Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

An Assessment Framework for Interdisciplinary Competence of Engineering Students Based on Combination Weighting Method

Zhiwei Qi
Yunnan University
Wei Xu
xuwei1132@stu.ynu.edu.cn

Yunnan University
Yuqing Liu
Yunnan University
Wenlin Liu
Yunnan University

Article

Keywords: engineering students, interdisciplinary competence, assessment framework, combination weighting method

Posted Date: March 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8942296/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

The interdisciplinary competence of engineering students (ICES) is critical to addressing complex engineering challenges in social, cultural, and economic contexts. However, there are few studies on the assessment of engineering students' interdisciplinary competence, and a comprehensive assessment framework has not yet been established. Therefore, we develop a framework for assessing the ICES. First, a set of initial assessment indicators for interdisciplinary competence is proposed by analyzing relevant studies on the assessment of interdisciplinary competence. Subsequently, the Delphi method is adopted to conduct expert consultations, and an assessment framework for ICES is formed that consists of 5 first-level indicators: cognition, thinking, socializing, practice, and reflection. Finally, we use the combination weighting method to determine the weights of each indicator and analyze the development situation, group differences, and students' attitudes towards interdisciplinary competence among five polytechnic colleges in China. Analysis results showed that the overall ICES scores were relatively low with significant group differences. To investigate the reasons for the low ICES scores, we conducted interviews with 30 participants and found that school curricula, assessment methods, and teacher's guidance were the main factors hindering the development of ICES.

1 Introduction

As engineering knowledge systems are becoming increasingly complex and integrated, traditional single-discipline engineering knowledge and skills have become inadequate for effectively addressing multifaceted and systemic engineering challenges (Xu & Wu, 2025; Beldad & Miedema, 2025; Wang et al., 2025). This trend has imposed new requirements on engineering talent cultivation, as engineers with single-disciplinary backgrounds can no longer adapt to future developmental needs. Consequently, developing interdisciplinary competence has emerged as a critical direction for higher engineering education reform (Xia et al., 2026). Furthermore, technological breakthroughs and scientific discoveries often emerge at the intersection of different disciplines (Mahringer et al., 2023; Sun et al., 2024). From 1901 to 2024, 227 Nobel Prizes in natural sciences were won. Among the winners, the proportion with interdisciplinary backgrounds rose from 35% to 71.4%. This data indicates the contemporary trend where scientific breakthroughs heavily rely on interdisciplinary integration. Engineers with interdisciplinary competence are better equipped to explore and seize innovation opportunities, drive technological progress, and effectively tackle comprehensive challenges in complex engineering projects (Zhang et al., 2025; Donatelli et al., 2025). Developing the interdisciplinary competence of engineering students (ICES) aligns with the inherent logic of engineering education development and ensures that future engineering talents maintain core competitiveness in an intensely competitive marketplace.

An effective framework for assessing ICES is essential for the quality of engineering education, which provides clear feedback for engineering educators and thus truly achieves the goal of developing interdisciplinary engineering talents. However, existing research and practice in the assessment of ICES have faced some challenges: (a) Lack of a systematic assessment framework (Sajdakova et al., 2022; Feng et al., 2025). The engineering field highly demands core competencies like practical application,

innovation, critical reflection, and teamwork (Guo et al., 2025), but existing assessment instruments for interdisciplinary competence often fail to capture these dimensions holistically. (b) Lack of scientific methods for determining indicator weights. Single-method determination of indicator weights has limitations: subjective methods are susceptible to the personal experience and biases of assessors; objective methods often overlook implicit issues, such as the adaptability of assessment scenarios and content, thereby weakening the effectiveness of indicator weights.

Action learning theory focuses on real-world problems and is often used to improve students' problem-solving competence by engaging students in real problem-driven, teamwork, doing, and reflection refinement (Zuber-Skerritt & Wood, 2019). This core logic aligns with the practical needs of engineering education, which involves solving complex engineering problems, integrating interdisciplinary resources, and achieving technological implementation. Therefore, adopting this theory as the theoretical foundation for the ICES assessment framework ensures the consistency between the assessment direction and the training objectives of engineering education.

Our research aims to address the following questions in view of the above analysis:

1. What are the core elements of ICES?
2. How to ensure the validity and reliability of our ICES assessment framework?
3. What is the current situation of ICES development?

2 Literature review

2.1 Core elements of interdisciplinary competence

Interdisciplinary competence is an observable and measurable sustainable competence to solve practical problems by using multiple disciplines. We summarize the core elements of interdisciplinary competence via a review of relevant research into four aspects.

2.1.1 Knowledge integration and multidimensional analysis

Knowledge integration is the foundation of interdisciplinary innovation (Allen, 2021; Voge & Hunecke, 2024). Steinheider et al. (2009) suggested that knowledge integration was a core predictor of success in interdisciplinary teams. When students faced interdisciplinary problems, they often generated diverse perspectives based on different disciplinary backgrounds (Lam, 2025). However, a genuine understanding of the interdisciplinary problem did not simply involve combining these disciplinary perspectives, which required identifying the underlying connections among these perspectives to form

an integrated interdisciplinary understanding (Svingen et ai., 2026). This required students to actively link different scientific perspectives and identify their logical relationships. Multidimensional analysis was the practical application of knowledge integration, which enabled students to address problems from multiple disciplinary perspectives and grasp comprehensive solutions. As Zhou (2023) noted, genuine interdisciplinary competence was not just about knowing multiple disciplines but about enabling knowledge to flow among different fields and generate new meanings.

2.1.2 Critical thinking and reflective behavior

Critical thinking is a situated and dynamic process that emerges in authentic learning contexts, think independently (Berkmans et al., 2025), and develop new insights in their learning (Vincent-Lancrin, 2024). When solving engineering problems, students generate diverse disciplinary opinions and need to select the optimal one (Heim et al., 2025). Thus, critical thinking becomes indispensable, as it enables students to break free from the constraints of a single discipline and analyze opinions from diverse disciplines. Reflection can deepen critical thinking, by which students recognize the limitations of their discipline and assess the strengths and weaknesses of different perspectives (Raveendran & Chunawala, 2015; Panova, 2018). This process helps students propose unified and practical solutions that will be systematic breakthroughs in engineering problems.

2.1.3 Communication and teamwork

Effective communication and strong teamwork are essential for successful interdisciplinary work (Moirano et al., 2020; Fantini, 2024). In interdisciplinary teamwork, students with different disciplinary backgrounds, knowledge structures, and thinking styles work together. Clear communication helps break down disciplinary barriers. Teamwork refers to the process of collaborating with others to complete interdisciplinary projects, which provides students with more opportunities for competence development (Gil-Molina et al., 2024). For example, biology students focus on ecological compatibility, while engineering students prioritize structural stability. Teamwork allows these perspectives to complement each other, which results in solutions that are scientific, innovative, and practical.

2.1.4 Innovative decision-making and implementation effectiveness

Innovative decision-making is a core step in interdisciplinary scenarios, where students use integrated knowledge and critical reflection to select innovative and feasible solutions (Scott et al., 2024; Liu et al., 2024). This process requires creative thinking and encourages students to challenge existing frameworks while seeking breakthroughs at the intersections of different disciplines (Suherman & Vidákovich, 2024). Implementation effectiveness measures how well innovative decisions translate into practical solutions, which focus on producing effective results. Students in interdisciplinary teams must

turn ideas into actionable plans, which is a crucial step from conception to execution (Kamp, 2023). Engineering is an extremely practical discipline. First, engineers must have a solid theoretical foundation and professional skills to solve real-world problems (Ming et al., 2024). Second, analysis and resolution competence of multidisciplinary problems is a core driver of engineering work, which enables a comprehensive examination of problems from multiple dimensions, such as technology, economy, and the environment. Finally, teamwork and innovative thinking are crucial for remaining competitive in the engineering field.

2.2 Assessment instrument of interdisciplinary competence

Interdisciplinary competence assessment instruments have two key functions: the accurate evaluation of students' competence levels and the provision of evidence for teaching practice and reform. Existing instruments are categorized into those for basic education and higher education.

In basic education, assessment instruments focus on students' mastery of core subjects and awareness of applying knowledge to solve problems. Yang (2017) noted that assessment should prioritize students' competence to comprehensively use interdisciplinary thinking and methods to creatively address practical problems, guiding related research. Wang & Song (2021) found that secondary school science education remains dominated by single-subject assessment, highlighting the need for interdisciplinary competence measurement instruments. Luo et al. (2024) developed an interdisciplinary literacy assessment model for primary students integrating cognitive and non-cognitive factors, reflecting an understanding of the holistic nature of interdisciplinary learning.

Compared with basic education, higher education assessment instruments for interdisciplinary competence emphasize professional mastery and operational skills, as well as students' application of interdisciplinary thinking to complex problem-solving (Groeneveld, 2022). Engineering education, a core field for interdisciplinary competence cultivation, has increasingly focused on assessment instruments, including self-report scales, behavioral observation instruments, and mixed assessment systems. Lattuca et al. (2012) developed an engineering undergraduate scale, while Cruz et al. (2019) criticized single-method assessments, calling for more diverse and contextualized instruments. Perpignan et al. (2020) integrated sustainability into engineering education assessments.

Existing assessment instruments of interdisciplinary competence need to be improved for the following three reasons. First, there is a lack of a specific assessment framework for engineering students, since existing assessment instruments fail to fully align with the core requirements of engineering education (practice-oriented, technology integration). Second, the determination of indicator weights mostly relies on single methods. Subjective methods are susceptible to experiential biases, while objective methods overlook scenario adaptability, both failing to ensure the scientificity of assessments. Third, assessment dimensions focus on cognitive and knowledge levels, insufficiently covering non-cognitive factors such

as reflection and teamwork. These dimensions fail to fully cover the logical path “problem-teamwork-practice-reflection” in engineering scenarios. Therefore, constructing an assessment framework for ICES is necessary, which is crucial for guiding the development of assessment instruments because the framework ensures a comprehensive evaluation of skills that are essential in engineering education.

3 Assessment framework

Our assessment framework for ICES was constructed through three main steps. First, two levels indicators of the preliminary assessment framework were identified through content analysis of relevant policy documents and literature. Second, the indicators of the preliminary assessment framework were refined through three rounds of expert consultations by using the Delphi method, and the structural validity of the ultimate assessment framework was verified by using SPSS 29. Finally, indicator weights were determined through the combination of the analytic hierarchy process (AHP) and improved criteria importance through intercriteria correlation (Improved CRITIC).

3.1 Preliminary assessment framework

The core elements of the preliminary assessment framework were first identified through a review of relevant policies from multiple countries. Multi-country leading international organizations, such as the World Economic Forum and the Organization for Economic Cooperation and Development, have emphasized that future engineers would need core competencies, including complex problem-solving competence, critical thinking, and creativity. The core competencies of future engineers correspond to the core elements of the preliminary assessment framework.

These core elements could be extended according to the logical path problem-driven, teamwork, doing, and reflection refinement of action learning theory. The extended core elements included knowledge (the foundation of problem-solving), thinking (the core of problem analysis), socializing (the guarantee of teamwork), and practice (the key to doing, enabling competence iteration through reflection) as first-level indicators in our preliminary assessment framework for ICES.

After knowledge, thinking, socializing, and practice were identified as the first-level indicators of the assessment framework, the first-level indicators needed further refinement into second-level indicators. (a) Under the first-level indicator of knowledge, three second-level indicators were set as knowledge integration, multidimensional analysis, and comprehensive analysis. These three second-level indicators represented the process of knowledge acquisition and reconstruction in interdisciplinary contexts, in response to the urgent need for engineers to integrate knowledge and perform multidimensional analysis in modern engineering projects (Zhang, 2021). (b) Under the first-level indicator thinking, two second-level indicators were set as critical thinking and innovative thinking. These two indicators, identified by some research as the dual engines of engineering innovation, served as core drivers for interdisciplinary competence development (McCuen, 2023). (c) Under the first-level indicator of socializing, two second-level indicators were set as communication and teamwork. The collaborative

nature of engineering projects requires engineers to have effective communication and teamwork competence (Asthana, 2024). (d) Under the first-level indicator practice, two second-level indicators were set as problem-solving and reflection. Engineering education emphasized learning through practice, and the addition of reflection significantly enhanced students' strategic diversity and self-regulation competence in solving complex problems (Panova, 2018). Finally, through the above systematic process, we initially constructed an assessment framework for ICES that included 4 first-level indicators and 8 second-level indicators.

3.2 Revision of assessment framework

To ensure the scientificity and effectiveness of the research, we adopted the Delphi method and consulted 23 experts from the engineering and education fields for the indicator revision of our assessment framework. Among them, 15 experts were engineering education professors with an average of 12 years of experience in interdisciplinary curriculum design and talent cultivation; 8 experts were frontline interdisciplinary teaching practitioners with an average of 9 years of practical experience. A preset assessment criterion was established that the agreement rate of experts' ratings on indicator importance must reach ≥ 80%. Followed by three rounds of expert consultation, consultation questionnaires were distributed to experts via email, consisting of research background, expert information, indicator importance assessment based on a 5-point Likert scale, and a suggestion section. After each round, the expert rating data were statistically analyzed in Table 1, revision suggestions were summarized, and the indicator of the framework was supplemented, revised, or deleted accordingly. This iterative process continued until the agreement rate of experts' ratings on all core indicators of the framework met the preset consensus standard of ≥ 80%.

Table 1
Analysis of three-round expert consultations

Round	Indicator mean	Standard deviation	Variation coefficient	p
First round	> 3.62	0.83 ~ 2.11	5 items > 0.2	< 0.001
Second round	> 3.97	0.76 ~ 2.41	2 items > 0.2	< 0.001
Third round	> 4.26	0.41 ~ 1.87	0 items > 0.2	< 0.001

The main revisions of the assessment framework were as follows. (a) In the first round, six experts suggested revising the first-level indicator from knowledge to cognition. They pointed out that knowledge typically refers to the sum of acquired information, facts, and skills, whereas cognition encompasses broader psychological processes, including perception, attention, and memory. This revision reflects the complexity of knowledge processing. Seven experts recommended removing comprehensive analysis from the second-level indicators due to conceptual overlap with the existing multidimensional analysis. This indicator was removed to simplify the assessment framework. (b) In the second round, six experts proposed designating the second-level indicator reflection as a first-level indicator, and action learning theory also emphasizes the closed loop of reflection and action. We further

refined the first-level indicator reflection by adding two second-level indicators: summarization and improvement. Then the first-level indicator practice is divided into two second-level indicators: program formulation and program implementation. This division was motivated by the practice-oriented characteristics of engineering education, a detailed analysis of problem-solving processes, and observations of students' performance at different educational stages. This division enabled educators to more accurately identify the specific difficulties students encounter during the problem-solving process. (c) The third round of expert consultations concluded without further modification suggestions. The final assessment framework for ICES was obtained, including 5 first-level indicators and 10 second-level indicators, as shown in Table 2.

Table 2
Assessment framework for ICES

First-level indicators	Second-level indicators	Interpretation of the indicators
A Cognition	A1 Knowledge integration	ž Reorganize and construct knowledge from different disciplines systematically, break the isolation of disciplinary knowledge, and form a new knowledge system.
	A2 Multidimensional analysis	ž Analyze engineering problems from the perspectives of multiple disciplines, break through the limitations of single-discipline thinking, and understand the nature of the problem comprehensively and deeply.
B Thinking	B1 Critical thinking	ž Scrutinize rationally and question the existing views, theories, and methods; think independently and do not unquestioningly accept the established conclusions.
	B2 Innovative thinking	ž Break through traditional thinking and integrate thinking from different disciplines to propose innovative ideas and solutions from new and unique perspectives.
C Socializing	C1 Communication	ž Express oneself clearly and accurately in an interdisciplinary team or learning environment while effectively understanding the opinions of others.
	C2 Teamwork	ž Work closely with members from different disciplinary backgrounds and utilize the strengths of the engineering profession to accomplish tasks together.
D Practice	D1 Program formulation	ž Apply interdisciplinary knowledge and skills to identify the core aspects of a problem and develop an effective solution.
	D2 Program implementation	ž Translate predefined solutions into practical actions and ensure effective implementation of the solutions to achieve the desired goals.
E Reflection	E1 Summarization	ž Make a complete inventory of learning, researching, and practicing, and draw lessons and experiences from them.
	E2 Improvement	ž Take adequate measures for self-improvement and optimization based on lessons learned.

3.3 Determination of the indicators' weight in the assessment framework

The combination weighting method integrates data characteristics and fully utilizes expert knowledge, providing more reliable support for subsequent decision-making (Lu et al., 2015). The combination of AHP and Improved CRITIC is adopted, whose core advantage lies in its complementarity: AHP integrates experts' experience to capture the theoretical importance of indicators; Improved CRITIC automatically generates weights through analysis of data dispersion and correlation, reducing subjective biases and being more suitable for educational assessment (Mukhametzyanov et al., 2021). Compared with other combination methods, this combination has both subjective theoretical support and an objective empirical nature.

The AHP has three main calculation steps: (a) Construct a judgment matrix by using Saaty's 1–9 scale (Saaty, 1990). (b) Perform a consistency test on the judgment matrix. (c) Determine subjective weights by normalizing the judgment matrix. Following these steps, we obtained the final subjective weights of each indicator W^{α}. The Improved CRITIC has three specific steps: (a) Normalize the initial matrix *X*. (b) Calculate the coefficient of variation, correlation coefficient matrix, and independence coefficient. (c) Calculate the objective weight of each indicator. According to these steps, we obtained the objective weights $W^{\beta}$of each indicator.

The obtained subjective weight W^{α} and objective weight W^{β} were used to calculate the importance coefficients α_i (for subjective weights) and β_i(for objective weights) for the *i*-th indicator by using Eq. (1), respectively. The target optimization method was adopted to calculate the importance coefficients of subjective and objective weights, which not only retained the subjectivity of expert experience but also maintained the objectivity of the data, thus making the results more consistent with the actual situation (Xu et al., 2025).

$$\begin{cases} \alpha_i = \dfrac{W_i^{\alpha}}{\left(W_i^{\alpha}+W_i^{\beta}\right)} \\ \beta_i = \dfrac{W_i^{\beta}}{\left(W_i^{\alpha}+W_i^{\beta}\right)} \end{cases} (i = 1,2,\cdots,n)$$

1

After obtaining the importance of the coefficients $\alpha_i$and β_i, we used $W_i^{\alpha}\alpha_i + W_i^{\beta}\beta_i$ to represent the weight contribution value of the *i*-th indicator to comprehensively consider the subjective weight and objective weight. Thus, the combined weight $W_i^{q}$of the *i*-th indicator can be calculated by using Eq. (2), as shown in Table 3.

$$W_i^{q} = \frac{W_i^{\alpha}\alpha_i + W_i^{\beta}\beta_i}{\sum_{i=1}^{n}\left(W_i^{\alpha}\alpha_i + W_i^{\beta}\beta_i\right)}$$

2

As shown in Table 3, the first-level indicators cognition (0.240) and thinking (0.217) had relatively high combined weights, indicating that these two indicators were core elements of interdisciplinary competence. The high subjective weight (0.310) of the first-level indicator cognition reflected experts' emphasis on the understanding of interdisciplinary knowledge. In contrast, the subjective weight (0.225) and objective weight (0.207) for the first-level indicator thinking reflected its significant mediating role in integrating knowledge and facilitating practical application in an interdisciplinary context. The weights of the first-level indicators, socializing (0.177), practice (0.190), and reflection (0.188), were relatively balanced. However, these three indicators showed distinct characteristics in subjective and objective contributions. The first-level indicator socializing had an objective weight (0.200) that exceeded its subjective weight (0.145), indicating the importance of teamwork and communication in interdisciplinary projects. The first-level indicator practice had an objective weight (0.206) and a subjective weight (0.170), reflecting its core link in knowledge translation. For the first-level indicator reflection, the objective weight (0.186) and subjective weight (0.190) indicated their roles in interdisciplinary competence iteration and optimization. Finally, we calculated the combined weights of the second-level indicators corresponding to each first-level indicator, and determined their combined weights in the overall assessment framework for ICES, as shown in Table 4.

Table 3
Weight of first-level indicators

Items	W^{α}	W^{β}	α_i	β_i	W^{q}
Cognition	0.310	0.202	0.572	0.428	0.240
Thinking	0.225	0.207	0.521	0.479	0.217
Socializing	0.145	0.200	0.420	0.580	0.177
Practice	0.170	0.206	0.452	0.548	0.190
Reflection	0.190	0.186	0.505	0.495	0.188

Table 4
Weight of each-level indicators

First-level indicators	Second-level indicators	Combined weight
Cognition (0.240)	Knowledge integration (0.578)	0.139
	Multidimensional analysis (0.422)	0.101
Thinking (0.217)	Critical thinking (0.536)	0.116
	Innovative thinking (0.464)	0.101
Socializing (0.177)	Communication (0.496)	0.088
	Teamwork (0.504)	0.089
Practice (0.190)	Plan formulation (0.480)	0.091
	Plan implementation (0.520)	0.099
Reflection (0.188)	Summarization (0.501)	0.094
	Improvement (0.499)	0.094

3.4 Questionnaire construction and adaptation

3.4.1 Pretest procedures

The questionnaire was designed based on the assessment framework, and the number of questionnaire items were allocated by the indicator weight of the assessment framework: 8 items for cognition (0.240) and thinking (0.217), 7 items for practice (0.190) and reflection (0.188), and 6 items for socializing (0.177). The questionnaire included two sections: basic information and 36 items using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Eight engineering teachers with ≥ 5 years of teaching experience and 15 randomly selected undergraduate students reviewed the items, eliminated 2 ambiguous items, and determined a 34-item final version. A non-random purposive sampling method was adopted to collect data from 479 undergraduate engineering students (306 males, 173 females) at a polytechnic college in J Province, China, covering mechanical engineering (40.1%), electronic and information engineering (33.2%), and artificial intelligence (26.7%) majors. The participants were informed of voluntary participation, anonymous confidentiality, and the right to withdraw at any time. After excluding invalid questionnaires, 399 valid responses were obtained with a validity rate of 83.3%.

3.4.2 Reliability and validity evidence

The questionnaire's reliability was assessed through item discrimination, internal consistency, and inter-item correlations: using the critical ratio method, items showed significant differences between high- and low-ICES performance groups ($p < 0.001$), confirming effective differentiation of competence levels; the overall Cronbach's alpha coefficient was 0.879, indicating high internal consistency among items;

and Pearson correlation coefficients ($r = 0.585 \sim 0.855$, $p < 0.001$) further validated consistent content across items.

The questionnaire's validity was verified via exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), with a random split of 240 samples for EFA and 239 for CFA to avoid cross-dataset measurement errors. For EFA, data suitability was confirmed by a KMO coefficient of 0.967 (> 0.7) and significant Bartlett's test ($p < 0.001$), as shown in Table 5; 10 factors (matching the 10 second-level indicators) were extracted with 69.97% cumulative variance explained, and Promax rotation led to deleting items with loadings < 0.4 (E23) and cross-loadings (E11) to optimize structural validity. All CFA fit indices met acceptable standards, confirming the theoretical structure of the ICES questionnaire aligns with empirical data, as shown in Table 6. Collectively, these results demonstrate the questionnaire's good reliability and validity.

Table 5
Results of KMO and Bartlett's test of sphericity

KMO		**0.967**
Bartlett's test of Sphericity	Approximate chi-square	8999.957
	df	496
	p	0.000

Table 6
Results of fit indices

Fit indices	**Standards**	**Results**	**Assessment**
CMIN/DF	1–3	2.827	well
RMSEA	< 0.08	0.056	well
RMR	< 0.08	0.021	well
CFI	> 0.90	0.957	well
IFI	> 0.90	0.957	well
TLI	> 0.90	0.949	well

4 Results

4.1 Setting and participants

We selected engineering students from five polytechnic colleges in Province J, China, as the research subjects. As these five polytechnic colleges differ in stage of education, disciplinary advantages, and training orientation, their differences can well reflect the differential characteristics of engineering students' interdisciplinary competence in various training environments. We distributed 1306

questionnaires to engineering students at different educational stages of five polytechnic colleges. 254 of 1306 questionnaires were deemed invalid based on polygraph questions, and additional invalid ones were also eliminated because their completion time was less than 90 seconds or they had the same result for all items. Finally, 943 valid questionnaires were retained with a valid response rate of 72.16%.

4.2 Analysis

The systematic analysis of questionnaire replies included analysis of the development situation of ICES, group differences of ICES, and the attitude of engineering students towards interdisciplinary competence.

4.2.1 Development situation of ICES

The development situation of ICES was measured by the comprehensive development index of first-level indicators and the development index of each first-level indicator of ICES for five polytechnic colleges. We used the weighted calculation method to calculate the comprehensive development index and the development index. The five polytechnic colleges were denoted as P1 to P5 (P representing polytechnic college). The steps of calculating the comprehensive development index were as follows. First, based on the determined weights of indicators at each level, we calculated the original questionnaire scores of the second-level indicators for each college. We then standardized these original questionnaire scores to eliminate differences in measurement units and subsequently multiplied each standardized original score by the weight of its corresponding second-level indicators. Second, for the second-level indicators that belong to the same first-level indicator, we multiplied each of their standardized scores by their respective weights and summed these products to calculate the scores of the first-level indicators. Finally, we multiplied the scores of the first-level indicators by their respective weights to get the comprehensive development index *I*.

$$I = \sum_{k=1}^{m} W_k \cdot \left(\sum_{i=1}^{n_k} w_{ki} \cdot X_{ki} \right)$$

3

where$m$ is the number of first-level indicators, W_k is the weight of the kth first-level indicators; n_k the number of second-level indicators under the *k*th first-level indicator, w_{ki} is the weight of the ith second-level indicators under the kth first-level indicators, and X_{ki} is the standardized score of the second-level indicators.

When calculating the development index I_m of indicators, we could use the weighted calculation based on the scores and weights of the indicator.

$$I_m = \sum_{i=1}^{n_m} w_{mi} \cdot X_{mi}$$

where n_m is the number of second-level indicators included under the mth first-level indicators; w_{mi} is the weight of the ith second-level indicators under the mth first-level indicators; X_{mi} is the score of the ith second-level indicators under the mth first-level indicators after standardization.

Table 7 shows each polytechnic college's ranking in comprehensive development, the comprehensive development index of the indicator, the development index of each first-level indicator, and changes in rank. The comprehensive development indices of ICES in the five polytechnic colleges were 50.75, 48.40, 47.59, 46.57, and 46.41, respectively, and the mean value of the comprehensive development index was 47.94. The mean value intuitively indicated that the overall level of ICES in the five polytechnic colleges was at a low level and needed to be improved. Among the five polytechnic colleges, only the comprehensive development indices of P1 and P4 exceeded the mean value (47.94), while the comprehensive development indices of the remaining three (P2, P3, and P5) were all below the mean value. Notably, there was a significant difference between the rankings of the comprehensive development index and the rankings of the development index of first-level indicators of each college.

The overall level of ICES among the five colleges was relatively low, and there were significant inter-school differences. Each college showed unique advantages and disadvantages in the first-level indicators, which provided a basis for subsequent analysis of group differences and also raised further questions about why the overall level was relatively low.

Table 7
Statistics of five polytechnic colleges

Rank	College	Comprehensive development index of indicators	Development index of each indicator				
			Cognition	Thinking	Socializing	Practice	Reflection
1	P1	50.75	52.33—	53.27—	48.10—	51.07—	46.00↓
2	P4	48.40	48.20—	49.65↓	46.72↓	49.85—	47.34↑
3	P3	47.59	47.42—	50.60↑	46.35↓	49.75—	42.57↓
4	P2	46.57	45.35↓	47.93↓	47.48↑	49.07—	44.43↑
5	P5	46.41	45.69↑	49.02↑	45.39—	47.89—	43.70↑
Mean value		47.94	47.80	50.09	46.81	49.53	44.81

Note: The symbol "↑, ↓, —" indicates that the development index rankings of each college in various indicators are rising, falling, or consistent, relative to the comprehensive development index rankings.

We calculated each polytechnic college's discrepancy index of comprehensive development to understand the development situation of polytechnic colleges' ICES, where the discrepancy index indicated the difference between the comprehensive development indices and their mean value. Then,

we conducted clustering analysis based on these discrepancy indices, and the uneven comprehensive development level of ICES in each college was shown in Fig. 1. The five polytechnic colleges could be categorized into two groups. The first group was high-level colleges with a positive discrepancy index, such as P1 and P4, and these colleges were in the first quadrant of the chart, with comprehensive development index values above the mean value and discrepancy index, such as P1 and P4, and these colleges were in the first quadrant of the chart, with comprehensive development index values above the mean value and a discrepancy index of comprehensive development above 0. The second group was low-level colleges with an unfavorable discrepancy index, such as P2, P3, and P5. These colleges were in the third quadrant of the chart, with a comprehensive development index value below the mean value and a discrepancy index of comprehensive development below 0.

We aimed to gain a deeper understanding of the development situation of the first-level indicators of five polytechnic colleges. Therefore, we used the discrepancy indices of the indicator to draft a line chart (Fig. 2). In Fig. 2, the discrepancy indices of indicator development above 0 indicated that they were higher than the mean value, and the indices below 0 indicated that they were lower than the mean value. The line chart results were as follows. As for P1, all the discrepancy indices of indicator development for the five indicators were above 0, indicating that P1 performed better than the other four polytechnic colleges in the five indicators. As for P2, the discrepancy indices of indicator development for cognition, thinking, practice, and reflection were all below 0, with only the socializing indicator's discrepancy index above 0. The discrepancy indices of indicator development for its indicators generally showed a decreasing trend. As for P3, the discrepancy indices of indicator development for thinking and practice were above 0, indicating a positive development trend. However, the discrepancy indices of indicator development for cognition, socializing, and reflection were below 0, showing a negative trend and resulted in an imbalanced overall development level. As for P4, the discrepancy indices of indicator development for cognition, practice, and reflection were positive and above 0, with reflection showing a particularly outstanding advantage. The discrepancy indices of indicator development for thinking and socializing were negative and showed a slight downward trend, but the overall development was relatively bright. As for P5, the discrepancy indices of indicator development for the five indicators were all below 0; among the five polytechnic colleges, P5 ranked the lowest in development and lagged overall.

4.2.2 Group difference of ICES

We used SPSS 29 to analyze ICES group differences and how background factors (gender, educational stage, double degree) affected it. Grouping by these factors, we conducted multiple-group CFA. Across the five colleges, no significant differences in invariance test parameters (factor loading, error variance, latent variable variance-covariance, residuals) were found, justifying fair inter-group comparisons. Independent samples t-tests were used to compare ICES between genders and double-degree holders, while one-way ANOVA examined educational-stage differences (junior college, undergraduate, master's, PhD and above). Shapiro-Wilk ($p > 0.05$) and Levene (homogeneity of variance, $p > 0.05$) were used to

test the data, the results satisfying *t*-test and ANOVA assumptions. The results of group differences are in Tables 8–10.

Table 8
Statistical results of gender differences

First-level Indicators	*t*	*p*	Difference Description
Cognition	-2.375	0.018	Female students scored significantly higher than male students.
Thinking	-0.152	0.078	No significant gender difference
Socializing	-0.217	0.041	Female students scored significantly higher than male students.
Practice	-0.908	0.365	No significant gender difference
Reflection	1.236	0.037	Male students scored significantly higher than female students.

Table 9
Statistical results of differences in whether students pursued a double degree

First-level Indicators	*t*	*p*	Difference Description
Cognition	1.987	0.034	Double degree students scored significantly higher than non-double degree students.
Thinking	-0.305	0.041	Double degree students scored significantly higher than non-double degree students.
Socializing	0.264	0.606	No significant difference
Practice	-0.300	0.874	No significant difference
Reflection	1.122	0.262	No significant difference

Table 10
Statistical results of differences across educational stages

First-level Indicators	*F*	*p*	Difference Description
Cognition	4.529	0.005	Master's students > Undergraduates, Junior college students
Thinking	2.935	0.033	PhD students and above > Undergraduates > Junior college students
Socializing	2.357	0.022	Master's students > Undergraduates
Practice	2.413	0.012	Master's students > Undergraduates
Reflection	1.790	0.074	No significant difference across educational stages

4.2.3 Attitude of engineering students

We had objectively analyzed the developmental differences and group differences of ICES, but the underlying causes behind these differences had not yet been analyzed in depth. To analyze these underlying causes more deeply, students' subjective attitudes were investigated and quantified. The survey results demonstrated engineering students' attitudes towards interdisciplinary competence. Among the 943 engineering students in the survey, over 80% of students expressed a positive attitude toward the importance of interdisciplinary competence. 32.13% of students considered interdisciplinary competence very important, 49.2% of students considered it important, and only 1.6% of students considered it unimportant or very unimportant. Our findings suggested that engineering students had a positive attitude regarding the importance of interdisciplinary competence. Moreover, students considered the necessity of developing interdisciplinary competence for enhancing their comprehensive competitiveness.

Our survey results revealed that over 80% of students considered the importance of interdisciplinary competence, but their interdisciplinary competence was generally low. Thus, we further investigate the reasons for the low interdisciplinary competence. We interviewed 30 engineering students who had participated in the survey and asked about the shortcomings of colleges in the development of interdisciplinary competence. The results of the interview were as follows. (a) Curriculum: 76.7% of the interviewed students reported that interdisciplinary courses were dominated by theoretical lectures and lacked interactive processes, which resulted in their cognition staying at the conceptual level. (b) Assessment method: 63.3% of the interviewed students reported that the current assessment was still mainly on the mastery of knowledge within disciplines, with a relatively low percentage of interdisciplinary competence assessment. (c) Teachers' guidance: 53.3% of the interviewed students reported that teachers rarely guided interdisciplinary discussions in the classroom. This result suggested that teachers lacked interdisciplinary experience, and this lack made it hard to inspire students' interdisciplinary thinking. (d) Practice opportunities: 43.3% of the interviewed students reported that they seldom had the opportunity to participate in actual projects and could not apply their interdisciplinary

knowledge and skills in real-life scenarios. (e) Hardware equipment: 36.7% of the interviewed students reported that some programs of interdisciplinary practice required specific hardware resources, such as experimental equipment and instruments, but the colleges of these interviewed students were inadequately equipped with these hardware resources.

5 Discussion

5.1 Development situation of ICES

ICES development varied significantly across the five polytechnic colleges: The comprehensive development index values of P1 (50.75) and P4 (48.40) were above the mean values (47.94), while P2 (46.57), P3 (47.59), and P5 (46.41) lagged behind, which reflects uneven development. The values of P1 ranked highest due to its curriculum integration + practice platforms + interdisciplinary mentors training system, which aligns with Lattuca et al. (2017)'s emphasis on these three core pillars. The values of P4 excelled in cognition, practice, and reflection, with reflection (47.34) outperforming its overall rank, consistent with action learning theory (Zuber-Skerritt & Wood, 2019). However, the values of P4 lacked interdisciplinary teamwork courses, which limit thinking and socializing competencies. The values of P3 showed unbalanced development: strong in thinking (50.60) and practice (49.75) but weak in cognition (47.42) and socializing (46.35), linked to its technology-focused, knowledge-integration-deficient training orientation. The values of P2 only performed well in socializing (47.48), due to a lack of supporting interdisciplinary courses and platforms, resulting in weak knowledge integration (45.35) and practice (49.07). The values of P5 underperformed across all indicators, attributed to prominent disciplinary barriers, fewer interdisciplinary courses, insufficient hardware, and no full-time interdisciplinary faculty. This aligns with Ming et al. (2024)'s finding that interdisciplinary engineering education relies on adequate resource allocation. Overall, ICES enhancement requires synergistic support from curriculum integration, practice platforms, and faculty configuration (Ming et al., 2024).

5.2 Group differences of ICES

The group differences of ICES are significant in terms of gender, double-degree, and educational stage, with distinct characteristics in core indicators:

(a) Double-degree students: They only have advantages in the two high-weighted indicators of cognition (0.240) and thinking (0.217) compared to non-double-degree students, and no advantages in socializing, practice, or reflection. This is because current double-degree programs overemphasize theoretical knowledge integration while lacking interdisciplinary practical collaboration, leading to insufficient transformation of knowledge into practical competence (Kanthan & Ng, 2023; van Goch & Lutz, 2023). The cultivation of interdisciplinary competence requires deep integration of theory and practice.
(b) Gender differences: Female students had significantly higher scores in cognition and socializing, which may be due to their empathic advantage in interdisciplinary communication (Xu et al., 2021). In contrast, male students had a significant advantage in reflection, possibly related to their greater

tendency toward logical, problem-oriented reflection methods. No significant differences were found in thinking and practice, which reflects that gender gaps in core STEM competence are narrowing.

(c) Educational stage: Master's students had significant advantages over undergraduates and junior college students in cognition, socializing, and practice, due to their greater participation in interdisciplinary projects. PhD students and above had an advantage only in thinking, as overspecialization hinders broader interdisciplinary development (Aguayo-Arrabal & Gómez-Parra, 2022; Dalton et al., 2022). Undergraduates exceeded junior college students in thinking, while no significant differences were found in reflection across different stages.

Overall, the group differences indicate that ICES development is influenced by curriculum design, practical exposure, and the intensity of academic training. Theory-focused courses and overspecialization can limit the development of comprehensive competence, while diverse practical opportunities help promote balanced development.

5.3 Attitude and suggestion

The analysis results of engineering students' attitudes showed that most students held a positive attitude towards interdisciplinary competence. Students' positive attitudes indicated that they were willing to accept courses and activities to promote their interdisciplinary competence. These positive attitudes also suggested that educational institutions could further make use of this positive attitude to design more targeted and effective interdisciplinary activities and curricula. The following suggestions are made based on our interview results:

(a) Curriculum: For the theoretical and interactive-less courses reflected by 76.7% of students, the college should increase the proportion of project-based teaching in interdisciplinary courses to over 60%, and design modules driven by real engineering problems for the problem.
(b) Assessment: For the 63.3% of students are concerned about assessment centralization. The college should increase the weight of interdisciplinary competence assessment to 30% of the total score and adopt a combined model of formative assessment and summative assessment for the problem.

(c) Faculty: For the insufficient interdisciplinary experience among teachers pointed out by 53.3% of students, the college should conduct annual training in interdisciplinary teaching competence with no less than 40 hours per year for the problem.

(d) Practice: For the practical needs of 43.3% of students, the college should build at least two college-level interdisciplinary practice platforms and collaborate with enterprises to develop engineering projects in real-world scenarios for the problem.

(e) Hardware: For the hardware insufficiency that was reflected by 36.7% of students, the college should prioritize the allocation of experimental equipment required for interdisciplinary practice to ensure the implementation of interdisciplinary projects for the problem.

6 Conclusion

We constructed a comprehensive assessment framework to assess the interdisciplinary competence of engineering students. The indicators at each level of our framework were determined by content analysis and the Delphi method. To ensure the reliability and validity of the assessment framework of ICES, the weights of the indicators were scientifically determined by a combination weighting method, including AHP and the Improved CRITIC. Following the indicator determination and indicator empowerment, we constructed the final assessment framework for ICES that consisted of 5 first-level indicators and 10 second-level indicators. On the basis of the assessment framework, we designed the questionnaire of ICES and presented the following results by analyzing the questionnaire data. The analysis results included overall ICES, group differences of ICES, and engineering students' attitudes towards interdisciplinary competence. The overall ICES of these colleges was relatively low with significant inter-college differences, and each college showed different strengths and weaknesses. The group difference of ICES had significant differences in gender, educational stage, and whether students pursued a double degree program. Students had a positive attitude toward the importance of interdisciplinary competence, and their interdisciplinary competence was generally low. This low interdisciplinary competence showed the shortcomings in the existing development of ICES, such as courses, assessments, and practices of ICES.

Our purpose was to construct the assessment framework for ICES, so that we did not conduct an in-depth analysis of the impact mechanism, such as students' backgrounds and individual characteristics, and how they impact the development of interdisciplinary competence. Future research should employ longitudinal designs and structural equation modeling to examine the impact mechanisms of different factors on ICES development. Furthermore, assessment indicators and development strategies of ICES should be adjusted on time. Future research may also focus on reform measures related to the implementation of engineering education, such as developing courses, designing practical projects, formulating assessment methods, and conducting long-term tracking and assessment of their effects. This will help formulate a comprehensive and scientific development strategy for the development of ICES.

Declarations

Competing interests

None.

Ethical approval

The Ethics Committee of Yunnan University granted approval for this research (approval number: 50/03/2025); approval date: March 10, 2025. The study's methodology adhered strictly to the principles outlined in the Declaration of Helsinki; ethical clearance was sought and obtained before any data

collection activities began. This ensured that all research procedures were in compliance with established ethical guidelines.

Informed consent

Informed consent was obtained in writing via oral consent form prior to data collection (June 5, 2025). All the survey participants were adults capable of providing consent, and no vulnerable individuals or minors were involved. Consent encompassed voluntary participation, the use of anonymized data for academic analysis and publication, assurances of confidentiality and secure data storage in accordance with institutional research ethics guidelines, and the right to withdraw at any time without any penalty.

Author Contribution

ZQ: Funding acquisition, Supervision, Resources, Project administration, Writing–review & editing. WX: Writing–original draft, Investigation, Visualization, Methodology, Validation, Formal analysis, Writing–review & editing. YL: Formal analysis, Conceptualization, Writing – review & editing. WL: Formal analysis, Conceptualization, Writing–review & editing.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (62567008) and the Yunnan Provincial Basic Study Program General Project (202401AT070462).

Data Availability

The raw data, survey instrument, and interview outline are available from the corresponding author upon reasonable request.

References

1. Asthana HK (2024) The Integration of soft skills in civil engineering: enhancing professional competence and project success. Int J Sci Res Eng Manage 08(6):1–5. https://doi.org/10.55041/ijsrem35975
2. Aguayo-Arrabal N, Gómez-Parra ME (2022) Open to better? Teachers' perceptions of curriculum integration in the Erasmus Mundus PETaL master's degree. J New Approaches Educational Res 11(2):186–208. https://doi.org/10.7821/naer.2022.7.826
3. Allen KA (2021) The transdisciplinary nature of educational and developmental psychology. The Educational and Developmental Psychologist, 38 (1), 1–2. https://doi.org/10.1080/20590776.2021.1956868

4. Beldad AD, Miedema HAT (2025) Introducing a framework for designing an interdisciplinary engineering curriculum: educating new engineers for complex sociotechnical challenges. Eur J Eng Educ 1–18. https://doi.org/10.1080/03043797.2025.2507243
5. Berkmans F, Bigerelle M, Lemesle J, Nys L, Wieczorowski M, Brown C (2025) Peer assessment in interdisciplinary learning: Measuring reliability and engaging critical thinking. Think Skills Creativity 101950. https://doi.org/10.1016/j.tsc.2025.101950
6. Chandra P, Hitchcock S, Seno-Alday S (2025) Assessment style in interdisciplinary education–challenges in creating equitable assessment opportunities. Stud High Educ 50(3):525–536. https://doi.org/10.1080/03075079.2024.2345187
7. Cruz ML, Saunders-Smits GN, Groen P (2019) Assessment of competency methods in engineering education: a systematic review. Eur J Eng Educ 45(5):729–757. https://doi.org/10.1080/03043797.2019.1671810
8. Dalton A, Wolff K, Bekker B (2022) Interdisciplinary research as a complicated system. Int J Qualitative Methods 21:16094069221100397. https://doi.org/10.1177/16094069221100397
9. Donatelli CM, Vandenberg M, Martinez L, Schulz AK, Paig-Tran EWM, Cohen KE,P.-T., M (2025) The bioinspiration feedback loop: An interdisciplinary exchange of processes and progress between biologists and engineers. Integr Comp Biol 65(1):icaf128. https://doi.org/10.1093/icb/icaf128
10. Fantini E (2024) Podcasting for interdisciplinary education: active listening, negotiation, reflexivity, and communication skills. Humanit Social Sci Commun 11:1583. https://doi.org/10.1057/s41599-024-04119-6
11. Feng X, Sundman J, Aarnio H, Taka M, Keskinen M, Varis O (2025) Towards transformative learning: students' disorienting dilemmas and coping strategies in interdisciplinary problem-based learning. Eur J Eng Educ 50(2):428–450. https://doi.org/10.1080/03043797.2024.2424197
12. Gil-Molina P, Cruz-Iglesias E, Rekalde-Rodriguez I (2024) Developing competences in a cross-border interdisciplinary project: student and teacher perceptions of the Ocean i3 project. J Coll Teach Learn Pract 21(1):17–42. https://doi.org/10.53761/677rfm42
13. Groeneveld W, Becker BA, Vennekens J (2022) How creatively are we teaching and assessing creativity in computing education. Proceedings of the 53rd ACM Technical Symposium on Computer Science Education, 934–940. https://doi.org/10.1145/3478431.3499360
14. Guo H, Zhou Z, Ma F et al Critical thinking and AI-Assisted creativity in engineering education: differences between Undergraduate, Master's, and doctoral students[J]. Educ Inform Technol, 2025: 1–26. https://doi.org/10.1007/s10639-025-13844-7
15. Heim AB, Lawrence G, Agarwal R, Smith MK, Holmes NG (2025) Perceptions of interdisciplinary critical thinking among biology and physics undergraduates. Phys Rev Phys Educ Res 21(1):010138
16. Kamp A (2023) Engineering education in the rapidly changing world: Rethinking the vision for higher engineering education. TU Delft OPEN Publishing https://doi.org/10.1103/PhysRevPhysEducRes.21.010138

17. Kanthan KL, Ng KT (2023) Development of conceptual framework to bridge the gap in higher education institutions towards achieving Sustainable Development Goals (SDGs). Proceedings Series on Social Sciences & Humanities, 12, 22–26. https://doi.org/10.30595/pssh.v12i.768
18. Lam MHA (2025) From defining to enacting interdisciplinary education: Curriculum integration strategies among Hong Kong undergraduate interdisciplinary programmes. Stud High Educ 50(12):2762–2781
19. Lattuca LR, Knight DB, Bergom IM (2012) Developing a measure of interdisciplinary competence for engineers. In Proceedings of the 2012 ASEE Annual Conference & Exposition (pp. 25–415). https://doi.org/10.18260/1-2-21173
20. Lattuca LR, Knight D, Seifert TA, Reason RD, Liu Q (2017) Examining the impact of interdisciplinary programs on student learning. Innov High Educ 42(4):337–353. https://doi.org/10.1007/s10755-017-9393-z
21. Liu J, Gong X, Xu S, Huang C (2024) Understanding the relationship between team diversity and the innovative performance in research teams using decision tree algorithms: Evidence from artificial intelligence. https://doi.org/10.1007/s11192-024-05183-0. Scientometrics
22. Luo S, Zhang H, Song N, Mei H, Tang S, Tong M (2024) Research on the construction and application of an interdisciplinary competency assessment model for primary school students. China Educational Technol 1(5):9–16. https://doi.org/10.3969/j.issn.1006-9860.2024.05.002
23. Mahringer CA, Baessler F, Gerchen MF, Haack C, Jacob K, Mayer S (2023) Benefits and obstacles of interdisciplinary research: insights from members of the young academy at the heidelberg academy of sciences and humanities. iScience 26(12):108508. https://doi.org/10.1016/j.isci.2023.108508
24. McCuen RH (2023) Critical thinking, idea innovation, and creativity. CRC. https://doi.org/10.1201/9781003380443
25. Ming X, van der Veen J, MacLeod M (2024) Competencies in interdisciplinary engineering education: constructing perspectives on interdisciplinarity in a Q-sort study. Eur J Eng Educ 50(2):406–427. https://doi.org/10.1080/03043797.2024.2397419
26. Moirano R, Sánchez MA, Štěpánek L (2020) Creative interdisciplinary collaboration: A systematic literature review. Think Skills Creativity 35:100626. https://doi.org/10.1016/j.tsc.2019.100626
27. Mukhametzyanov IZ (2021) Specific character of objective methods for determining weights of criteria in MCDM problems: Entropy, CRITIC, SD. Decis Making: Appl Manage Eng 4(2):76–105. https://doi.org/10.31181/dmame210402076i
28. Panova L, Plugina N, Kaminsky A, Kondrashova E, Guryanova I, Martynova N (2018) Development of reflective competence in students in technical colleges of Russia. Istrazivanja i Projektovanja za Privredu 16(4):538–552. https://doi.org/10.5937/jaes16-19490
29. Perpignan C, Baouch Y, Robin V, Eynard B (2020) Engineering education perspective for sustainable development: a maturity assessment of cross-disciplinary and advanced technical skills in eco-design. Procedia CIRP 90:748–753. https://doi.org/10.1016/j.procir.2020.02.051

30. Raveendran A, Chunawala S (2015) Values in science: making sense of biology doctoral students' critical examination of a deterministic claim in a media article. Sci Educ 99(4):669–695. https://doi.org/10.1002/sce.21174
31. Saaty TL (1990) How to make a decision: the analytic hierarchy process. Eur J Oper Res 48:9–26. https://doi.org/10.1016/0377-2217(90)90057-I
32. Sajdakova J, Carey E, Dhokia V, Newnes L, Parry G (2022) Proposal of a self-assessment competency framework for transdisciplinary engineering. J Industrial Integr Manage 9(3):373–396. https://doi.org/10.1142/S2424862222500221
33. Scott EK, White BR (2024) An empirical study of cultivating innovative practice abilities in an interdisciplinary education environment in Australia. Res Adv Educ 3(5):53–63. https://doi.org/10.56397/rae.2024.05.06
34. Steinheider B, Bayerl PS, Menold N, Bromme R (2009) Entwicklung und Validierung einer Skala zur Erfassung von Wissensintegrationsproblemen in interdisziplinären Projektteams (WIP). Zeitschrift für Arbeits-und Organisationspsychologie A&O, 53 (3), 121–130. https://doi.org/10.1026/0932-4089.53.3.121
35. Suherman S, Vidakovich T (2024) Role of creative self-efficacy and perceived creativity as predictors of mathematical creative thinking: Mediating role of computational thinking. Think Skills Creativity 53:101591. https://doi.org/10.1016/j.tsc.2024.101591
36. Sun X, Liu S, Lin M, Xu F, Lu T (2024) The bio-thermo-mechano-electrophysiology. Appl Math Mech 45(6):651–669. https://doi.org/10.21656/1000-0887.450079
37. Svingen E, Tsirova E, Khalilova U (2026) Developing critical thinking through the lens of interdisciplinarity: a case study of a criminological theory module. Humanit Social Sci Commun. https://doi.org/10.1057/s41599-026-06517-4
38. Van Goch M, Lutz C (2023) Scholarly learning of teacher-scholars engaging in interdisciplinary education. J Interdisciplinary Stud Educ 12(SI):67–90. https://doi.org/10.32674/jise.v12iS1.5313
39. Vincent-Lancrin S (2024) Critical thinking. In OECD Skills Outlook 2024 (pp. 124–128). OECD Publishing. https://doi.org/10.4337/9781035317967.ch27
40. Wang Q, Hou S, Wan S, Feng X, Feng H (2025) Applying knowledge graph to interdisciplinary higher education. Eur J Educ 60(2). https://doi.org/10.1111/ejed.70078
41. Wang Z, Song G (2021) Towards an assessment of students' interdisciplinary competence in middle school science. Int J Sci Educ 43(12):1–24. https://doi.org/10.1080/09500693.2021.1877849
42. Vogel O, Hunecke M (2024) Fostering knowledge integration through individual competencies: the impacts of perspective taking, reflexivity, analogical reasoning and tolerance of ambiguity and uncertainty. Instr Sci 52(2):227–248. https://doi.org/10.1007/s11251-023-09653-5
43. Xia Q, Weng X, Huang W et al (2026) Is generative artificial intelligence (GenAI) a game changer for interdisciplinary collaborative learning in higher education? Educ Inf Technol 31:143–166. https://doi.org/10.1007/s10639-025-13812-1

44. Xu C, Wu CF (2025) What factors may contribute to the improvement of students' interdisciplinary integration competencies? —a comparative study of various interdisciplinary curriculum patterns. Humanit Social Sci Commun 12(1):1–23. https://doi.org/10.1057/s41599-025-05950-1
45. Xu X, Zhu X, Xue J, Wei Z (2025), September A Review of The Research on the Index Weighting Method of Multi-Factor Evaluation Problem. In 2025 6th International Conference on Management Science and Engineering Management (ICMSEM 2025) (pp. 632–645). Atlantis Press.https://doi.org/10.2991/978-94-6463-845-5_65
46. Xu YJ, Jacobs E, Astorne-Figari C, de Jongh Curry AL, Roberts SG, Deaton RJ (2021) Empathy and low participation of women in engineering: is there a hidden link. J Educ Train Stud 9(6):16–28. https://doi.org/10.11114/jets.v9i6.5237
47. Yang C, Yang D, Min W, Zhang Y (2017) The college examination reform under the goal of cultivating innovative talents. In 2017 7th International Conference on Education, Management, Computer and Society (EMCS 2017) (pp. 1412–1416). Atlantis Press. https://doi.org/10.2991/emcs-17.2017.275
48. Zhang E, Jiang M, Zhang Z (2025) From algorithms to artistry: Promoting high school students' creativity through interdisciplinary integration of creative coding and smart design. Think Skills Creativity 101910. https://doi.org/10.1016/j.tsc.2025.101910
49. Zhang J (2021) Research on the interdisciplinary competence and its influencing factors of engineering college students under the emerging engineering education. In Proceedings of the 2021 International Conference on Education, Knowledge and Information Management, 163–169. https://doi.org/10.1145/3488466.3488486
50. Zhou H, Guns R, Engels TCE (2023) Towards indicating interdisciplinarity: Characterizing interdisciplinary knowledge flow. J Association Inform Sci Technol 74(11):1325–1340. https://doi.org/10.1002/asi.24829
51. Zuber-Skerritt O, Wood L (eds) (2019) Action learning and action research: Genres and approaches. Emerald Publishing Limited. https://doi.org/10.1108/9781787695375

Figures

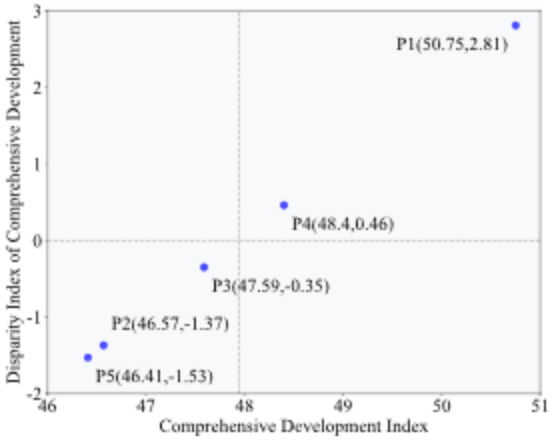


Figure 1

Quadrant distribution of development situations among five polytechnic colleges