Instructional design and pilot validation of an interdisciplinary cooperative problem-based learning module for STEM higher education

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ABSTRACT

Current instruction in Chinese higher science, technology, engineering, and mathematics (STEM) education often relies on traditional lecture formats, which can limit students' development in collaborative problem-solving (CPS) and self-efficacy (SE). To address this gap, this study applied the Dick and Carey instructional design model to develop and validate a cooperative problem-based learning (CPBL) module. Structured around an engineering design task, the module integrates cooperative elements into problem-solving workflows and includes mechanisms to support equitable participation, such as mandatory role rotation. A multidisciplinary expert panel (N=6) assessed the module's content validity, and a pilot study with undergraduate students (N=33) evaluated instructional feasibility and instrument reliability. Results showed high scale-level content validity index (S-CVI=.98) and strong internal consistency for the adapted CPS and SE scales (Cronbach's α>.80). These findings confirm the module's validity, feasibility, and reliability. Ultimately, this CPBL module offers a validated pedagogical framework for interdisciplinary STEM instruction to concurrently cultivate the technical and transversal skills required in higher education.

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1. INTRODUCTION

Today's labor market requires graduates to integrate science, technology, engineering, and mathematics (STEM) to solve complex problems [1]. Technical knowledge alone is no longer enough. Employers increasingly expect high-level collaborative problem-solving (CPS) skills and strong self-efficacy (SE) [2], [3]. This mismatch between graduate output and workforce demand highlights a pressing need for instructional reform. Consequently, higher education institutions are shifting from traditional, single-discipline teaching toward interdisciplinary approaches. These educational strategies aim to build transversal skills and better prepare students for real-world, ill-structured challenges [4], [5]. To build these collaborative and cognitive competencies, problem-based learning (PBL) and cooperative learning (CL) are widely recognized as effective strategies rooted in social constructivism [6]–[8]. However, navigating complex, interdisciplinary tasks imposes high cognitive and psychological demands. When placed in unstructured groups without effective scaffolding, students often struggle with low SE and conflict avoidance [9]. This leads to superficial teamwork and increased frustration [9], [10]. While PBL is frequently adopted, it is often implemented without explicit collaborative scaffolding, resulting in inefficient teamwork and unequal participation [9], [11]. Furthermore, existing empirical studies on PBL and CL predominantly focus on K-12 settings [12] or single-discipline courses such as clinical medicine [13]. This leaves interdisciplinary STEM higher education largely underexplored. Without validated modules, universities risk continuing fragmented instruction that fails to prepare students for integrated engineering challenges [14], [15]. Therefore, there is a critical need for a standardized, validated instructional module that systematically integrates CL structures into the PBL framework.

To address this gap, this study aims to systematically engineer and validate an instructional module that operationalizes abstract cooperative principles to effectively support CPS and SE. The specific objectives are: i) to design a cooperative problem-based learning (CPBL) module that embeds structured cooperative scaffolding into complex interdisciplinary STEM tasks, and ii) to evaluate the content validity, usability, and pilot feasibility of the module. The core research question is: how can an instructional module be systematically engineered and validated to operationalize cooperative principles for CPS and SE in interdisciplinary STEM higher education?

This study employs the Dick *et al.* [16] instructional design model to develop the CPBL module, applying it to a complex mechanical design task. Crucially, this research proposes a "dual-driven" mechanism that systematically integrates CL into a validated PBL framework, providing a validated CPBL module tailored for interdisciplinary STEM higher education. Unlike traditional PBL, this module ensures equity through structured, gender-inclusive scaffolding, such as mandatory role rotation and the inclusion of female role models. This study contributes a methodologically rigorous framework bridging abstract pedagogical theory with classroom reality. It explicitly creates a cognitive-psychological synergy that simultaneously enhances students' transversal skills (CPS) and psychological resilience (SE). Theoretically, it expands instructional design literature by demonstrating how collaborative scaffolding synergizes skill acquisition and psychological readiness. Practically, it provides educators with a validated, ready-to-use tool to break disciplinary silos. Finally, this research offers policymakers an evidence-based framework to operationalize large-scale educational reforms, particularly the "new engineering" initiative globally and within Chinese higher education [17], [18]. Despite policy mandates to remove disciplinary barriers and cultivate composite talents, a significant gap remains between educational rhetoric and classroom reality [14], [15]. STEM instruction remains fragmented, with lecture-based delivery dominating [18], [19]. This isolation prevents students from developing genuine interdisciplinary thinking. It sustains a "structural contradiction" where universities produce a surplus of STEM graduates, yet employers consistently report a shortage of talent capable of cross-disciplinary application and innovation [10], [13], [19], [20]. By providing a tailored CPBL module, this study directly addresses this systemic mismatch.

2. THEORETICAL FRAMEWORK

2.1. Problem-based learning

PBL reverses traditional instruction by utilizing ill-structured, real-world problems to stimulate self-directed inquiry and simulate professional STEM practice [9], [21]. However, unstructured PBL often results in cognitive overload, social loafing, or dominant behaviors by high-achieving students [9], [22]. Without explicit guidance, students may often struggle with the open-endedness of the problems, especially those accustomed to rote learning, leading to cognitive overload or inefficient trial-and-error strategies [9], [23], [24].

2.2. Cooperative learning

To address the collaborative deficits in PBL, CL offers a structured solution. CL is a learner-centered teaching strategy, always occurs when individuals in a team communicate and cooperate to achieve a common learning goal [6], [25]. Johnson and Johnson [8] posited that simply placing students in groups does not constitute CL; true cooperative activities must incorporate five basic elements: positive interdependence, where members perceive that they cannot succeed unless everyone succeeds; individual accountability, ensuring each member contributes; promotive interaction, facilitating face-to-face support; interpersonal skills, such as communication and conflict resolution; and group processing, where teams reflect on their effectiveness [8]. Integrating CL principles into STEM education has been proven to enhance students' psychological safety and engagement. By structuring how students interact, CL reduces the anxiety associated with complex tasks and promotes a supportive academic learning environment.

2.3. The conceptual framework of CPBL module

This study proposes a CPBL conceptual framework that systematically synthesizes Tan [26] five-phase PBL cycle with Johnson [8] CL elements. This study deliberately utilizes CL as the structural pedagogical mechanism (the scaffold), by engineering rigid positive interdependence and individual accountability, the cooperative structures act as a necessary intervention to compel and sustain the high-level collaborative behaviors required to solve complex problems. Table 1 outlines the theoretical foundations underpinning the CPBL module's specific activities.

Table 1. The different theory related to CPBL module

Theoretical support	Contributions	Examples embodied in the CPBL module
Constructivism theory	Learning is a process in which learners actively explore and construct new knowledge based on prior experience [21]	Students engage in active thinking about real engineering problems and construct new understandings of their knowledge based on self-directed research and discussion.
Social constructivism	Knowledge is constructed through social interaction. The "zone of proximal development" of Vygotsky provides collaborative scaffolding mechanisms [27].	Emphasis on effective group discussion processes and interactions between groups. Emphasis on peer learning processes, especially for the highly skilled.
Social cognitive theory	Reciprocal interactions model [14].	Emphasis on positive feedback from peers and teachers. Enhance behavior by collaborative environment in CPBL module.

2.4. Target competencies: collaborative problem-solving and self-efficacy

The CPBL module targets two primary student outcomes. The first, CPS is defined by the Programme for International Student Assessment (PISA) 2015 framework as a multidimensional construct where agents share understanding and effort to reach a solution [28]. This framework intersects the interaction between social competence and problem-solving ability, comprising 12 sub-skills. While CPS is the target competency, spontaneous collaboration often fails in STEM classrooms; therefore, the CPBL's structured cooperative mechanisms are designed to explicitly train CPS skills through these three sub-dimensions [28]. The second outcome, SE is rooted in social cognitive theory and reflects an individual's belief in their capacity to execute necessary behaviors [14], [29]. In STEM higher education, SE is a strong predictor of academic persistence, motivation, and career choice [7], [13]. Students with high SE view difficult engineering tasks as challenges to be mastered rather than threats to be avoided. Bandura [14] identifies mastery experiences, vicarious experiences, social persuasion, and physiological states as SE's primary sources. Traditional lectures rarely offer complex mastery experiences, diminishing student confidence. Conversely, the CPBL module directly enhances SE by providing scaffolded mastery milestones through the PBL phases and rich vicarious experiences via intensive peer interaction.

3. METHOD

3.1. Research design

This study employed a research and development design, utilizing the systematic Dick *et al.* [16] instructional model to construct and validate the CPBL module. Rather than a generic application, the module was specifically contextualized within a "fundamentals of mechanical design" course for undergraduate energy and power engineering (EPE) students. The whole module can be deployed according to the length of a specific course, and tutors can extend the CPBL cycle by adding time for student independent learning or collaborative activities depending on the topic of the course. Learner analysis revealed a significant lack of practical experience and distinct gender-based preferences regarding collaborative tasks, necessitating a blended pedagogical strategy. Subsequently, specific behavioral objectives were drafted, and a dual-evaluation system was established to assess technical competency alongside CPS and SE. Consequently, the instructional strategy was designed to integrate Tan [26] five-phase PBL model with Johnson and Johnson [8] CL principles. As illustrated in Figure 1, this blended framework systematically embeds CPS 12 sub-skills and the four sources of SE across five iterative learning phases to balance independent inquiry with structured teamwork [14], [28].

3.2. Participants

The validation process involved two distinct groups. The multidisciplinary expert panel comprised six specialists (two in mechanical engineering, two in STEM education, and two linguists) selected via purposive sampling to evaluate content accuracy, pedagogical alignment, and linguistic clarity. This sample size aligns with established methodological guidelines [30], which suggest that a panel of 5 to 10 experts provides sufficient control for chance agreement while ensuring diverse, comprehensive evaluation. Subsequently, a pilot sample of 33 second-year EPE undergraduates participated in a preliminary trial to assess the module's practical feasibility and the internal consistency of the measurement instruments. This sample size was determined based on the statistical rule of thumb for preliminary instrument reliability testing (N>30), enabling a realistic and statistically viable preliminary examination of the module's applicability and effectiveness in an authentic educational context. Although the pilot involved 33 students from one program, this group reflects the typical demographic and academic characteristics of Chinese STEM undergraduates, making the findings highly relevant for this initial validation. All students provided informed consent and participated anonymously to minimize self-report bias.

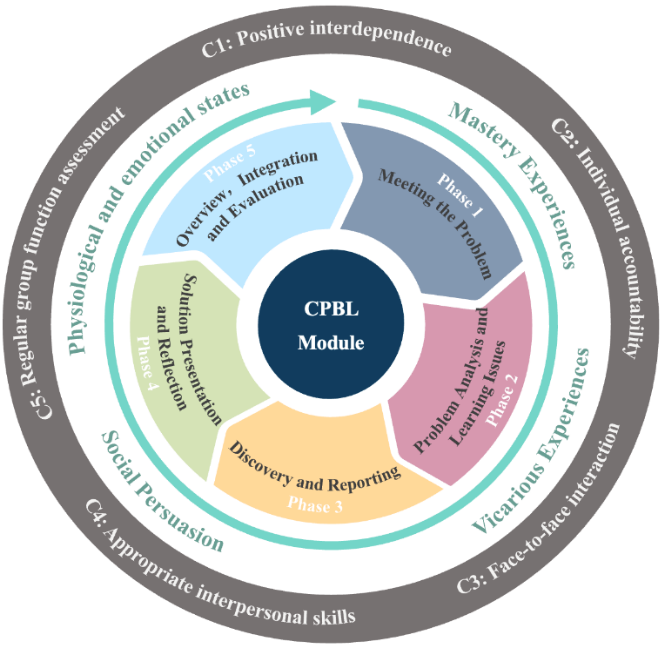

Figure 1. CPBL cycle integrating PBL and CL principles

3.3. Instruments

To rigorously evaluate the intervention, a custom 33-item validation instrument was developed to assess the module's content quality, activity design, and phase structure on a 4-point relevance scale (Appendix A). During the pilot phase, target competencies were measured using two standardized tools. The collaborative problem-solving scale (CPSS) [28], based on the PISA 2015 framework, comprises 12 items across three dimensions: establishing and maintaining shared understanding, taking appropriate action, and establishing and maintaining team organization (Appendix B). The general self-efficacy scale (GSES) [31], consists of 10 items measuring two distinct dimensions: action SE and coping SE (Appendix C). Additionally, a post-pilot open-ended survey was administered to capture students' direct qualitative feedback on cognitive load, instructional clarity, and group dynamics.

3.4. Data analysis

Data collected from the validation and pilot phases were analyzed using both quantitative and qualitative methods to ensure a rigorous evaluation. Quantitative expert consensus was measured using the item-level content validity index (I-CVI) and scale-level content validity index/average (S-CVI/Ave). Items scoring, I-CVI<0.78 were flagged for mandatory revision. For the pilot data, the internal consistency and reliability of the CPSS and GSES were evaluated via Cronbach's alpha and inter-item correlation analyses using SPSS. Furthermore, thematic analysis was also conducted on qualitative data such as written comments and students' open-ended survey responses in the expert panel's evaluation guidelines. This process involved coding the feedback into specific operational categories (e.g., "scaffolding needs," "gender dynamics," "instructional clarity") to directly guide the evidence-based, iterative revisions of the module.

4. RESULTS AND DISCUSSION

The initial validation of the CPBL module utilized a structured review by a multidisciplinary panel of six experts. The CVI served as the primary quantitative metric to assess theoretical and pedagogical alignment.

4.1. Validation of content validity and iterative refinement

To evaluate the content validity of the module, the CVI was analyzed at both the item level (I-CVI) and the scale level (S-CVI/Ave). Based on Polit and Beck [32] criteria, an I-CVI of ≥0.78 and an S-CVI of ≥0.90 indicate excellent content validity. As shown in Table 2, 30 of the 33 evaluation items (91%) achieved an I-CVI of 1.00. Three items scored slightly lower (I-CVI=0.83), quantitatively corroborating the qualitative feedback. These items related to "integration of SE/CPS" (Item 9), "gender inclusivity" (Item 15), and "support for low-ability learners" (Item 17). Overall, the S-CVI/Ave reached 0.98, providing strong empirical evidence that the module is structurally sound.

Table 2. Results of the evaluation of the content validity of the CPBL module

Number	No. of experts in agreement (rated 4 or 5)	I-CVI (item-level)
A. Content (10 items)		
Item 1-6, 8, 10	6/6	1
Item 7	6/6	1
Item 9	5/6	0.83
B. Activities (10 items)		
Item 11-14, 16, 19-20	6/6	1
Item 15	5/6	0.83
Item 17	5/6	0.83
Item 18	6/6	1
C. CPBL module phases (13 items)		
Phase 1-5 items	6/6	1
Total items		
S-CVI/Ave		0.98

These indices provide strong empirical evidence that the module content is structurally sound and pedagogically appropriate. However, the slightly lower consensus on inclusivity and scaffolding items quantitatively aligned with the qualitative linguistic validation: while readability and clarity achieved 100% expert agreement, terminology consistency received only a 50% agreement rate. Specifically, three experts pointed out inconsistencies in technical terminology (e.g., mixing "stress coefficient" and "stress concentration factor") and overly complex instructional paragraphs. Following these targeted revisions, the linguistic content was deemed highly valid and accessible for the target students.

Beyond quantitative scoring, the panel provided qualitative feedback that guided targeted revisions. For example, two associate professors praised the theoretical accuracy of the module. However, they pointed out that the initial draft of phase two (problem analysis) lacked sufficient connection to authentic industrial contexts. One expert noted, "*although the principles of gear rotation in Module 4 are clearly presented, students would benefit greatly if they could see how these calculations are directly applied to fault diagnosis in modern wind turbine gearboxes. At present, the problems appear somewhat academic in nature*." Therefore, the revised version of the CPBL module directly used real engineering photos and background stories of wind turbine gearbox fractures to enhance the realism of the mission. To further refine clarity and address expert concerns regarding ambiguities, technical terminology was standardized (e.g., uniformly replacing "stress coefficient" with "stress concentration factor"), long activity instructions were rewritten into short, numbered steps, and a bilingual glossary was created. Additionally, initially broad learning objectives (e.g., "Students will understand gear design principles") were rewritten using measurable verbs, ensuring students can "calculate stress distribution for spur gears and evaluate design alternatives in collaborative groups."

Furthermore, reviewers expressed concern that the task complexity could overwhelm students with lower prior knowledge. An expert observed, "*the group discussion template is a promising starting point, but weaker students need clearer guidance to connect individual thinking with group collaboration.*" In response, a structured "discussion record template" was introduced, dividing the broader task into manageable prompts such as "what we need to know" and "our action list." To provide more targeted support and explicitly operationalize SE theory within these activities, a "design principles" section was added to the module handbook. The research team mapped Bandura [14], four sources of SE to specific instructional actions: i) mastery experiences were built by decomposing the large-scale design task into three progressive subtasks ('force analysis' to 'material selection' to 'strength verification'); ii) vicarious experiences were integrated via two short video interviews with outstanding alumni sharing their project experiences; iii) verbal persuasion was implemented by training teachers to provide concrete, encouraging feedback (e.g., "your preliminary design has taken dynamic loading into account, which represents a significant step forward"); and iv) physiological and emotional states were regulated by introducing a three-minute mindfulness breathing exercise prior to intensive group discussions to reduce student anxiety.

Reviewers also highlighted the need to operationalize gender inclusivity more explicitly. The expert suggested that the roles themselves should be more explicitly defined to enhance accountability. Specifically, providing students with “role cards” that clearly outline the responsibilities of the facilitator, recorder, and summarizer at the initial stage was recommended as a useful strategy. Based on this feedback, researchers introduced a role rotation system in the revised version of the module. It explicitly stipulates that male and female students must take turns serving as facilitators or speakers, and includes more inspirational examples of female engineers to foster an inclusive learning environment. To further strengthen this proactive integration of diverse perspectives, the first class uses the story of Beatrice Hicks founding the Society of Women Engineers to reframe student teams as “mini engineering societies,” while the systems modeling and computation section highlights Edith Clarke’s invention of the graphical calculator. Furthermore, to avoid role duplication and address assessment issues, guided questions tailored to the roles undertaken that day were incorporated into a post-session self-reflection form to facilitate self-assessment. This equity mechanism ensures that female students are not relegated to passive roles (e.g., mere note-takers) and male students do not monopolize technical decision-making, thereby fostering a genuinely inclusive learning environment. All those feedback highlighted gaps between theoretical design and practical application, necessitating the targeted, evidence-based revisions detailed.

4.2. Feasibility and reliability of instruments

During the pilot study, the internal consistency of the CPSS and the GSES was assessed using Cronbach’s alpha (α). Both the total CPSS (Cronbach’s α=0.870) and the total GSES (Cronbach’s α=0.808) demonstrated high reliability, exceeding the recommended threshold of 0.70 [33]. Inter-item correlation analysis for the CPSS, as shown in Table 3, indicated that items within each dimension are appropriately related (Pearson correlation coefficients range from 0.401 to 0.759, all $p<0.05$). Similarly, the inter-item correlation matrix for the GSES, as seen in Table 4, validated that item within each subscale are positively and significantly correlated (Pearson correlation coefficients range from 0.306 to 0.740, $p<0.05$). These initial results suggest the instruments reliably measure the multidimensional nature of collaborative skills and students’ confidence in initiating interdisciplinary tasks within this pilot context. Ultimately, the high content validity of the module and the reliability of the measurement instruments indicate the study is methodologically sound for full-scale implementation.

Table 3. The correlation analysis of items with different dimensions in CPSS scale

Dimensions	Items	1	2	3	4	5	6	7	8	9	10	11	12
CPS-A	1												
	2	0.505**											
	3	0.716**	0.714**										
	4	0.660**	0.586**	0.670**									
CPS-B	5												
	6					0.596**							
	7					0.539**	0.742**						
	8					0.622**	0.759**	0.737**					
CPS-C	9												
	10									0.631**			
	11									0.401*	0.492**		
	12									0.560**	0.478**	0.641**	

**. Correlation is significant at the 0.01 level (2-tailed). CPS-A=Establishing and maintaining shared understanding; CPS-B=Taking appropriate action to solve the problem; CPS-C=Establishing and maintaining team organization.

Table 4. Correlation analysis of items with different dimensions in self-efficacy

Dimensions	Items	1	2	3	4	5	6	7	8	9	10
ASE	1										
	2	0.688**									
	3	0.444**	0.468**								
	4	0.619**	0.610**	0.405*							
	5	0.740**	0.603**	0.414*	0.644**						
CSE	6										
	7						0.377*				
	8						0.400*	0.452**			
	9						0.306	0.725**	0.457		
	10						0.506**	0.493**	0.585	0.631**	0.533**

**. Correlation is significant at the 0.01 level (2-tailed).
ASE=Action self-efficacy; CSE=Coping self-efficacy

4.3. Critical analysis of the "dual-driven" mechanism

This study was initiated to address the instructional design gap in interdisciplinary higher STEM education, specifically the disconnect between the demand for interdisciplinary competencies and the prevalence of fragmented, lecture-based pedagogy. As highlighted in the introduction, while the 'new engineering' initiative advocates for integration, current educational practices often lack the systematic scaffolding required to support complex, cross-disciplinary learning. This study successfully developed and validated a gender-inclusive CPBL instructional module. The findings provide robust empirical evidence: the module demonstrated exceptional content validity and high instrument reliability, confirming that an evidence-based design can effectively operationalize abstract competency goals into actionable classroom interventions. This success aligns with social constructivist theory. As Vygotsky [27] posited, cognitive development is socially situated. However, while PBL emphasizes real-world problem-solving, it often fails to ensure equitable participation in practice, frequently leading to unstructured group dynamics where some students dominate while others withdraw [6]. Our findings suggest that meaningful interaction does not occur through mere proximity [34]. Simply placing students in groups does not automatically yield collaboration, especially given cultural tendencies toward passive learning or conflict avoidance in traditional classrooms [6]. By systematically embedding cooperative structures, the CPBL module directly addresses this weakness. The expert validation indicates that the CPBL module works specifically because it enforces "positive interdependence". By embedding specific mechanisms, such as the failure diagnosis matrix, the module functions as a structural intervention that forces students to rely on one another's diverse disciplinary knowledge. These scaffolds prevent the common "divide-and-conquer" approach to group work; instead, they require students to externalize their thinking and actively negotiate meaning, theoretically transforming peers into indispensable cognitive resources within the zone of proximal development.

This study also addresses the challenge of translating Bandura [14] social cognitive theory into actionable curriculum. In traditional Chinese STEM classrooms, the exam-oriented culture often restricts opportunities for mastery experiences, which are a primary source of SE [10]. This theoretical alignment was achieved by explicitly engineering the sources of SE into the daily workflow. For instance, as validated by the expert panel, decomposing complex gear design tasks into progressive milestones provides the structural capacity for students to accumulate small successes, countering the anxiety often produced by high-pressure environments. The high reliability and positive preliminary results of the CPS and SE measures suggest that the structured role rotation and cooperative scaffolding successfully activated Bandura [14] sources of SE, particularly vicarious experiences and social persuasion. Similarly, the deliberate design of peer modeling in Phase 3 creates targeted opportunities for students to observe peers overcoming challenges. Additionally, by redefining the teacher's role from a transmitter of knowledge to a facilitator, the module ensured that feedback was process-oriented rather than just result-oriented [7]. These findings critically analyze how the CPBL module operates as a "dual-driven" mechanism: it simultaneously lowers the cognitive threshold for complex tasks through collaborative scaffolding (enhancing CPS) while structurally guaranteeing opportunities for mastery and vicarious experiences (enhancing SE). Moving forward, this framework offers a practical approach for educators to integrate mental resilience building directly into rigorous engineering curricula, proving that psychological support and technical training are mutually reinforcing.

4.4. Structural disruption for gender inclusivity

Furthermore, an important contribution of this study is its approach to gender inclusivity. Literature indicates that female students in Chinese STEM contexts often face stereotype threats and report lower SE due to cultural expectations [29]. While many educational interventions stop at mere verbal encouragement, this module enacts structural disruption. Mandatory role rotation disrupted traditional gendered task divisions, ensuring that female students gained direct technical experience (e.g., as technical facilitators) while male students equally engaged in collaborative dialogue and recording. The integration of female role models like Hicks directly counters the masculine narrative typically associated with engineering. By institutionalizing this equity architecture, the module actively dismantles hegemonic behaviors where male students typically dominate technical tasks. It creates a safe, accountable space where participation is dictated by assigned role responsibilities rather than entrenched gendered norms, effectively ensuring equitable skill acquisition for all learners.

4.5. Implications and limitations of the study

The findings of this study offer highly actionable insights extending beyond theoretical validation. At the classroom level, the CPBL framework can be integrated into existing mechanical design courses with minimal restructuring, providing frontline STEM instructors with a ready-to-use pedagogical tool. It demonstrates that interdisciplinary teaching does not require diluting technical content, but rather restructuring how students interact with it. At the policy level, this validated module offers policymakers and institutional leaders a practical, scalable tool to operationalize the 'new engineering' initiative, translating top-down interdisciplinary mandates into equitable, bottom-up classroom realities. However, this study's single-institution pilot sample (N=33) restricts immediate generalizability, and evaluating CPS and SE via self-reported scales introduces inherent subjectivity, despite anonymous data collection. Future research should evaluate the refined module through a full-scale, multi-institutional quasi-experimental design, incorporating objective behavioral analytics (e.g., recorded group interactions) alongside self-reports to comprehensively assess the evolution of collaborative and psychological competencies.

5. CONCLUSION

This study developed a validated CPBL module to address a gap in instructional design within Chinese interdisciplinary STEM education. Framed as a "dual-driven" approach, the module appears to support both CPS and students' SE by intentionally structuring social interdependence to reduce fragmented learning experiences. The study suggests three implications. Methodologically, it indicates that the development of higher-level CPS may benefit from purposeful social interdependence in STEM learning contexts. Sociologically, it points to the potential of structural arrangements, such as mandatory role rotation, to support more inclusive gender participation. Practically, it translates abstract sources of SE into classroom strategies that are more actionable for teachers. Overall, the CPBL module shows promise in terms of validity, feasibility, and reliability, and may provide a useful framework for interdisciplinary STEM education.

Despite these contributions, the long-term impact of this pedagogical intervention requires further investigation. The initial validation relied on a pilot cohort (N=33) and self-reported metrics, leaving it unclear whether these enhanced competencies persist once the CPBL structural scaffolds are removed. Further studies should test the module across diverse institutions and larger samples. Future research must also incorporate objective behavioral analytics, such as coding recorded group interactions, alongside self-reported data to rigorously quantify learning outcomes. Exploring the long-term retention of these skills will fully establish the CPBL framework's capacity to align graduate outcomes with the complex demands of the modern STEM labor market.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [KO], upon reasonable request.

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APPENDIX

Appendix A: CPBL instructional module content validity expert validation form

Dear expert: Thank you for agreeing to validate the cooperative problem-based learning (CPBL) instructional module. The purpose of this validation is to assess the **relevance**, **representativeness**, and **clarity** of the module's content and activities in relation to the instructional goals (enhancing STEM competencies). Please rate each item using the 4-point content validity scale below. We also invite your qualitative suggestions for any item rated 1 or 2.

Rating scale:

– 1 = not relevant (the item is not appropriate for the module’s goals).
– 2 = somewhat relevant (the item needs major revision to be relevant).
– 3 = quite relevant (the item is relevant but needs minor alteration).
– 4 = highly relevant (the item is appropriate and essential).

No.	Items (assessment criteria)	Relevance rating (1-4)				Suggestions for revision (especially for ratings <3)
A. Content		1	2	3	4	
1	Content includes knowledge and skills specified in the fundamental machine engineering.					
2	Concepts, facts and terms are correct and up-to-date.					
3	Concepts, facts and terms are accurate.					
4	Instructional strategies follow the concept of constructivism and social cognitive theory.					
5	Instructional strategies follow the structures and problem-based learning and the principle of cooperation learning.					
6	Order of content is presented based on the section III principle of mechanics and section IV mechanical engineering design					
7	The content relates knowledge, skills and values learnt with its application in the realm of work and daily life.					
8	Knowledge and skills are introduced from easy to complex.					
9	The approach of introducing training SE and CPSS proficiency in the CPBL module is appropriate.					
10	The processing of materials is designed and easy to follow.					
B. CPBL Module activities		SD	D	U	A	SD
11	Activities are appropriate and allow the learner to master concepts and skills and achieve learning outcomes.					
12	Activity offerings can stimulate the curiosity of the learner.					
13	Activities involve students collaborate in groups.					
14	Activities can guide learners to find appropriate solutions to research questions.					
15	Activities emphasis the principle of gender inclusive.					
16	Activities can make students realize the value and importance of engineering design in their studies and daily life.					
17	Activities are appropriate for students at high and low-ability stage learners.					
18	Activities emphasize the development of proficiency in the SE and CPSS.					
19	Directions and steps in activities are easy to understand, clear, complete and precise.					
20	This activity is designed to improve students' understanding of Section III Principles of Mechanics and Section IV Mechanical Engineering Design.					

No.	Items (assessment criteria)	Relevance rating (1-4)				Suggestions for revision (especially for ratings <3)
C. CPBL Module phase		SD	D	U	A	SD
21	The learning process begins with the identification of a problem that needs to be solved.					
22	The activity activates the learner's existing knowledge.					
23	Activities allow learners to make existing knowledge connections to unknown knowledge.					
24	Activities allow learners to identify cognitive biases and knowledge gaps					
25	Students have the opportunity to participate in group discussions and gather information.					
26	Activities allow learners to use existing knowledge to generate new ideas and explore issues					
27	Students can practice the skills required to solve problems to achieve the learning outcomes.					
28	Activities allow other peers to share and exchange ideas about their existing ideas					
Phase 4 Solution presentation and reflection		SD	D	U	A	SD
29	Learners have opportunities to share with peers, exchange ideas and get feedback.					
30	Students have the opportunity to gain a deeper understanding of the problem and demonstrate solutions.					
31	Students have opportunities to reflect on their knowledge and proficiency.					
32	Learners receive additional information and adequate skills.					
33	Teachers evaluate students' knowledge and proficiency in the learning outcomes.					
34	Directions and steps in activities are easy to understand, clear, complete and precise.					

Appendix B

The collaborative problem-solving scale (CPSS) is an instrument based on the PISA (2015) CPS rubric. The scale is used to assess the level of the 12 key skills in the CPS framework matrix. Please read each item carefully, try to understand the contents of the items, and select the corresponding option based on your judgement of yourself. Try to be as honest as possible when responding to each item. There are no right or wrong answers, so answer based on your personal behavior or experiences. There are 12 items in this scale and each item has three options, with A, B and C representing scores of 0, 1 and 2 respectively.

Items	Options
1. When it comes to discovering the perspectives and abilities of your teammates, which statement best describes you?	A. I do not share information about myself when asked, nor do I inquire about the abilities and perspectives of other group members. B. I share information about myself when asked, but I do not inquire about the abilities and perspectives of other group members. C. I share information about myself when asked, and I also inquire about the abilities and perspectives of other group members.
2. In understanding the necessary interactions and goals to solve a problem, which statement best describes you?	A. I neither respond to requests from my teammates nor inquire about the actions, tasks, and plans needed to solve the problem. B. I respond to requests from my teammates, but I do not inquire about the actions, tasks, and plans needed to solve the problem. C. I respond to requests from my teammates and also inquire about the actions, tasks, and plans needed to solve the problem.
3. Regarding understanding the roles required to solve a problem, which statement best describes you?	A. I neither acknowledge nor inquire about the roles of other group members and my actions suggest I am trying to solve the problem by myself. B. I acknowledge the roles of other group members but do not inquire about them. My actions show I am aware that I am part of a group. C. I both acknowledge and inquire about the roles of other group members, taking the initiative to understand what different roles are needed.
4. When it comes to building a shared understanding of a problem, which statement best describes you?	A. I neither respond to nor initiate requests for clarification about the problem's goals, constraints, tasks, or roles. B. I respond to requests for clarification about the problem's goals, constraints, tasks, or roles, but I do not initiate these requests myself. C. I both respond to and initiate requests for clarification about the problem's goals, constraints, tasks, and roles.

Items	Options
5. In terms of identifying and describing the tasks that need to be completed, which statement best describes you?	A. I do not acknowledge or confirm tasks when prompted, nor do I take the initiative to identify, propose, describe, or change tasks. B. I acknowledge or confirm tasks when prompted, but I do not take the initiative to identify, propose, describe, or change them. C. I both acknowledge or confirm tasks when prompted and take the initiative to identify, propose, or change them, especially when we face obstacles.
6. With regard to describing roles and team organization, which statement best describes you?	A. I do not acknowledge or confirm my role or others' roles when prompted, nor do I take the initiative to propose or change roles. My actions suggest I am working alone. B. I acknowledge or confirm my role and the roles of others when prompted, but I do not take the initiative to propose or change them. C. I both acknowledge and take the initiative to propose or change roles, and I suggest reassigning roles if the situation changes or a team member is not contributing.
7. How do you typically communicate with your team about actions and tasks? Which statement best describes you?	A. I do not communicate with my team about the completion of my tasks, and I do not ask others about their tasks. B. I communicate about my tasks when asked, but I do not proactively share this information or ask others about their progress. C. I communicate about my tasks when asked, and I also proactively share updates and ask my teammates about their progress.
8. When it comes to putting plans into action, which statement best describes you?	A. I do not take actions that follow the team's plan for tasks, nor do I help solve unexpected problems B. I take actions that follow the team's plan for tasks, but I do not take action to solve unexpected problems. C. I take actions that follow the team's plan for tasks, and I also take action to solve unexpected problems.
9. Regarding following team rules and fulfilling your role, which statement best describes you?	A. I do not follow the planned tasks for my role, and I do not respond appropriately when asked to complete my assignment. B. I follow the planned tasks for my role and respond appropriately when asked, but I do not prompt other team members to complete their tasks. C. I follow the planned tasks for my role, respond appropriately when asked, and also take the initiative to prompt others to complete their assignments.
10. When it comes to monitoring and fixing misunderstandings within the team, which statement best describes you?	A. I do not acknowledge gaps or errors in our shared understanding when prompted, nor do I try to troubleshoot or repair these misunderstandings. B. I acknowledge gaps or errors in our shared understanding when prompted, but I do not take action to troubleshoot or repair them. C. I acknowledge gaps or errors when prompted, take action to troubleshoot potential issues, and take the initiative to repair misunderstandings.
11. In monitoring progress and dealing with obstacles, which statement best describes you?	A. I do not acknowledge, describe, or troubleshoot obstacles when they occur, nor do I help create new plans to overcome them. B. I acknowledge and describe obstacles when they occur, but I do not take action to troubleshoot them or help create new plans to overcome them. C. I acknowledge and describe obstacles, take action to troubleshoot them, and help create new plans to overcome them.
12. When it comes to monitoring and adapting the team's structure and roles, which statement best describes you?	A. I do not acknowledge, describe, or troubleshoot problems with our team's organization or roles, nor do I communicate with others to make changes. B. I acknowledge and describe problems with our team's organization or roles, but I do not take action to troubleshoot these problems or communicate with others to make changes. C. I acknowledge and describe problems with our team's organization or roles, take action to troubleshoot them, and communicate with others to make necessary changes.

Appendix C

The general self-efficacy scale measures your perceived self-efficacy or belief in your ability to cope with different situations and accomplish goals. Please read each item carefully and try to understand what it is asking. Respond to each item based on your agreement or disagreement with the statement. Check the box of the response that best describes your view. Try to be as honest as possible when responding to each item. There are no right or wrong answers, so answer based on your personal experiences and beliefs.

1="not true at all" 2="hardly true" 3="moderately true" 4="exactly true"

	Items	Score			
1.	I can always manage to solve difficult problems if I try hard enough.				
2.	If someone opposes me, I can find the means and ways to get what I want.	1	2	3	4
3.	It is easy for me to stick to my aims and accomplish my goals.	1	2	3	4
4.	I am confident that I could deal efficiently with unexpected events.	1	2	3	4
5.	Thanks to my resourcefulness, I know how to handle unforeseen situations.	1	2	3	4
6.	I can solve most problems if I invest the necessary effort.	1	2	3	4
7.	I can remain calm when facing difficulties because I can rely on my coping abilities.	1	2	3	4
8.	When I am confronted with a problem, I can usually find several solutions.	1	2	3	4
9.	If I am in trouble, I can usually think of a solution.	1	2	3	4
10.	I can usually handle whatever comes my way.	1	2	3	4

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