



Cultivating Future Engineers: An Integrated Project-based Learning Model in Learning Factory – A Case Study in Chinese Engineering Education

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Abstract

With the rapid development of artificial intelligence and automation technology, the role of information technology and human-machine interaction in modern engineering manufacturing has become increasingly prominent. However, traditional engineering education curricula are mostly limited to single-discipline knowledge transmission, making it difficult to meet the demands of future engineers for composite knowledge, systematic thinking, and innovative capabilities. To address this, we proposed a 3D project-based learning (PBL) model that integrates the "Learning Factory" concept. The model relies on high-fidelity industrial production environments, introduces real engineering constraints, and designs a tiered task structure of "general entry + open challenge." By constructing a 3D teaching framework comprising "Design Thinking – Do (engineering practice) – Develop (iterative extension)," it standardizes and guides the implementation of project directions across different specialties. Currently, this model has been implemented on a university engineering practice teaching platform, covering real industrial projects including intelligent manufacturing production lines, industrial robot material handling, and intelligent audio systems. An analysis of 575 undergraduate students shows that student performance in the project course is positively correlated with prior academic achievement (GPA) but was not fully explained by GPA. This suggests that the model provides students with opportunities to demonstrate abilities through forms of performance beyond conventional academic assessment.

Keywords: Learning Factory, Engineering Education, Project-Based Learning

1. Introduction

Manufacturing work is increasingly organized around digital systems, automation, data, and human-machine collaboration. In Industry 4.0 settings, production is connected with cyber-physical systems, networked services, real-time data, and flexible manufacturing, which has pushed engineering programs to reconsider curriculum, laboratory work, and student project activities [5], [8]. Studies of future engineers' skills under Industry 4.0 also suggest that universities need to respond to changing educational and workforce requirements rather than treating digital production as a matter external to engineering education [13]. Discussions of Industry 5.0 extend this pressure by highlighting disciplinary convergence, human-centric design, and human-machine interaction as parts of future engineering work [6].

For undergraduate education, this change requires more than adding new technical content. Future engineers need to handle complex, cross-disciplinary problems and connect engineering knowledge with professional skills and real-world practice [7], [17]. PBL environments have been associated with students' perceived development of teamwork, communication, self-directed learning, and problem solving, which helps explain why generic competences have become a central concern in engineering education [3]. The curriculum problem therefore concerns both what students should know and how students move from problem framing through design, implementation, and iteration.

Project-based learning offers one route for creating such experiences. Reviews of PBL in engineering education show that it has been widely adopted because of its expected contribution to professional knowledge and transferable skills [4]. Recent work also links PBL with real-world skill development when



projects are connected with technology, integrated curriculum, multidisciplinary work, simulation, and professional environments [11]. However, a project becomes educationally valuable when the task is well framed, students are supported during implementation, and the learning process connects to broader curriculum goals. This problem becomes sharper in engineering practice courses that contain multiple project modules. PBL practices differ across course, cross-course, curriculum, and project levels, and recurring challenges appear for students, teachers, and institutions [4]. For a large-scale engineering training platform, the central question is how different projects can share a common learning process across modules.

Multidisciplinary PBL cases make this point more concrete. Collaborative engineering projects involving several specialties require coordination of project phases, partner roles, resources, and assessment of both technical and professional learning [9]. Integrated multidisciplinary PBL cases using Design Thinking also show the need for targeted supervision, trained teaching teams, and attention to the learning process rather than the prototype alone [14]. Teachers need to act as instructional designers and scaffolders; without this, PBL adaptations lose effectiveness [16]. These studies show that cross-disciplinary project learning requires coordinated scaffolding across project assignments.

Learning Factory approaches provide a useful environment for this kind of curriculum problem. Abele et al. [1] describe Learning Factories as systems that combine learning or teaching with production environments and support experiential learning in realistic manufacturing settings. The Heilbronn Learning Factory shows how project-based production engineering can be organized around industrial-like activities while developing professional and social competences [2]. Sackey et al. [15] propose didactic design parameters for an Industry 4.0 Learning Factory. Learning Factory thinking is relevant because it makes production flow, constraints, collaboration, and improvement visible as connected parts of engineering practice.

The present case is situated in a Chinese university engineering training center, where extensive equipment and practice resources serve students from diverse majors, years of study, and technical backgrounds. In this setting, the main challenge is how to organize diverse project directions into a coherent curriculum.

In this paper, we proposed an integrated Learning Factory-based 3D PBL model for a university-wide engineering practice course platform. The model connects different project directions through Design Thinking, Do, and Develop, and is illustrated through industrial production-line and other smart-product projects. Student-level GPA and course-score data are used as a supplementary exploratory analysis of whether project-course performance reflects practical and integrative performance beyond prior academic achievement. The study does not test the causal effectiveness of PBL; its contribution is to explain a curriculum construction logic for large-scale, cross-disciplinary engineering practice education.

2. A Learning Factory-Based 3D PBL Course Platform

The course design examined in this paper starts from an institutional context. The engineering training center serves the whole university, receives students with varied technical backgrounds, and operates a portfolio of short-cycle engineering projects. In this setting, the main curriculum problem is how to organize diverse project directions into one coherent engineering practice platform. The Learning Factory-based 3D PBL model is used for this purpose. It gives different project directions a shared process of Design Thinking, Do, and Develop, while each direction retains its own technical content.

The engineering training center is a university-wide unit that provides engineering literacy and skill development. Engineering training is a required, credit-bearing component with variable load depending on the program: art and management students may take one- or two-credit craft projects; those in engineering typically complete three to five credits, totaling 32 to 160 training hours.

The center serves more than 3,000 students each year, drawn from engineering, science, art, management, and other schools, most participating between the second and third undergraduate years. Some need initial exposure to engineering processes and product thinking; others are ready for circuits, robotics, programming, or system-level design. A curriculum for this setting has to preserve disciplinary differences while maintaining course coherence.



2.1 Project-Based and Learning Factory-Based Curriculum

To make the system more effective, each project is constructed as a project-based engineering practice unit. Most project units carry 1-2 credits. A typical unit is a two-credit, 64-hour project completed over approximately two weeks by teams of three to four students. The expected outputs include a physical artifact or operational system, a technical development report, and a final presentation or defense. These outputs define a complete practice cycle: students interpret a task, plan functions, divide work, learn necessary techniques, implement and test the system, and explain the result.

The project portfolio currently contains around fifteen directions and continues to expand. These directions are grouped into four major clusters: Aerospace and Advanced Systems, Intelligent Systems and Robotics, Smart Devices and Embedded Systems, and AI and Intelligent Perception. Figure 1 presents the full project portfolio. These directions are project tracks within one course platform. They carry distinct technical requirements, but they are governed by a common learning process.

The platform uses a tiered task structure to make this common process workable for mixed-background students. Teachers provide a project theme and a function list divided into basic, advanced, and open-ended functions. Basic functions define the minimum task boundary for all teams. Advanced functions create technical depth. Open-ended functions allow students to add features, optimizations, or product ideas according to interest and capability. This structure accommodates students at different preparation levels.

The Learning Factory approach turns the center's equipment and projects into a curriculum environment. The engineering training center has equipment, practice spaces, embedded systems, robots, manufacturing resources, and intelligent application scenarios. These resources create the material basis for engineering practice, but the old curriculum mainly focus on equipment operation. A student may operate a machine, assemble a component, or complete a procedure without understanding system flow, design constraints, team coordination, or the relation between a technical decision and an application context. In this course platform, Learning Factory logic treats project tasks, tools, constraints, collaboration, testing, and iteration as connected parts of learning. This enables a shared 3D PBL process to guide diverse project directions.

2.2 The 3D PBL Model for Course Organization

The 3D model operates at the course-module level rather than the curriculum-system level. Frameworks such as CDIO guide how entire engineering programs are structured across multiple years. The 3D model addresses a different problem: how to govern the practical process within short-cycle project modules so that diverse directions share a common learning sequence. As shown in **Figure 2**, the model consists of Design Thinking for task entry, Do for implementation under engineering constraints, and Develop for iterative improvement and explanation.

Design Thinking creates the entry into the engineering problem. Students analyze the task context, identify user or application needs, examine requirements, and recognize constraints before implementation begins. Market analysis and application investigation bring scenario, demand, cost, feasibility, safety, product function, and industrial relevance into the task. Students also draw system flowcharts, decompose functions and technologies, and identify the knowledge they need to learn during implementation. This phase gives students with different backgrounds a shared way to interpret the project before they begin using equipment or writing code.

Do turns the planned solution into technical work. Depending on the project direction, students may design circuits, order and solder PCB boards, model product housings, manufacture parts, assemble mechanisms, program controllers, configure industrial robots, integrate sensors, apply AI algorithms, test systems, or debug abnormal behavior. Implementation exposes dependencies among requirements, components, manufacturing conditions, testing environments, and team decisions. Operation is tied back to the functions and constraints identified earlier.

Develop turns first completion into improvement and explanation. Students examine whether the outcome meets the original requirements, identify remaining problems, refine the solution where possible, document the process, and present the result. Teacher guidance and process review continue



throughout the project rather than appearing only at final submission. The open-ended function items make iteration necessary because teams often need to adjust goals, improve stability, refine interfaces, or optimize systems after feedback. A partially successful project can still produce learning when students can explain what failed, why it failed, and how the solution could be improved.

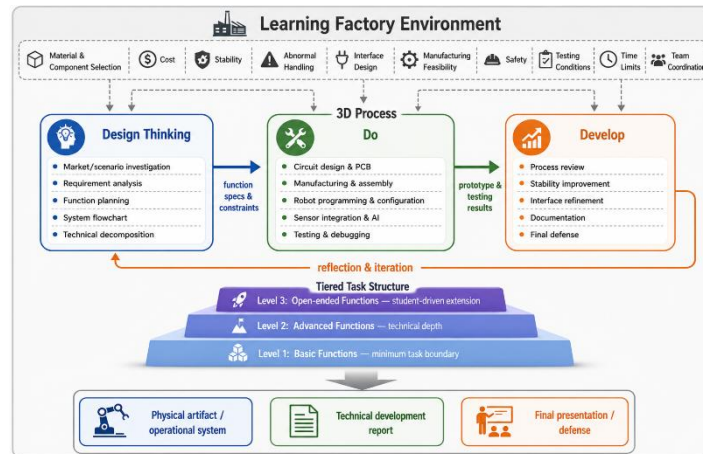


Fig. 2. The integrated Learning Factory-based 3D PBL model

2.3 Course Assessment

The 3D model aligns project directions through process requirements. Design Thinking focuses on problem framing and function planning, Do on implementation and testing, and Develop on review, documentation, and defense. This alignment works for a broad course platform whose project directions are technically diverse.

Assessment follows the same construction logic. In the current course design, project quality acceptance accounts for 40% of the grade, final defense for 20%, technical development report for 20%, and engineering literacy for 20%. Project quality focuses on whether the artifact or system meets required functions and operates with acceptable stability. The report and defense evaluate how students explain design decisions, testing results, and improvement plans. Engineering literacy is assessed through process observations, including collaboration, safety awareness, cost consciousness, and professional conduct.

This assessment structure keeps the platform from being judged only by final product completion. The final artifact is one piece of evidence alongside the broader process of implementation, testing, and iteration. The 3D model thus gives technically diverse project directions a common educational structure.

3. Representative Project Cases

The cases in this section are selected to make two routes of the course platform visible. The industrial robot production-line project represents learning through production flow, equipment coordination, tooling, and process stability. The electronic system and smart product projects represent learning through demand analysis, circuit design, fabrication, debugging, product integration, and presentation. They are representative rather than exhaustive. Other directions in the platform, such as AI vision inspection, intelligent vehicles, UAV autonomous systems, spacecraft design, aircraft power systems, and flapping wing robots, follow the same course logic with different technical content.

3.1 Case 1: Industrial Robot Production-Line Project

The industrial robot production-line project places students in a production-like task environment. The baseline task requires teams to complete a product-oriented process around an aluminum workpiece. Students must connect robot motion with tooling, process sequence, safety, and product quality.

In Design Thinking, students analyze the production task, identify required operations, clarify the handling and processing sequence, and draw a process flowchart. The teacher-provided function list gives all teams a baseline task, while advanced and open-ended items allow teams to go further. One



advanced task asks students to adapt a gripper so the robot can hold a writing brush and complete calligraphy strokes. This requires a non-standard end-effector: students must handle grip structure, trajectory control, and tool-center-point setting.

In Do, students work with robot programming environments to configure task paths, test action sequences, adjust coordinates, and debug failures. Typical problems include inaccurate positioning, unstable transfer, unsuitable processing paths, and unsafe motion. In Develop, teams compare the result with original requirements, revise parameters, and present their debugging process in the final report and defense.

3.2 Case 2: Electronic System and Smart Product Development Projects

Electronic system and smart product projects represent another route of the course platform. Examples include oscilloscope systems, smart sockets, and intelligent audio systems. These projects require students to develop a usable device, from demand analysis through circuit design, fabrication, and product assembly.

In Design Thinking, students analyze the use situation and product functions before circuit design begins, clarifying measurement, control, safety, and interface requirements. The function-list structure defines a clear design scope for each project: basic functions set the minimum product behavior, advanced functions add technical depth, and open-ended functions allow teams to improve stability and usability. This structure also supports mixed-background teams, as students can contribute through different roles.

In Do, students use EDA software to design circuits, fabricate PCB boards, solder components, model an enclosure, and integrate the circuit, housing, interface, and program into a product prototype. Implementation problems often appear as noisy signals, unstable measurement, poor circuit-housing fit, or unreliable control. In Develop, teams revise circuits, adjust enclosures, improve stability, and explain remaining limitations in the final defense. The product allows students to discuss trade-offs among function, cost, reliability, and usability.

The two cases show how different project carriers enact the same curriculum construction logic. In both cases, students begin by clarifying the problem and constraints, then implement a system under practical conditions, and finally review, document, and defend their work. This shared process keeps the portfolio coherent.

4. Learning Effects and Exploratory Analysis

Due to data limits, the analysis has a narrower diagnostic purpose. It examines whether the project course gave students opportunities to demonstrate forms of performance that were not fully predicted by prior academic foundation.

GPA serves as the comparison variable because it represents prior academic foundation accumulated through conventional, examination-oriented coursework. If the project course assessed the same type of learning as theory courses, course scores would closely mirror GPA rankings. The analysis uses complete matched records of 575 students from one college who had both GPA and numeric course scores in the project course. Course registration data for a subset of students provided additional boundary indicators, such as self-reported prior foundation and team average GPA. Project directions were not compared because students selected certain project as they wanted.

The 575-student sample shows a high level of course completion and performance. The mean course score was 86.74, with a standard deviation of 7.24 and a median of 88. The score distribution was concentrated in the upper range: 69.7% of students scored 85 or higher, and 39.8% scored 90 or higher. This pattern fits the nature of a guided project-based engineering practice course.

The high-score concentration should be interpreted through the assessment standard. The final grade is based on project quality acceptance, technical development report, defense, and engineering literacy. This process-oriented assessment gives students multiple ways to demonstrate performance through implementation, debugging, collaboration, documentation, and presentation. It also creates a ceiling



effect, because final scores alone cannot fully distinguish the quality of design reasoning, teamwork, iteration, or engineering judgment.

4.1 GPA and Course Score Correlation

Prior GPA was positively associated with project-course performance. In the matched sample, the Pearson correlation between GPA and course score was $r = 0.43$, $p < 0.001$, and the Spearman correlation was $\rho = 0.49$, $p < 0.001$. A simple linear regression showed that GPA explained 18.9% of the variance in project-course scores, $R^2 = 0.189$. A sensitivity check excluding scores below 60 produced a similar result, $r = 0.42$ and $R^2 = 0.176$. These results show that prior academic achievement matters in the project course.

The same results also show that GPA has limited explanatory power over course performance. If project-course scores were almost entirely determined by GPA, the course would mainly reproduce students' existing academic ranking. The observed pattern shows that GPA is related to performance, but most score variation remains outside the GPA-only model. This result is consistent with the assessment structure of the course, which includes implementation quality, technical reporting, defense, and engineering literacy in addition to task completion.

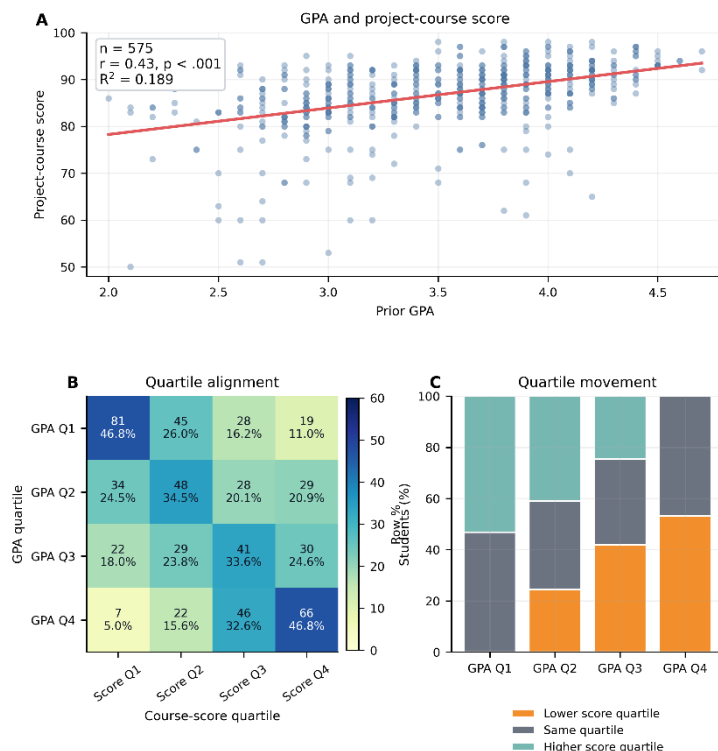


Fig. 3. Association between prior GPA and project-course scores ($N = 575$). **(a)** Scatterplot of GPA vs. course score with regression line ($r = 0.43$, $R^2 = 0.189$); **(b)** Cross-tabulation of GPA quartiles and course-score quartiles. Only 41.0% of students remained in the same quartile; **(c)** Movement from GPA quartile to course-score quartile.

The quartile comparison provides additional descriptive evidence. The cross-tabulation between GPA quartiles and course-score quartiles showed a statistically significant but moderate association, $\chi^2(9, N = 575) = 122.99$, $p < 0.001$, $Cramer's V = 0.27$. Only 41.0% of students were in the same GPA and course-score quartile, while 59.0% were placed in a different course-score quartile. Among students in the lowest GPA quartile, 53.2% moved to a higher course-score quartile. This comparison should be read as supplementary because course scores were concentrated in the upper range, but it supports the same bounded interpretation: the course-score distribution was not a one-to-one reproduction of the GPA distribution.

The lower-GPA group provides a concrete view of this performance space. Among students with GPA at or below 3.0, 41.3% obtained project-course scores of 85 or higher, and 14.7% obtained scores of 90 or higher. In the lowest GPA quartile, 46.2% reached 85 or higher and 17.9% reached 90 or higher. A



residual check led to a similar interpretation: 60.7% of students in the lowest GPA quartile scored above their GPA-predicted value, and 26.6% exceeded the predicted value by more than five points. The supported claim is narrow: strong project-course performance was not restricted to students with the strongest prior GPA.

The subset of registration data helps define the boundary of this claim. Students who reported prior research experience, competition experience, or related technical preparation had higher project-course scores than those without such records, with an average score of 89.94 compared with 86.56. In the metadata-linked subset, adding self-reported prior foundation increased the explained variance only slightly, from 21.8% to 23.6%. Team average GPA was also associated with course score, $r = 0.43$, $p < 0.001$. These results confirm that background experience and team conditions still matter in an open-ended engineering practice environment.

The exploratory analysis supports a bounded interpretation of the curriculum: the project course gave students different opportunities to demonstrate performance. This interpretation is supported by the fact that project-course performance was associated with prior GPA but had substantial unexplained variance. The course-score distribution partly departed from GPA-based academic ranking, and many lower-GPA students achieved strong or above-predicted project-course outcomes. These findings are consistent with the idea that the course assessed practical, collaborative, and process-oriented work in addition to prior academic achievement.

5. Discussion and Conclusion

The Chinese engineering training center context gives the model a specific educational meaning. Such centers often function as university-wide platforms rather than as ordinary course units. They may have substantial hardware resources, manufacturing spaces, robots, embedded systems, and digital equipment, while also serving large numbers of students from different schools. This institutional form creates a tension. The center has the resources to provide rich engineering practice, but its students vary widely in background, motivation, professional goals, and technical preparation.

The integrated 3D PBL model addresses this tension by combining accessibility with challenge. Basic functions give all teams a feasible entry point. Advanced functions provide technical depth. Open-ended functions allow students with stronger preparation or clearer interests to extend the project. Teacher guidance and process review prevent the course from becoming an unguided competition in which only previously prepared students can benefit. The Learning Factory environment keeps the work connected to engineering constraints.

The model also fits the cross-disciplinary nature of the platform. Students from non-engineering or less technically intensive programs may complete different levels of technical exploration compared with students from automation, computer science, or mechanical engineering. They can still participate meaningfully through user scenario analysis, product design, process planning, documentation, presentation, or market-oriented investigation. Students with stronger engineering backgrounds can engage more deeply with control, circuit design, programming, AI, manufacturing, or system integration. The shared process allows both forms of participation to remain within one course system.

Several limitations should be made explicit. The study is based on a single university engineering training center, so the model should be understood as a context-rich case rather than a universally validated framework. The quantitative evidence is exploratory and does not include a comparison group, pre-post competence measures, or validated scales. The current analysis also does not directly measure the competencies that the model targets, such as systems thinking, interdisciplinary integration, or innovation. These require more direct evidence aligned with the 3D process in future work.

Within the limits of a single-case exploratory design, this study offers a practical contribution to engineering education. The integrated Learning Factory-based 3D PBL model provides a curriculum mechanism for making project-based learning coherent, guided, and expandable in a large-scale practice platform. By aligning problem framing, implementation, and iterative development, the model helps diverse students encounter engineering work as a process of reasoning, making, testing, improving.



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