modes in practice, which can affect learning outcomes [13,19]. Seamless learning provides a new perspective to address this issue. Seamless learning emphasizes continuity and seamlessness in learning, organically integrating formal and informal learning, as well as on-campus and off-campus learning, thereby offering students a richer and more diverse learning experience [20]. Therefore, the "seamless integrated project-based learning" advocated in this study is a new learning approach that combines project-based learning with the concept of seamless learning, aiming to create a continuous and uninterrupted learning experience for students by integrating various learning resources and environments.

Seamless integrated project-based learning focuses on the organic integration of learning objectives, the deep fusion of the learning process, the collaborative coordination of learning resources, and the effective combination of learning assessment (see Figure 1). In terms of integrating learning objectives, it is essential to ensure that the knowledge goals of different learning stages and disciplines are interconnected. For instance, Wen, in his research on the Chinese vocabulary learning system, merges family learning with classroom learning objectives to promote students' comprehensive mastery of vocabulary knowledge [21]. The integration of the learning process requires breaking the temporal and spatial limitations of traditional learning, achieving smooth connections between formal and informal learning and enabling students to continue learning in diverse contexts. This aligns with the research concepts of Ozdemir and Kalinkara regarding seamless learning in the metaverse environment, where they emphasize that learning should achieve seamless transitions across different scenarios [22]. The coordination of learning resources means fully integrating various resources, including a wide range of online and offline channels, to provide students with rich and appropriate learning materials. In terms of joint learning assessment, a comprehensive use of multiple assessment methods is necessary to evaluate students' performance in the project-based learning process, such as knowledge mastery, skill enhancement, teamwork, and other competencies. Through the synergistic effects of these aspects, seamless integrated project-based learning aims to create a coherent, efficient, and effective learning environment for students, promoting a comprehensive improvement in their qualities and holistic development.

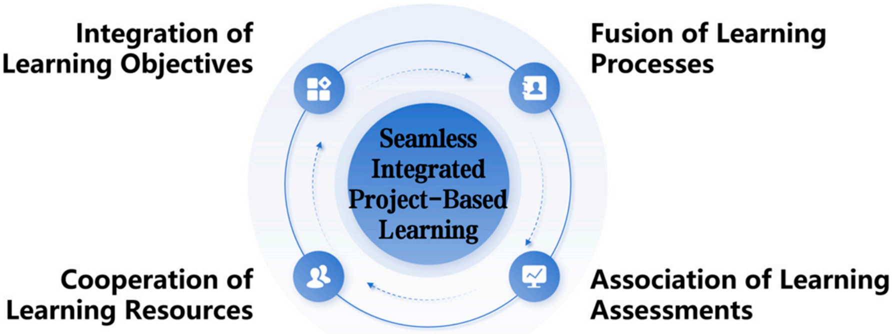

Figure 1. The distribution of the learning opportunities provided by teachers.

In the context of the "Teachers' Apartments Interior Design" project, the EPBL platform has played a crucial role in facilitating seamless integration of project-based learning. The platform automatically recommended interdisciplinary project cases related to architecture, aesthetics, and economics, which has helped students to better understand the project requirements and promoted the integration of cross-disciplinary knowledge. It also integrated online resources such as virtual laboratories and offline practical activities. Students could access design tools and materials in the virtual laboratory on the platform for simulation experiments and designs and at the same time conduct field investigations and practical operations in real life, achieving a seamless connection between online and offline learning. Moreover, the EPBL platform had the function of real-time data collection and analysis. It recorded students' learning behaviors, design schemes, and test scores during the project implementation process. Through data analysis, the platform provided personalized feedback and suggestions to students, helping them to adjust their learning strategies in a timely manner and improve learning outcomes. For example, the platform could analyze the innovative points and shortcomings in students' design schemes and provide targeted suggestions for improvement, promoting continuous progress in the project implementation process. In addition, the EPBL platform supported multi-terminal synchronous collaboration. Students could work on project design and collaboration on different devices such as computers, tablets, and mobile phones. The platform provided real-time collaboration tools like online document editing, design sketch sharing, and discussion zones, making it convenient for students to collaborate at different times and places and realizing the continuity and seamlessness of learning.

3.1. Integration of Learning Objectives

Seamlessly integrated project-based learning incorporates the cultivation of core competencies throughout the entire process of project-based learning, enabling students to not only master knowledge and skills but also to develop critical thinking, innovation capabilities, and a spirit of collaboration [22]. Personalized learning objectives and content are provided based on students' interests, abilities, and learning needs, allowing students to fully leverage their strengths and achieve individualized development within project-based learning [23].

3.2. Integration of Learning Processes

Seamlessly integrated project-based learning organically combines formal and informal learning, allowing students to engage in effective learning across various environments such as classroom learning, extracurricular practices, and community activities [22]. For example, students can learn theoretical knowledge related to the project in class and then delve deeper into the project's content through practical activities and online learning outside of class, applying what they have learned to real-life situations. This integration of in-school and out-of-school learning breaks down the boundaries between them, tightly linking school education and social education, enabling students to learn in various settings such as schools, communities, and families [24]. For instance, schools can collaborate with communities to conduct off-campus practical activities, allowing students to understand and serve society while applying their knowledge in practice, thereby enhancing their practical skills and sense of social responsibility. Learning time is continuous, breaking the limitations of learning time, allowing students to learn at different times and locations [25]. For example, students can engage in project-based learning during spare time, weekends, and holidays, making full use of fragmented time to improve learning efficiency.

3.3. Coordination of Learning Resources

Seamlessly integrated project-based learning integrates various diverse learning resources, including textbooks, online resources, practice bases, and community resources, providing students with rich learning materials and support. At the same time, a shared learning resource platform is established to promote resource sharing and collaboration among students, teachers, and schools, enabling students to access more learning resources and improve learning outcomes [26].

3.4. Integration of Learning Assessment

Seamlessly integrated project-based learning adopts a diversified assessment approach, including self-assessment by students, peer assessment, teacher evaluation, and parent evaluation, providing a comprehensive assessment of students' learning processes and outcomes [27]. It emphasizes the combination of formative and summative assessments, providing timely feedback on students' learning situations in formative assessments to help them adjust their learning strategies, while also not neglecting summative assessments, which evaluate students' project outcomes to assess their learning effectiveness and mastery of knowledge [28].

"Seamlessly integrated project-based learning" is an innovative learning approach that combines project-based learning with the concept of seamless learning, offering students a richer, more diverse, and continuous learning experience, which helps cultivate their comprehensive abilities and innovative spirit, promoting their overall development [23].

4. Construction of Seamless Integrated Project-Based Learning Design Model

The design of seamless integrated project-based learning can be approached from two aspects: teacher behaviors and student behaviors. This involves progressively connecting concept clusters, problem chains, goal layers, task chains, and evidence sets, while utilizing technology to facilitate the connections between various learning spaces, ultimately aiming at cultivating core competencies (see Figure 2).

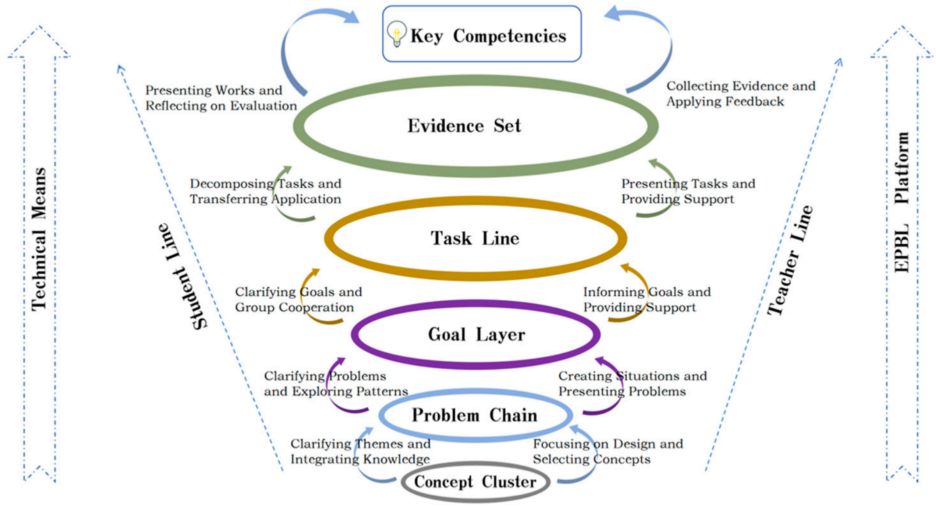

Figure 2. A project-based learning design model with seamless integration.

4.1. Constructing Concept Clusters

Firstly, designers should conduct an in-depth analysis of the theme of the project-based learning they are designing, clarifying its core concepts and key elements. For example, if the theme is "Sustainable Development of Urban Ecosystems", relevant core concepts might include "ecological balance", "resource utilization", and "environmental protection".

Secondly, they should integrate relevant conceptual systems and establish interdisciplinary integration that transcends the boundaries of different subjects, incorporating concepts from physics, biology, geography, sociology, and so on. For instance, in the "Sustainable Development of Urban Ecosystems", the concept of energy conversion from physics can be used to understand the efficiency of urban energy utilization, while the ecological cycle concept from biology can be applied to study the material flow in urban ecosystems.

Thirdly, the relevant concepts should be hierarchically constructed. The integrated concepts should be organized into a structured hierarchy to form a conceptual network. This can be constructed from macro to micro, and from abstract to concrete, ensuring that the logical relationships between concepts are clear.

Finally, technological tools should be utilized for support. For instance, mind mapping software such as XMind 8 and MindManager 2020 can visually display the hierarchical structure and connections between concepts. This clear presentation is extremely important for both students and teachers. These pieces of software provide rich editing features, enabling users to add, modify, and move nodes, making the construction of concept clusters more flexible and convenient. Additionally, online knowledge mapping tools like Baidu Brain Map and Notion can be utilized to build more complex and dynamic concept clusters. These tools can visualize the relationships between concepts and support integration with other tools and resources, facilitating further learning and research.

4.2. Organizing Problem Chains

Firstly, designers should propose questions based on the concept clusters. Starting from the constructed concept clusters, they should guide students to formulate questions related to each concept. For example, regarding the concept of "ecological balance", questions such as "What factors in the city can disrupt ecological balance?" and "How to maintain ecological balance in urban areas?" can be posed.

Secondly, they should determine the levels and progression of the questions. The design of questions should follow the principle of progressing from simple to complex, gradually guiding students to think more deeply. Some foundational questions could be initiated, such as definitions and characteristics of concepts, before gradually transitioning to deeper and more complex questions, such as the relationships between concepts and their application scenarios. It is essential to ensure that there is a progressive relationship among the questions, where the resolution of the previous question provides a foundation for the next question. For instance, while addressing the question "What factors in the city can disrupt ecological balance?", students may identify "emission of pollutants" as a significant factor, leading them to subsequently ask, "How can the emission of pollutants be effectively controlled?"

Finally, the focus should be on real-life situational problems. Designers should choose specific cases from real life to allow students to experience the practicality of knowledge while solving problems. For example, using a river pollution incident in a certain city as a case study, students may be guided to analyze the causes of pollution, its impacts, and possible solutions. The problems should also have a certain degree of challenge and appeal to spark students' interest and initiative in learning. Strategies such as creating suspense or introducing hot topics can be employed to capture students' attention and encourage their active participation in the problem-solving process.

4.3. Linking Goal Layer

First, the overall goals should be clarified. Based on the theme and problem chain of project-based learning, the overall goal of the project can be determined. The overall goal should have clear directionality, encompassing the core content and expected outcomes of the project. For example, the overall goal of the "Sustainable Development of Urban Ecosystems" project could be "to propose a set of sustainable development solutions for urban ecosystems through research and practice, thereby enhancing urban residents' environmental awareness and ecological literacy".

Secondly, sub-goals should be decomposed and refined. Based on the learning stages, the overall goal can be broken down into multiple sub-goals, with each sub-goal corresponding to a learning stage or task. For example, in the initial phase of the project, a sub-goal could be set as "understanding the composition and structure of urban ecosystems"; in the mid-phase, a sub-goal could be "analyzing the current status and issues of urban ecosystems"; and in the later phase, a sub-goal could be "proposing sustainable development solutions for urban ecosystems". Furthermore, associate learning content can be used to ensure that sub-goals are closely related to the learning content and can be achieved through the completion of learning activities and tasks. For instance, to achieve the sub-goal of "analyzing the current status and issues of urban ecosystems", students need to learn relevant investigation methods, data analysis techniques, etc., and conduct field investigations and data collection.

Lastly, a hierarchical goal structure should be established. A pyramid structure can be used to place the overall goal at the top level, the sub-goals at the middle level, and specific learning tasks and activities at the bottom level. This system can clearly display the hierarchical relationship between goals, making it easier for students to understand and grasp the focus and direction of learning. Additionally, it allows for dynamic adjustments; based on project progress and students' learning needs, timely adjustments and optimizations to the goal hierarchy can be made to ensure that the goals remain targeted and feasible, effectively guiding the implementation of learning activities.

4.4. Structuring Task Lines

First, tasks should be designed based on goals. Corresponding learning tasks and activities can be designed according to the refined sub-goals. Tasks and activities should have clear goal orientation, helping students to achieve sub-goals and ultimately the overall goal. For example, to achieve the sub-goal of "understanding the composition and structure of urban ecosystems”, the following tasks can be designed: consulting relevant materials to learn about the components of urban ecosystems; visiting urban parks, sewage treatment plants, etc., to observe the operation of urban ecosystems in the field; and creating diagrams of the composition and structure of urban ecosystems.

Secondly, the order and association of tasks should be determined. The execution order of tasks can be arranged in a logical sequence to ensure continuity and progression between tasks. For example, when learning the concept of “energy conversion”, students could first learn about the types and characteristics of different energy sources, then study the principles and methods of energy conversion, and finally conduct experiments on energy conversion to deepen their understanding of the concept. Tasks should be interrelated and support each other, forming an organic whole. For instance, in the “Sustainable Development of Urban Ecosystems” project, there is a close relationship between the tasks of “investigating urban pollution sources” and “analyzing the impact of pollution sources on ecosystems”; completing the former task can provide data and information support for the latter.

Lastly, diverse types of tasks should be introduced. Exploratory tasks such as experimental investigations, field surveys, and literature studies can be designed to cultivate students’ inquiry abilities and innovative spirit. For example, students could conduct water quality testing experiments to investigate the water quality conditions of urban rivers, or students could perform field surveys on urban waste management to understand the current situation and issues of waste disposal.

Cooperative tasks such as group discussions and project collaborations should be arranged to cultivate students’ teamwork and communication skills. For example, students could work in groups to collaboratively create a model of the urban ecosystem, or they may engage in collaborative projects on urban sustainable development to collectively propose solutions. Alternatively, creative tasks may be set up, such as creative design and artwork creation, to foster students’ creativity and imagination. For instance, students could design a planning scheme for an urban ecological park or create a poster about urban ecological protection.

4.5. Clarifying Evidence Sets

First, the types of evidence should be determined. Based on the goals and tasks of project-based learning, one must identify the types of evidence that need to be collected and analyzed. Evidence types can include data, facts, cases, images, videos, etc. For example, in the “Sustainable Development of Urban Ecosystems” project, it may be necessary to collect data on urban energy consumption, environmental quality data, and survey data on residents’ environmental awareness.

Secondly, evidence collection methods should be designed. Observation methods may include collecting firsthand data by observing and recording natural phenomena, social phenomena, etc. For example, changes in the water quality of urban rivers and the ecological conditions of urban parks can be observed. Survey methods may include collecting public opinions and views through questionnaires, interviews, etc. For example, surveys on urban residents’ environmental awareness may be conducted to understand their attitudes and behaviors towards urban ecological protection. Experimental methods include designing and conducting experiments to verify hypotheses and conclusions. For example, experiments on energy conversion may be carried out to explore the efficiency and environmental friendliness of different energy conversion methods. Literature research methods involve referring to the existing literature and materials to obtain relevant information and knowledge. For example, policies and regulations on urban ecological protection and research reports from both domestic and international sources can be reviewed.

Lastly, an evidence management system should be establish. Electronic spreadsheets and software such as Excel should be used to organize and categorize the collected evidence. Classification can be based on evidence type, collection time, source, etc., to facilitate subsequent analysis and use. Online knowledge management tools, such as Notion, Confluence, etc., should be used to create a shared evidence repository. Students and teachers can upload, share, and manage evidence within this knowledge base, achieving resource co-construction and sharing. Data analysis software, such as SPSS 26.0, R4.4.2, etc., should be used to analyze and process large amounts of collected data, extracting information and patterns from the data. Through data analysis, one can provide a basis for decision-making and improvements in the project.

5. Empirical Analysis of Seamless Integrated Project-Based Learning

Based on the design model of seamless integrated project-based learning, we took the students' experiences after a campus visit as an opportunity, in conjunction with the ongoing teachers' apartment renovation project at the school. We initiated a proposal for all third-grade students around the theme of "Interior Space Design of Teachers' Apartments", which is closely related to student life and has a certain design aesthetic. Given the background of a relatively high number of young teachers and limited space in the teachers' apartments, while also needing to meet the housing needs of these young teachers, we asked the following question: As excellent small space designers, how can we design a teacher's apartment that meets the housing needs of young teachers living on campus while also considering smart and eco-friendly features within a limited budget?

The project lasted a total of 40 class hours (1 h/class). It integrated the concepts of project-based learning and seamless learning, provoking thought through real-life selected scenarios, and was driven by challenging guiding questions to engage students' higher-order thinking. Through knowledge construction and practical operations, students achieved deep learning, applying knowledge to solve problems. The process was guided by "resource integration", including resource acquisition, selection, combination, and optimization, with a clear focus on interdisciplinary concepts. This empirical study delved into the practical application and efficacy of a seamlessly integrated project-based learning model. This study employed a quasi-experimental design, leveraging pre- and post-test comparisons to appraise the influence of this EPBL approach on students' capacity to apply interdisciplinary knowledge, foster core competencies, and engage in the learning process.

This research involved 75 third-grade students, aged between 8 and 9 years, from an elementary school. The project extended over a duration of 40 instructional hours. Cluster sampling was employed to ensure the full participation of all students within the grade level. The participants exhibited foundational subject knowledge and fundamental learning skills requisite for engaging in PBL activities.

A diverse array of data collection methods were utilized, encompassing

- Interdisciplinary knowledge tests to ascertain pre- and post-project proficiency;
- Evaluations of student design proposals based on quality rubrics;
- Learning engagement surveys to gauge student motivation and involvement;
- Focus group discussions to glean in-depth insights into student experiences and perceptions;
- Teacher observations to document student performance and engagement throughout the project.

In the "Teachers' Apartments Interior Design" project, a total of 75 students participated in the pre- and post-project assessments. The mean total score before the project was 57.48 with a standard deviation of 4.12, and the mean total score after the project was 84.11 with a standard deviation of 5.22. The mean score improvement was 26.63 with a standard deviation of 6.31. These descriptive statistics provide a clear indication of the central tendency and dispersion of the scores, highlighting the significant improvement in students' performance. Specifically, for the four evaluation criteria, the mean scores and standard deviations were as follows: space utilization had a pre-project mean score of 17.00 (SD = 2.12) and a post-project mean score of 24.12 (SD = 2.31); functional zoning rationality had a pre-project mean score of 16.00 (SD = 2.01) and a post-project mean score of 22.46 (SD = 2.23); budget planning accuracy had a pre-project mean score of 10.87 (SD = 1.23) and a post-project mean score of 13.79 (SD = 1.45); and creativity and uniqueness had a pre-project mean score of 12.51 (SD = 1.54) and a post-project mean score of 14.44 (SD = 1.67). These statistics not only demonstrate the substantial progress made by the students in all aspects but also enhance the scientific quality and credibility of the study.

5.1. Breakthroughs in Interdisciplinary Knowledge Application

This project serves as a model of seamless integrated project-based learning, achieving remarkable results in academic performance improvement. In the interdisciplinary knowledge application tests, its unique advantages were fully demonstrated. The teacher's apartment design project seamlessly integrated knowledge from multiple disciplines such as space design, cost accounting, and color matching through technical means, thus breaking traditional disciplinary boundaries. This enabled students to naturally and smoothly apply interdisciplinary knowledge to solve practical problems in real-life situations, significantly enhancing their ability to integrate and apply interdisciplinary knowledge. In the evaluation phase of the design proposal quality, a scientifically rigorous and comprehensive scoring standard was applied, with space utilization, rationality of functional zoning, accuracy of budget planning, and uniqueness of creativity accounting for 30%, 30%, 20%, and 20%, respectively. The average score of the students' design proposals before the project was 55, which significantly increased to 80 after the project, representing an increase of approximately 45.5% (as shown in Figure 3). This clearly indicates that students' mastery and application of relevant knowledge in a seamless learning environment had reached a higher standard, effectively achieving deep integration and efficient application of knowledge, thereby boosting academic performance. Students accessed design templates, budgeting tools and intelligent assessment modules through the EPBL platform, enabling seamless learning across scenarios.

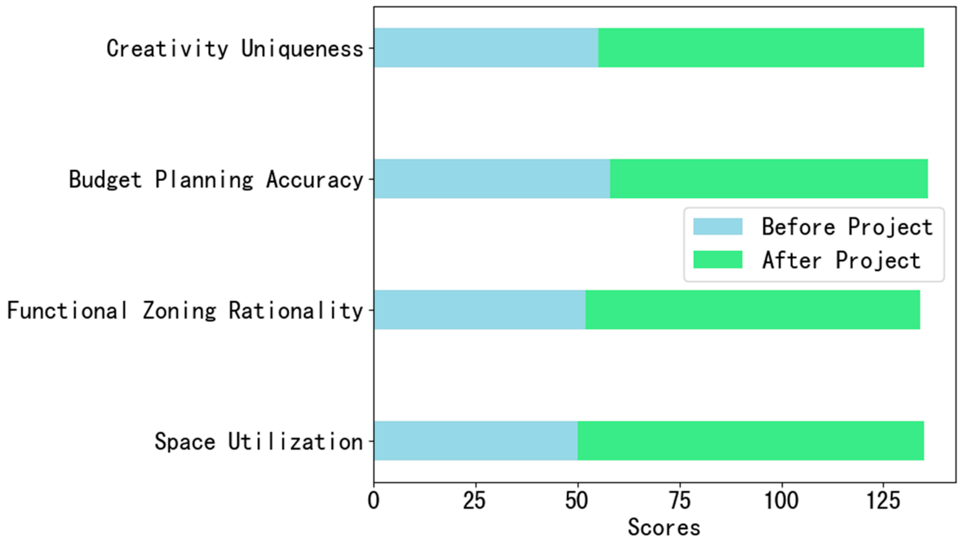

Figure 3. Comparison of pre- and post-test scores for student design solutions in the teacher's apartment design project.

5.2. Comprehensive Enhancement of Core Competencies and Significant Collaborative Development Outcomes

Throughout the project, students' abilities to solve various problems were exercised and significantly improved (as shown in Figure 4). For instance, in resolving spatial layout conflicts, only 30% of groups were able to adequately handle such issues within a week at the beginning of the project, while this proportion rapidly increased to 80% by the end of the project. Regarding budget overruns, only 20% of students could propose effective adjustment strategies initially, which rose to 60% later. In terms of problem-solving efficiency, the average time students needed to handle simple spatial layout adjustments decreased from 4 h at the project's outset to 1.5 h later, clearly reflecting a significant enhancement of students' abilities to analyze problems, devise solutions, and execute efficiently in complex situations.

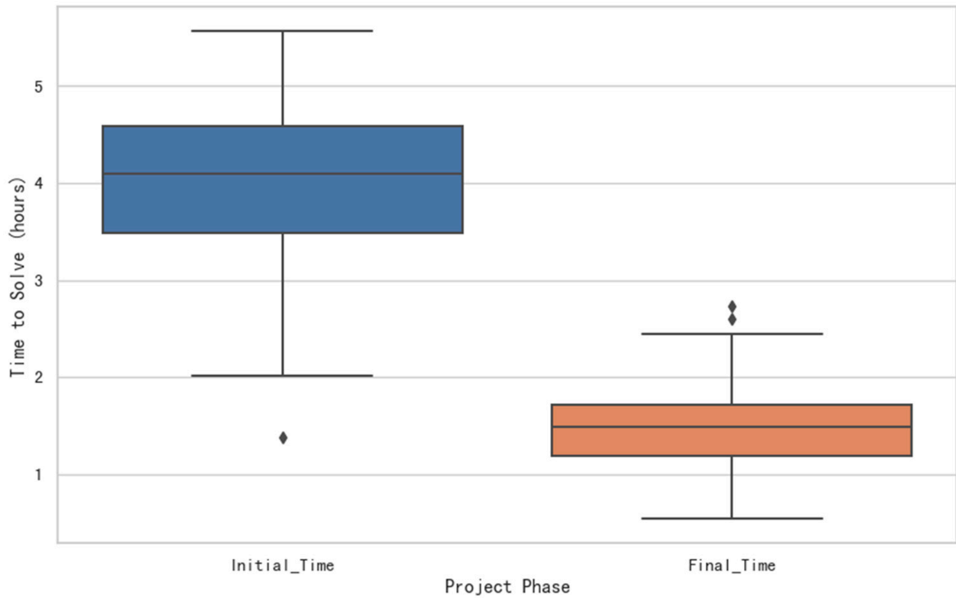

Figure 4. Box plot of changes in problem-solving efficiency of students in the teacher's apartment design project.

As shown in Figure 5, detailed analysis of team evaluation data revealed that in terms of task allocation rationality, only 40% of teams could clearly define responsibilities and maintain balanced division of labor at the beginning of the project, while this proportion surged to 85% by the end. In terms of communication smoothness among members, about 50% of teams faced varying degrees of communication barriers initially, which decreased to 20% later. Regarding the efficiency of collaborative problem-solving, the average time teams took to resolve problems reduced from 6 h at the project's outset to 3 h later. Further correlation analysis indicated a strong positive correlation between team collaboration assessment scores, which improved from an average of 60 points (out of 100) at the beginning to 85 points later, and project outcome quality scores, which rose from 65 points to 90 points, demonstrating the crucial role of team collaboration in the successful implementation of the project (correlation coefficient r = 0.8).

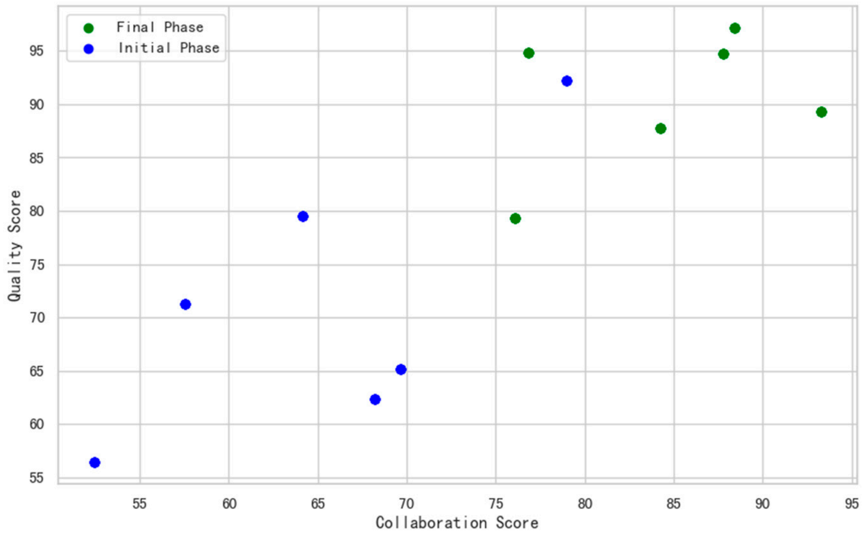

Figure 5. Scatter plot of correlation between team collaboration assessment scores and project outcome quality ratings in the teacher's apartment design project.

We observed stimulation of innovation ability; in terms of quantifying innovative outcomes, there was a significant increase in the number of innovative points proposed by students during the design process. For example, in terms of smart and eco-friendly design elements, each design had an average of only 2–3 innovative applications before the project, which increased to an average of 6–8 after the project. Regarding the deepening and adoption of innovative ideas, only 30% of innovative suggestions were incorporated into the final proposal at the beginning of the project, while this proportion grew to 65% by the end, fully demonstrating the increasing activity of students' innovative thinking and the continuous enhancement of their innovation capabilities.

5.3. Igniting Learning Enthusiasm and Fully Stimulating Inner Motivation

We observed significant enhancement of interest in learning; a comparison of the results from the learning interest survey revealed that project-based learning had a highly positive impact on students' learning interest (as shown in Figure 6). Prior to the project, the average interest rating of students regarding design-related project learning methods and relevant subject knowledge was 3 points (out of 5), whereas after the project, this average rating increased to 4.2 points, representing a growth rate of 40%. Further analysis of the feedback on interest at different stages of the project shows that students' interest rating for the model-making stage rose from 3.5 points to 4.8 points, for the user research stage from 2.8 points to 4 points, and for the poster design stage from 3.2 points to 4 points. Interest in each stage significantly improved, indicating that project-based learning comprehensively stimulated students' learning interest, leading them to engage more actively and proactively in the learning process.

We saw a dramatic increase in learning initiative; in terms of time invested in learning, the average time students spent on each stage of the project significantly increased compared to traditional classroom learning (as shown in Figure 7). In traditional classroom settings, students typically invested an average of 2 h per day, whereas during the project implementation, this number rose to 4.5 h, reflecting a 125% increase. In terms of the frequency of proactive learning behaviors, the number of times students actively consulted teachers with questions increased from an average of 3 times per week to 8 times, the frequency of spontaneous discussions organized among team members rose from 4 times per week to 12 times, and the instances of self-exploration of new design ideas grew from

2 times per week to 6 times. These data fully illustrate that students' proactive engagement in learning was greatly enhanced during the project-based learning process.

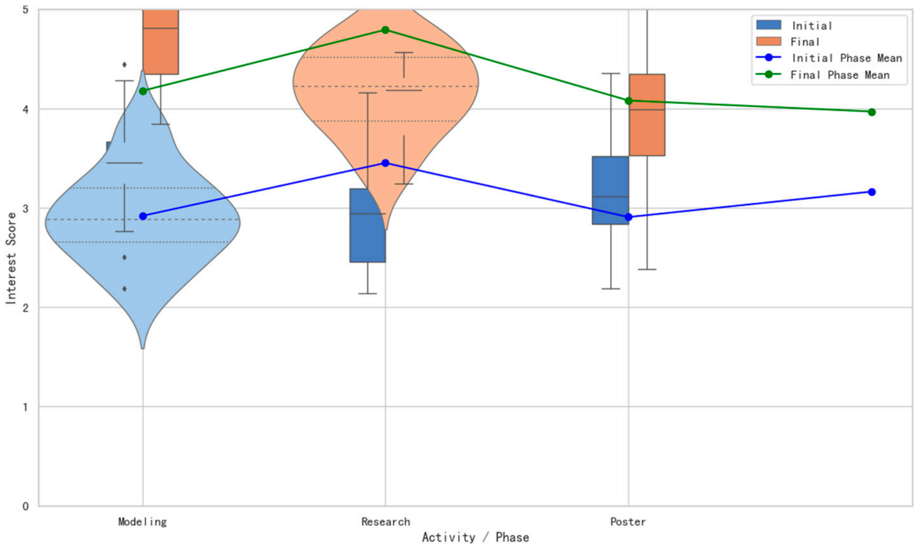

Figure 6. Changes in students' interest in each stage before and after the teacher's apartment design project, displayed in a violin plot.

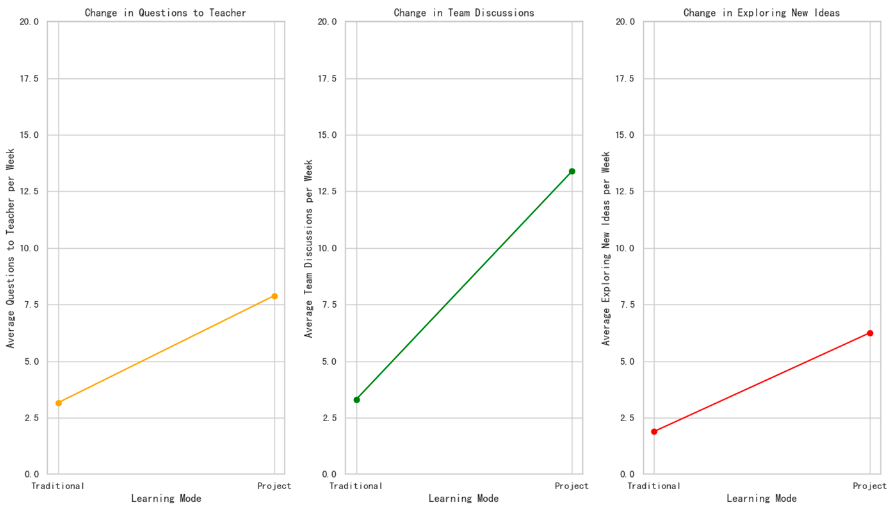

Figure 7. Changes in the frequency of students actively consulting teachers, spontaneously organizing discussions, and self-exploring new design ideas in the traditional classroom and during project implementation.

6. Conclusions and Discussion

From a macro perspective on educational philosophy, the temporal and spatial constraints of traditional learning, as well as the separation of disciplines, urgently need to be changed. As Chan pointed out, learning should break through traditional boundaries and move towards a more integrated and coherent model [2], and Klopfer et al. also mentioned that the development of mobile technology provides strong support for the transformation of learning models [29]. In this context, the deep integration of project-based learning and seamless learning has already become a key aim within educational progress. This requires educators to adeptly explore real-life scenarios and cleverly transform them into learning projects, creating a bridge through which students can apply knowledge in diverse contexts, achieving smooth transference and deep internalization of knowledge from theory to practice. This view aligns with the idea emphasized by Looi et al. about utilizing technology to achieve sustainable seamless learning to promote knowledge application [23]. At the same time, Csikszentmihalyi's theory of flow suggests that this integrated learning model can better stimulate students' intrinsic motivation to learn, allowing them to reach a state of immersion during the learning process, thereby enhancing the effectiveness of learning [30].

Focusing on the specific operational aspects of teaching practice, teachers bear the responsibility of constructing a systematic and rigorous learning framework. They need to accurately distill core concepts from a complex body of knowledge and then design progressively layered and clearly defined learning tasks according to logical connections, establishing a scientific and effective evidence collection and analysis system. Taking the "Teachers' Apartments Design" project as an example, through careful guidance, teachers encouraged students to successfully integrate multidisciplinary knowledge, achieving a comprehensive understanding of knowledge and enhancing their abilities while solving real-world problems, fully demonstrating the key role of systematic instructional design in promoting deep learning and ability development. This underscores the critical role of teachers in guiding students' learning processes, as mentioned by Rogers and Price, as well as the significance of systematic instructional design in facilitating deep learning [31].

Focusing on the core goal of student development, this learning model undoubtedly provides strong practical support, indicating its remarkable effectiveness in enhancing students' core competencies. Numerous studies have confirmed this, such as the research by Hmelo-Silver et al. on the impact of problem-based learning on students' abilities, which found that students showed significant improvement in problem-solving skills after participating in similar learning models, being able to more keenly perceive the essence of problems and efficiently devise solutions in complex situations [32]. Whether it is the ability to sensitively identify the essence of problems in complex contexts and efficiently devise solutions, the ability to complement each other and collaborate effectively in team cooperation, or the ability to break through traditional thinking limitations and generate novel and unique ideas, all have achieved qualitative leaps under the promotion of this learning model. As Sawyer pointed out, this integrated learning model breaks down the traditional barriers of disciplines and learning contexts, providing students with abundant opportunities for thinking collisions, which helps to overcome traditional thinking limitations and foster innovative and unique ideas [33]. The model's role in stimulating students' enthusiasm for learning should not be underestimated; this further alerts educators to place high importance on the careful shaping of learning experiences during teaching, fully creating a proactive and vibrant learning atmosphere, thereby steadily guiding educational reform towards comprehensiveness, practicality, and innovation in order to meet the diverse needs and high standards of talent cultivation in the contemporary era.

In conclusion, this study demonstrated the effectiveness of seamlessly integrated project-based learning in enhancing students' academic performance, learning motivation, and problem-solving abilities. However, it is important to acknowledge the limitations of this research. The sample size of this study is limited to third-grade students in a single school, which may limit the universality of the results. Additionally, the project cycle of 40 class hours is relatively short, and the long-term effects of this approach need to be verified in future research. Future studies could further explore the effectiveness of seamlessly integrated project-based learning in different educational stages, subject areas, and cultural backgrounds. Longitudinal studies could also be conducted to investigate the long-term impact of this approach on students' development. Moreover, the role of teacher training and professional development in the implementation of seamlessly integrated project-based learning could be examined to provide more insights for educational practice. By addressing these research directions, we can gain a more comprehensive understanding of the potential and limitations of seamlessly integrated project-based learning and contribute to the advancement of educational research and practice.

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