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Shuyu Qi
Beijing University of Technology
Mu Niu
Beijing University of Technology
Penglong Jiang
Beijing University of Technology
Xiaomu Ren
renxiaomu2002@163.com

Beijing University of Technology
Yuxuan Yang
Beijing University of Technology

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Multi- stakeholder collaboration in engineering education: Institutional mechanisms for STEM talent development in China

Shuyu Qi, Mu Niu, Yuxuan Yang, Penglong Jiang, Xiaomu Ren*

The Capital Research and Development Center for Engineering Education, Institute of Higher Education, Beijing University of Technology, Beijing 100124, China.

*Correspondence: renxiaomu2002@163.com

Abstract: In response to emerging technological and industrial demands, China has introduced a distinctive institutional reform to strengthen the development of high-level engineering talent through closer collaboration among universities, industry, and government. This reform, represented by the establishment of National Institutes for Excellent Engineers, seeks to align talent development with national strategic needs while connecting academic knowledge with engineering practice. Yet an important question remains: how can multi-stakeholder collaboration integrate knowledge and coordinate expertise in engineering talent development? Drawing on mixed-methods evidence from the implementation of this reform, this study examines how strategic priorities, knowledge development, institutional coordination, and resources are connected to training outcomes. The findings show that strategic priorities do not directly produce training outcomes. Instead, they are first translated into a shared knowledge system, which then provides a basis for collaborative governance and the coordination of resources and expertise. Collaborative governance, in turn, has the strongest direct association with training outcomes in the model. These findings suggest that effective multi-stakeholder collaboration depends not

simply on pooling resources, but on creating shared knowledge and governance arrangements through which different forms of expertise can be coordinated and translated into educational practice. The study offers a process-based account of how cross-organisational collaboration can support engineering talent development in response to rapidly changing technological and societal needs.

Keywords: National Institutes for Excellent Engineers; Collaborative Talent Development; Talent Development Outcomes; Mixed-Methods Research

1. Introduction

China has increasingly positioned the development of high-level engineering talent as a strategic priority in responding to rapid technological change and strengthening national scientific and technological capacity. Against this background, the country has introduced a distinctive institutional reform—the establishment of National Institutes for Excellent Engineers—to strengthen the capacity of universities to cultivate advanced engineering talent through closer collaboration among government, universities, and industry. Rather than representing a conventional university-based training programme, the Institutes constitute a strategic reform initiative that seeks to connect national development priorities with higher education, scientific and technological innovation, and industrial practice. Their development reflects China's broader effort to strengthen scientific and technological self-reliance while building institutional capacity for the cultivation of talent in strategically important and emerging technological fields.

The policy significance of this reform has been reinforced by a series of national

initiatives. The Report to the 20th National Congress of the Communist Party of China called for coordinated efforts to promote the integrated development of education, science and technology, and talent, placing talent development within a broader national strategy for scientific and technological advancement. In November 2025, the Ministry of Education issued the Accreditation Standards for Excellent Engineer Education, marking an important transition from the initial stage of institutional and policy design towards more standardised implementation of excellent engineer education. Together, these developments illustrate how China has sought to institutionalise collaboration among government, universities, and industry as part of a broader response to changing technological and industrial demands(CPC Central Committee and State Council, 2025). The Outline for Building a Leading Country in Education (2024-2035) further called for strengthening National Institutes for Excellent Engineers (Ministry of Education of the People's Republic of China, 2011). Since the first cohort of universities was designated in 2022, the initiative has expanded to three cohorts comprising 32 institutions (Ministry of Education of the People's Republic of China et al., 2018). By the end of 2025, universities and enterprises had jointly enrolled and trained nearly 26,000 engineering master's and doctoral students and assembled a team of 17,000 academic and industry supervisors (China Consortium for Excellent Engineer Education, 2023). The organisational structure of advanced engineering talent development has thus shifted from university-led training to multi-stakeholder collaboration among government, universities, and industry.

A substantial body of research has examined the collaborative training of Excellent engineers, primarily from three perspectives. First, studies on institutional development and collaborative training models generally identify deep university-enterprise cooperation as the central approach (Jiang, 2024 ; Lin, 2023a). Researchers have offered systematic recommendations based on analyses of development rationales and comparative cases (Lin, 2023b ; Jing and Zhong, 2020) and have drawn on the practices of the first cohort of universities to propose pathways for building a university-enterprise community with a shared future (Pi and Li, 2024) . Second, research on collaborative governance and operational mechanisms has explained the drivers and development pathways of these institutes from the perspective of changing modes of knowledge production (Liu, 2025), developed an ideal framework for collaborative university governance (Zhou and Yue, 2025), and clarified the essential characteristics of collaborative university-enterprise training (Shah and Gillen, 2024). Third, studies have examined the factors and mechanisms that shape the development of Excellent engineers' digital competencies. Using fuzzy-set qualitative comparative analysis (fsQCA), researchers have identified the configurational effects and differentiated training pathways generated by interactions among individual, motivational, and resource-related factors (Cheng and Hu, 2025). Other work has explained the value and practical logic of Excellent engineer education from the perspective of industry-education integration (Vuoriainen et al., 2025).

These studies have established a strong foundation by examining institutional

development, collaborative models, and governance mechanisms. Nevertheless, several gaps remain. First, research on the key factors influencing collaborative education has largely relied on policy interpretation, case analysis, and summaries of practical experience. Systematic tests of the underlying mechanisms using large-scale empirical data remain limited. Second, insufficient attention has been paid to the sequential relationships among training objectives, process variables, governance mechanisms, and training outcomes. The mediating effects among these elements have not been adequately tested quantitatively, and the underlying transmission mechanisms and processes of competence development remain unclear. Third, existing research has generally focused on constructing ideal frameworks for collaborative governance, whereas the pivotal role of collaborative governance mechanisms in multi-stakeholder education has yet to be confirmed empirically. In short, although previous studies have identified factors that influence collaborative education, they have not sufficiently explained how collaborative governance converts these factors into training outcomes.

Accordingly, this study addresses three progressively linked questions. First, what are the key factors in a collaborative education system? Second, through what pathways do these factors affect training outcomes? Third, what pivotal role does collaborative governance play in this transmission process? By systematically answering these questions, this study aims to reveal the mechanisms through which government-university-industry collaboration in National Institutes for Excellent Engineers evolves from institutional expansion toward mechanism optimization. The

findings are intended to provide a theoretical basis and policy recommendations for improving the excellent engineer education system.

2. Research Design

2.1 Exploratory Sequential Design

This study adopts an Exploratory Sequential Design，following the integrative logic of "qualitative first, quantitative follow-up." The aim is to leverage the in-depth insights from qualitative research to build a theoretical framework, which is then validated through the broad data collected via quantitative methods.Nils Buchholtz (2019) emphasizes that the essence of mixed-methods research lies not merely in using two methodologies, but in whether different research components meaningfully integrate around a central overarching research question.Therefore, this design was selected for the following reasons: First, as an emerging institutional practice, the National Institutes for Excellent Engineers has yet to establish a mature theoretical framework regarding the factors influencing collaborative education; thus, qualitative induction is needed to generate hypotheses from empirical materials.Second, collaborative education involves complex interactions among multiple stakeholders and elements, making it difficult for a single method to simultaneously address both factor identification and mechanism transmission.Third, qualitative findings can provide theoretical foundations for variable definition and hypothesis generation in scale development, while quantitative results can validate the external validity of the qualitative framework—creating a mutually reinforcing feedback loop.

The specific research process unfolds in three stages: In the first stage, grounded

theory's three-stage coding approach is applied to identify key influencing factors of collaborative education from multi-source texts, extract core categories, and construct a theoretical model.

In the second stage, the core categories from the theoretical model serve as measurement dimensions for the scale, with relationships among categories forming research hypotheses, thereby transforming qualitative insights into measurable variable relationships.

Finally, qualitative findings and quantitative results are integrated and discussed, forming a complete closed loop of "concept generation—instrument development—model validation—evidence integration."

2.2 Qualitative Data and Analytical Procedures

The qualitative data comprises three levels: first, policy documents issued by national and local governments; second, typical cases of training practices and work reports from the National Institutes for Excellent Engineers;； and third, academic research related to the National Institutes for Excellent Engineers.Following criteria of contextual appropriateness, heterogeneity and representativeness, and data completeness, an analytical database (over 800,000 words) was constructed. Systematic coding was conducted using Strauss’s three-stage coding method (Strauss and Corbin, 1990) to identify key elements in the collaboration process among government, universities, and enterprises. Twenty percent of the textual materials were reserved for testing theoretical saturation. The coding process was carried out using NVivo 15, with text sources labeled by type abbreviations: “ZF” for policy texts,

“XW” for press releases, and “QK” for journal articles. Results from the theoretical saturation test indicated that six main categories had reached saturation, with no new categories or relationships identified.

2.3 Questionnaire Design and Sample

This study focuses on 32 National Elite Engineer Colleges, including the initial 10 established in 2022, 14 newly added in 2023, and 8 more added in 2024. These institutions span comprehensive universities, science and engineering-focused universities, and industry-specific universities, covering regions across eastern, central, and western China. This initiative represents the most extensive and highest-level collaboration among government, universities, and enterprises in engineering education in China today, providing a representative institutional sample for analyzing collaborative talent development mechanisms.The specific list of institutions is shown in Table 1.

Table 1 List of National Institutes for Excellent Engineers for Construction(2022 - 2024)

No.	University Name	Year	No.	University Name	Year
1	Tsinghua University	2022	17	Nanjing University of Aeronautics and Astronautics	2023
2	Zhejiang University	2022	18	Nanjing University of Science and Technology	2023
3	Beihang University	2022	19	South China University of Technology	2023

4	Beijing Institute of Technology	2022	20	University of Electronic Science and Technology of China	2023
5	Harbin Institute of Technology	2022	21	Xi'an Jiaotong University	2023
6	Shanghai Jiao Tong University	2022	22	Xidian University	2023
7	Southeast University	2022	23	China University of Petroleum, Beijing	2023
8	Huazhong University of Science and Technology	2022	24	Southern University of Science and Technology	2023
9	Chongqing University	2022	25	Beijing Jiaotong University	2024
10	Northwestern Polytechnical University	2022	26	North China Electric Power University	2024
11	University of Science and Technology Beijing	2023	27	Northeastern University	2024
12	Beijing University of Posts and	2023	28	Shandong University	2024

	Telecommunications				
13	Tianjin University	2023	29	Wuhan University of Technology	2024
14	Dalian University of Technology	2023	30	Hunan University	2024
15	Harbin Engineering University	2023	31	Central South University	2024
16	Tongji University	2023	32	Southwest Jiaotong University	2024

The questionnaire design is based on the 6 core dimensions extracted through qualitative coding. A total of 37 questions are set, belonging to 5 primary dimensions: the compatibility of the training goals for high-end talents (5 questions on national strategic needs, 6 questions on international competitiveness), the integration of theoretical knowledge and practical application (6 questions on the construction of core knowledge system, 3 questions on the cultivation of practical application ability), the effectiveness of institutional coordination and resource integration (4 questions on the guarantee mechanism for institutional coordination, 4 questions on the mechanism for resource integration), the collaborative governance mechanism (4 questions) and the quality and effect of collaborative training (5 questions).This survey is conducted among the teachers and students of 32 colleges， and a total of 1001 questionnaires were randomly sampled and collected. After excluding invalid questionnaires， 963 valid questionnaires were retained， with an effective recovery rate of 96.2%. Data

processing was completed using SPSS 27.0 and Mplus 8.3 software.

3. Qualitative Findings and Development of the Theoretical Model

3.1 Identification of Factors Influencing Collaborative Education

The relevant texts were analyzed systematically to identify the mechanisms underlying the factors that influence collaborative education. During open coding, the source texts were screened, compared, classified, and labeled sentence by sentence to conceptualize and categorize the material. The 110 texts were divided into independent units of information, from which 95 concepts were abstracted. Related concepts were then grouped, while incidental and overlapping concepts were removed, resulting in 26 initial categories. Representative examples are presented in Table 2.

Table 2. Examples of Initial Categories Derived from Open Coding

Data source	Example from the original text	Data labels	Initial category
XW-01	The college and an enterprise signed an agreement to jointly establish an engineer technology center for embodied intelligent robots.	University-enterprise agreement; engineer technology center construction	University-enterprise cooperation mechanism

Data source	Example from the original text	Data labels	Initial category
QK-03	Develop leading engineering innovators who can serve national needs.	National needs orientation; engineering doctoral education	High-level talent development
XW-05	Doctoral students preparing to become leading engineering innovators conduct field research on engineering practice.	Engineering field research; leading innovators	Practical capability development
ZF-04	Zhejiang Province issued policy measures to support the development of Excellent engineers.	Local policy measures; support for Excellent engineers	Policy support measures
ZF-01	Develop a large cohort of Excellent engineers for the new era who can shoulder the mission of national rejuvenation.	Mission of national rejuvenation; talent for the new era	Research on educational goals

Data source	Example from the original text	Data labels	Initial category
QK-12	Research on program curricula under the Education and Training Plan for Excellent Engineers.	Program curriculum research; disciplinary development	Curriculum reform
QK-15	Construction of engineer technology centers for developing the practical capabilities of Excellent engineers.	Practical capability development; center construction	Practice-platform development
ZF-02	Participating enterprises should appoint experienced engineers as supervisors.	Industry supervisors; practice supervision	Faculty development
ZF-06	Priority support should be provided for international cooperation and exchanges involving students from universities participating in the Plan.	International cooperation and exchange; priority support	International cooperation and exchange

Data source	Example from the original text	Data labels	Initial category
ZF-08	Participating enterprises have priority in recruitment under joint training agreements.	Priority recruitment; enterprise rights	Employment support mechanism

3.2 Core Categories and Their Relationships

Axial coding further focused and refined the 26 initial categories, producing six main categories: institutional and resource support; a university-enterprise collaborative education platform; a teaching and practice system; a practical capability development system; a high-level talent development system; and internationalization and collaboration among faculty. Selective coding was then used to examine the relationships among these categories. Based on Haken's theory of synergetics (1983), the core category was defined as the government-university-enterprise collaborative talent development process in National Institutes for Excellent Engineers. This process follows three lines of logic: goal orientation, the educational process, and supporting conditions, which correspond to educational goals, the educational process, and educational support, respectively.

Table 3 was prepared to clarify how the qualitative categories were converted into quantitative variables. It shows how the six main categories derived through qualitative coding became the six measured variables in the structural equation model and identifies the role of each variable in the model.

Table 3. Conversion of Qualitative Main Categories into Quantitative Variables

Qualitative main category	Core meaning	Quantitative variable	Role in the model
High-level talent development system	Serving national strategic needs	National strategic needs	Antecedent variable (goal level)
Internationalization and collaboration among faculty	Alignment with international standards	International competitiveness	Antecedent variable (goal level)
Teaching and practice system	Reconstruction of the knowledge system	Construction of the core knowledge system	Process variable (process level)
Practical capability development system	Application in engineering settings	Development of practical application ability	Process variable (process level)
Institutional and resource support	Safeguarding responsibilities, rights, and rules	Institutional coordination and support mechanism	Process variable (support level)

Qualitative main category	Core meaning	Quantitative variable	Role in the model
University-enterprise collaborative education platform	Cross-organisational resource allocation	Resource coordination and allocation mechanism	Process variable (support level)

Note: The collaborative governance mechanism and educational outcomes were added through theoretical deduction based on synergetics and were specified as the mechanism-level and outcome-level variables, respectively.

3.3 Theoretical Model and Research Hypotheses

A model of government-university-enterprise collaborative talent development in National Institutes for Excellent Engineers was developed from the core category and storyline obtained through selective coding, together with propositions derived from synergetics. The model has four levels. At the goal level, national strategic needs and international competitiveness provide strategic direction for collaborative training. The process level comprises the construction of a core knowledge system, the development of practical application ability, the institutional coordination and support mechanism, and the resource coordination and allocation mechanism. These variables provide implementation pathways and support for achieving the educational goals. At the mechanism level, the collaborative governance mechanism provides the institutional channel through which the other elements are converted into educational outcomes. At the outcome level, educational outcomes indicate the overall

effectiveness of collaborative training. The six categories at the goal and process levels were derived from qualitative coding, whereas the mechanism and outcome levels were added through theoretical deduction based on synergetics. Figure 1 presents the resulting model. The following hypotheses were developed from the logical relationships among its dimensions.

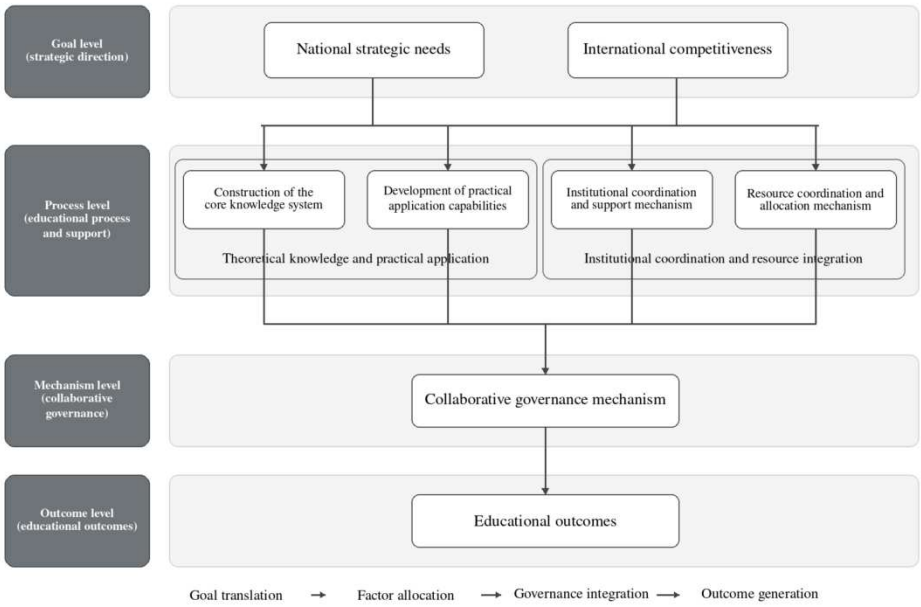


Figure 1. Model of Government-University-Enterprise Collaborative Talent Development in National Excellent Engineer Colleges

3.3.1 Goal-Orientation Hypotheses

Categories such as national needs orientation, high-level talent development, and research on educational goals appeared frequently in the qualitative coding. Axial coding further revealed that high-level talent development goals drive the teaching and practice system and the practical capability development system. From the perspective of synergetics, a system goal functions as an order parameter that determines the direction of coordination among subsystems. As the order parameter of the government-university-enterprise system, high-level talent development goals

establish a shared direction, reduce divergence among the goals of the subsystems, and coordinate the development of knowledge and practice systems. Previous studies also support this relationship. Marques (2026) argued that clear talent development goals encourage active coordination among the three parties. Sun and Xu (2024) found that clearly defined curriculum reform goals provide a more explicit direction for reform. Dahlin (2026) suggested that goals for developing innovative talent encourage universities to strengthen the teaching of advanced theory. When educational goals emphasize the strategic demand for high-level talent, participating organizations are more likely to design institutions, improve cooperation mechanisms, and coordinate curricula, faculty, platforms, and other resources around those goals. This creates a collaborative education structure characterized by aligned goals and shared resources. The following hypothesis is therefore proposed:

H1: High-level talent development goals have a significant positive effect on institutional coordination and resource integration.

High-level talent development goals shape both the organisational operation of collaborative education and the content and direction of capability development. Previous research suggests that developing the capacity to solve complex problems requires moving beyond conventional knowledge transmission and integrating theoretical learning with practical application (Tian et al., 2026). Clear educational goals can guide participating organizations in adjusting curricula and teaching methods, strengthen the connections among knowledge acquisition, engineering practice, and industry needs, and enable students to transfer knowledge and develop

capabilities in authentic contexts. Clearer high-level talent development goals should therefore promote deeper integration between theoretical knowledge and practical application. Accordingly:

H2: High-level talent development goals have a significant positive effect on the integration of theoretical knowledge and practical application.

3.3.2 Hypotheses on the Effects of the Governance Mechanism

Axial coding showed that the two main categories of institutional and resource support and the university-enterprise collaborative education platform are closely related to collaborative governance. From an institutional economics perspective, institutional coordination reduces transaction costs by clarifying the division of responsibilities and rights and the rules for distributing benefits, thereby providing binding constraints for governance. Resource coordination integrates heterogeneous resources and supplies the material basis for implementing the governance mechanism. Because the collaborative governance mechanism regulates collaborative behavior and integrates collaborative resources, its quality directly determines educational outcomes. Institutional arrangements can clarify the responsibilities of universities, enterprises, research institutions, and other actors; standardize cooperation procedures; and reduce uncertainty in interorganisational cooperation. Zhang and Gao (2016) found that inadequate institutional coordination fragments resource integration. Resource coordination, in turn, enables actors to complement one another in faculty expertise, platforms, technology, and practice settings, thereby providing sustained support for collaborative education. Zhou et al. (2025), for example, argued that

precise resource coordination grounded in institutional coordination improves resource-use efficiency. Zhou and Li (2026) reported that more developed collaborative governance mechanisms generate stronger collective capacity. The following hypothesis is proposed:

H3: Institutional coordination and resource integration have a significant positive effect on the collaborative governance mechanism.

Collaborative education also seeks to overcome the traditional separation between theoretical instruction and practical training by integrating knowledge systems with application settings. Research indicates that theoretical knowledge must serve as the foundation for capability development and must also be transformed and deepened through practice when high-level talent is developed. Effective connections between theory and application enable universities and industry partners to jointly design educational content and improve educational processes around shared goals. These connections can foster continuing interaction and governance relationships among the participating actors (Wu and Jiang, 2025). The degree of integration between theoretical knowledge and practical application should therefore influence the development of the collaborative governance mechanism. Li et al. (2023) argued that industry-education integration depends on autonomous action by both industry and educational institutions and examined which collaborative pathways improve the effectiveness of engineering talent development projects. An effective collaborative governance mechanism can strengthen information sharing, coordinated responsibility, and process interaction; improve the efficiency of educational resource allocation; and

connect educational goals, educational processes, evaluation, and feedback. These functions should improve the quality of collaborative training. The following hypotheses are proposed:

H4: The integration of theoretical knowledge and practical application has a significant positive effect on the collaborative governance mechanism.

H5: The collaborative governance mechanism has a significant positive effect on the quality and effectiveness of collaborative training.

3.3.3 Mediation Hypothesis

The storyline derived through selective coding indicates that institutional coordination and resource integration, as well as theoretical knowledge and practical application, do not directly produce educational outcomes. Their effects must be transmitted through the collaborative governance mechanism. Institutionalism and resource dependence theory suggest that institutional design and resource allocation can be converted into governance effectiveness and educational quality only when they are coordinated and implemented through a collaborative governance mechanism. Although institutional coordination and resource integration and the integration of theory and practice provide important foundations for better educational quality, neither automatically produces effective outcomes. The governance mechanism realizes their effects by clarifying the responsibilities and rights of government, universities, and enterprises and by establishing monitoring and evaluation procedures. These arrangements move theoretical and practical elements from formal participation to substantive integration. Hwang et al. (2026) found that participation in practice

mediates the effects of university-enterprise cooperative training. The collaborative governance mechanism therefore links upstream resource conditions to downstream educational outcomes. Diaz et al. (2026) found that reconstructing the elements of industry-education integration depends on collaborative governance mechanisms that convert inputs into effectiveness. Bae and Choi (2024) found that collaborative governance significantly mediates the relationship between economic and social performance. Accordingly:

H6: The collaborative governance mechanism mediates the effects of institutional coordination and resource integration and of theoretical knowledge and practical application on the quality and effectiveness of collaborative training.

4. Quantitative Testing

4.1 Measurement Model Testing

Confirmatory factor analysis (CFA) was conducted using Mplus 8.3. The Cronbach's α values for all variables ranged from 0.822 to 0.872, composite reliability (CR) values ranged from 0.826 to 0.874, and average variance extracted (AVE) values ranged from 0.520 to 0.682, all meeting acceptable standard. CFA results indicated that the eight-factor model exhibited good fit (χ^2 = 1379.620, df = 601, χ^2/df = 2.296, RMSEA [90% CI] = 0.037 [0.034, 0.039], CFI = 0.958, TLI = 0.953, SRMR = 0.033), with all item loadings on their corresponding factors exceeding 0.6. The square root of AVE for each factor (0.721–0.826) exceeded the inter-factor correlation coefficients (0.475–0.697), demonstrating that the measurement model possessed good reliability, convergent validity, and discriminant validity. Detailed test results are

presented in Table 4.

Table 4 Measurement Model Testing Results

Variable	Number of Items	Cronbach's α	CR	AVE	AVE√
National Strategic Needs	5	0.840	0.845	0.523	0.723
International Competitiveness	6	0.866	0.866	0.520	0.721
Core Knowledge System Construction	6	0.872	0.874	0.536	0.732
Practical Application Competence Development	3	0.863	0.865	0.682	0.826
Institutional Coordination Safeguard Mechanism	4	0.850	0.861	0.608	0.780
Resource Integration and Allocation	4	0.828	0.830	0.550	0.742

Mechanism					
Collaborative Governance Mechanism	4	0.822	0.826	0.542	0.736
Training Effectiveness 5	5	0.859	0.863	0.558	0.747

Note: √AVE denotes the square root of AVE; all inter-factor correlation coefficients (0.475–0.697) were less than the square root of AVE, indicating good discriminant validity.

4.2 Structural Path Testing

A structural equation model was constructed using Mplus 8.3, demonstrating good model fit (χ^2 = 1799.370, df = 615, χ^2/df = 2.926, RMSEA [90% CI] = 0.045 [0.042, 0.047], CFI = 0.936, TLI = 0.931, SRMR = 0.064).Path testing results are reported in three groups according to logical sequence.

First, the effects of target variables on process variables. National strategic needs exerted significant positive effects on all four process variables, with the strongest effect on core knowledge system construction (β = 0.476, $p < 0.001$), followed by resource integration and allocation mechanism (β = 0.455), institutional coordination safeguard mechanism (β = 0.423), and practical application competence development (β = 0.382). International competitiveness also significantly and positively predicted all four process variables, with relatively stronger effects on practical application competence development (β = 0.411) and core knowledge system construction (β =

0.386). Overall, the driving effect of national strategic needs exceeded that of international competitiveness, and both target variables ranked prominently in predicting core knowledge system construction.

Second, the effects of process variables on the collaborative governance mechanism. All four process variables significantly and positively predicted the collaborative governance mechanism, with core knowledge system construction exhibiting the strongest effect ($\beta = 0.383$, $p < 0.001$), followed by institutional coordination safeguard mechanism ($\beta = 0.237$), while resource integration and allocation mechanism ($\beta = 0.195$) and practical application competence development ($\beta = 0.184$) were relatively weaker. The path coefficient of core knowledge system construction was approximately twice that of practical application competence development, indicating that knowledge consensus played a substantially greater driving role in the operation of the governance mechanism than practical training per se.

Third, the effect of the collaborative governance mechanism on training effectiveness. The collaborative governance mechanism significantly and positively predicted training effectiveness ($\beta = 0.574$, $p < 0.001$), representing the strongest direct effect path in the full model, indicating that the collaborative governance mechanism serves as the core institutional channel for generating training effectiveness. Detailed path testing results are presented in Table 5.

Table 5 Structural Path Testing Results

Outcome Variable	Predictor	β	SE	t
Core Knowledge	National Strategic	0.476***	0.035	13.431

System Construction	Needs			
	International Competitiveness	0.386***	0.036	10.682
Practical Application Competence Development	National Strategic Needs	0.382***	0.038	9.916
	International Competitiveness	0.411***	0.038	10.818
Institutional Coordination Safeguard Mechanism	National Strategic Needs	0.423***	0.039	10.880
	International Competitiveness	0.334***	0.039	8.476
Resource Integration and Allocation Mechanism	National Strategic Needs	0.455***	0.039	11.677
	International Competitiveness	0.349***	0.040	8.798
Collaborative Governance Mechanism	Core Knowledge System Construction	0.383***	0.042	9.159
	Practical	0.184***	0.039	4.650

	Application Competence Development			
	Institutional Coordination Safeguard Mechanism	0.237***	0.038	6.300
	Resource Integration and Allocation Mechanism	0.195***	0.042	4.679
Training Effectiveness	Collaborative Governance Mechanism	0.574***	0.027	20.870

Note: ***p < 0.001.

4.3 Indirect Effect Testing

The Bootstrap method (5,000 resamples) was employed to test mediating effects; a mediating effect was considered established if the 95% confidence interval excluded zero. Results are presented in Table 6. The 20 indirect effect paths can be categorized into three types:

First, the antecedent mediating effects of process variables. Core knowledge system construction, practical application competence development, institutional coordination

safeguard mechanism, and resource integration and allocation mechanism all played significant mediating roles between national strategic needs and international competitiveness on the one hand and the collaborative governance mechanism on the other. Among these, core knowledge system construction exhibited the strongest antecedent mediating effect (national strategic needs path: 0.182 [0.120, 0.261]; international competitiveness path: 0.148 [0.093, 0.225]), approximately 1.5 to 2.6 times that of the other three process variables.

Second, the posterior mediating effect of the collaborative governance mechanism. The collaborative governance mechanism played a significant mediating role between all four process variables and training effectiveness, with the effect of "core knowledge system construction → collaborative governance mechanism → training effectiveness" being the highest (0.220 [0.151, 0.305]), approximately twice that of "practical application competence development → collaborative governance mechanism → training effectiveness" (0.105).

Third, the serial mediating effects of process variables and the collaborative governance mechanism. The four process variables each operated in conjunction with the collaborative governance mechanism to form serial mediating paths between national strategic needs, international competitiveness, and training effectiveness. Among these, the serial effect of "national strategic needs → core knowledge system construction → collaborative governance mechanism → training effectiveness" was the strongest (0.105 [0.066, 0.158]), followed by "international competitiveness → core knowledge system construction → collaborative governance mechanism →

training effectiveness" (0.085 [0.050, 0.135]). The remaining serial path effect values ranged from 0.039 to 0.057, all passing significance tests.

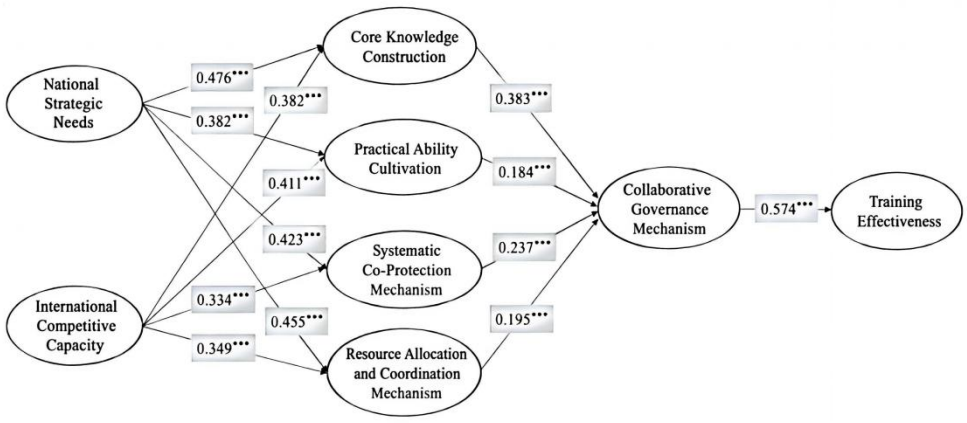


Figure 2. Path Diagram of the Mediation Model

Note. ***p < 0.001

Table 6. Results of Indirect Effect Tests

Path	**standardised Effect**	**SE**	**Bootstrap 95%CI**
National Strategic Needs→Core Knowledge System Construction→Collaborative Governance Mechanism	0.182	0.036	[0.120, 0.261]
National Strategic Needs→Practical Application Competence Development→Collaborative Governance Mechanism	0.070	0.026	[0.029, 0.134]
National Strategic Needs→Institutional Coordination Safeguard	0.100	0.033	[0.050, 0.179]

Mechanism→Collaborative Governance Mechanism			
National Strategic Needs→Resource Integration and Allocation Mechanism→Collaborative Governance Mechanism	0.089	0.033	[0.036, 0.168]
International Competitiveness→Core Knowledge System Construction→Collaborative Governance Mechanism	0.148	0.033	[0.093, 0.225]
International Competitiveness→Practical Application Competence Development→Collaborative Governance Mechanism	0.076	0.027	[0.034, 0.141]
International Competitiveness→Institutional Coordination Safeguard Mechanism→Collaborative Governance Mechanism	0.079	0.026	[0.039, 0.145]
International Competitiveness→Resource Integration and Allocation Mechanism→Collaborative Governance Mechanism	0.068	0.027	[0.027, 0.134]

Core Knowledge System Construction→Collaborative Governance Mechanism→Training Effectiveness	0.220	0.039	[0.151, 0.305]
Practical Application Competence Development→Collaborative Governance Mechanism→Training Effectiveness	0.105	0.033	[0.049, 0.179]
Institutional Coordination Safeguard Mechanism→Collaborative Governance Mechanism→Training Effectiveness	0.136	0.037	[0.075, 0.218]
Resource Integration and Allocation Mechanism→Collaborative Governance Mechanism→Training Effectiveness	0.112	0.039	[0.045, 0.197]
National Strategic Needs→Core Knowledge System Construction→Collaborative Governance Mechanism→Training Effectiveness	0.105	0.023	[0.066, 0.158]
National Strategic Needs→Practical Application Competence Development→Collaborative Governance Mechanism→Training Effectiveness	0.040	0.016	[0.017, 0.080]
National Strategic Needs→Institutional Coordination Safeguard	0.057	0.020	[0.028, 0.106]

Mechanism→Collaborative Governance Mechanism→Training Effectiveness			
National Strategic Needs→Resource Integration and Allocation Mechanism→Collaborative Governance Mechanism→Training Effectiveness	0.051	0.021	[0.019, 0.102]
International Competitiveness→Core Knowledge System Construction→Collaborative Governance Mechanism→Training Effectiveness	0.085	0.019	[0.050, 0.135]
International Competitiveness→Practical Application Competence Development→Collaborative Governance Mechanism→Training Effectiveness	0.043	0.016	[0.019, 0.081]
International Competitiveness→Institutional Coordination Safeguard Mechanism→Collaborative Governance Mechanism→Training Effectiveness	0.045	0.016	[0.022, 0.087]
International Competitiveness→Resource Integration and Allocation Mechanism→Collaborative Governance Mechanism→Training Effectiveness	0.039	0.017	[0.015, 0.081]

5. Integration of mixed evidence and implications for practice

The integration of the quantitative and qualitative findings suggests that effective collaborative education depends first on how broadly defined training goals are translated into concrete educational practices. The quantitative analysis shows that high-level talent development goals are positively associated with institutional coordination, resource integration, and the integration of theoretical knowledge with practical application. The qualitative evidence further suggests that collaboration among multiple stakeholders is not simply a matter of sharing resources. Rather, it depends on developing a shared understanding of training goals and translating broad strategic priorities into specific educational content and arrangements.

5.1. Translating strategic priorities into shared educational content

During the qualitative coding process, national strategic needs, high-level talent development, and curriculum reform were among the most frequently identified categories, suggesting a broad consensus among stakeholders regarding the strategic direction of talent development. The quantitative findings, however, provide a more differentiated picture. National strategic needs and international competitiveness, as goal-level variables, did not have significant direct effects on training outcomes. Instead, national strategic needs had the strongest effect on the development of a core knowledge system ($\beta = 0.476$, $p < 0.001$), while the core knowledge system had the strongest predictive effect on collaborative governance ($\beta = 0.383$, $p < 0.001$). Among all indirect pathways, the mediating effect through the core knowledge system was also the strongest (0.182).

Taken together, these findings suggest that strategic priorities do not translate directly into training outcomes. They first need to be reflected in the way curricula, knowledge, and engineering problems are organised, with the development of a core knowledge system representing a critical stage in this process.

The starting point for collaborative education, therefore, is not simply to bring more actors into the process. It is to translate national strategic needs into a shared body of knowledge and educational content that can be recognised by government, universities, and industry. Strategic priorities are more likely to shape subsequent collaboration when stakeholders reach what may be described as a second level of consensus: agreement not only on the overall direction of talent development, but also on what kinds of professionals should be cultivated, what knowledge they should acquire, and what engineering problems they should learn to address.

This helps explain why national strategic needs did not have a significant direct effect on training outcomes. Strategic priorities do not themselves generate educational outcomes. Their influence needs to be mediated through the reconstruction and organisation of knowledge before they can shape the collaborative processes through which education is delivered.

5.2. Integrating governance to connect resources with educational outcomes

The qualitative evidence contains numerous references to university–industry platforms, practice bases, engineering technology centres, and other forms of resource support. These findings suggest that many institutions have established a substantial foundation of infrastructure and educational resources. However, the quantitative

results indicate that the direct effects of institutional coordination ($\beta = 0.237$) and resource integration ($\beta = 0.195$) on collaborative governance were both smaller than that of the core knowledge system ($\beta = 0.383$). Moreover, none of the four process variables had a significant direct effect on training outcomes. In contrast, collaborative governance had a significant positive effect on training outcomes ($\beta = 0.574$, $p < 0.001$), representing the strongest direct effect in the model.

This finding calls into question the assumption that a greater number of platforms or a larger volume of resources will necessarily lead to more effective collaborative education. Knowledge, practical experience, institutional arrangements, and resources are important conditions for collaboration, but they do not automatically produce educational outcomes. Their value depends on how they are coordinated through processes such as the allocation of responsibilities, information sharing, the coordination of interests, and quality assurance.

Platforms and resources should therefore be understood as necessary rather than sufficient conditions for collaboration. Collaborative governance provides the organisational link through which available resources can be converted into meaningful educational opportunities and outcomes. This may also help explain why an emphasis on building platforms without sufficient attention to how these platforms are operated and coordinated can constrain the effectiveness of collaborative education.

The quantitative results further identify the strongest sequential pathway in the model as: national strategic needs → core knowledge system → collaborative governance →

training outcomes, with a standardised indirect effect of 0.105. International competitiveness showed an indirect effect of 0.085 through the same pathway. This pattern is consistent with the three dimensions identified through qualitative coding—goal orientation, process implementation, and institutional support—which correspond closely to the sequential relationships identified in the quantitative analysis.

Taken together, the findings suggest that collaborative education in National Institutes for Excellent Engineers should not be understood as a process in which training goals directly generate educational outcomes. Rather, it involves a sequence of transformations through which strategic priorities are translated into educational content, resources and institutional arrangements are organised, governance brings these elements together, and educational outcomes are subsequently generated.

Two transitions appear particularly important. The first is the translation of strategic priorities into a shared knowledge system. The second is the transformation of educational resources and processes into outcomes through effective governance. The coherence between these two transitions may be critical to the effectiveness of collaborative education.

5.3. Implications for practice

5.3.1. Using major engineering projects to translate training goals into shared knowledge

The findings show that the development of a core knowledge system has the strongest path coefficient among the four process variables ($\beta = 0.383$), while national strategic

needs have the strongest effect on the development of this knowledge system (β = 0.476). This suggests that the reconstruction of knowledge is a critical link between strategic priorities and educational outcomes. The starting point for government–university–industry collaboration should therefore be not simply the inclusion of more participating organisations, but the development of a shared understanding of what kinds of professionals should be cultivated, what knowledge they should acquire, and what engineering problems they should be prepared to address.

Emerging fields such as artificial intelligence, quantum technology, and biomanufacturing are generating demands for engineering talent that extend beyond the requirements of existing occupations. Training goals therefore need to be developed with a forward-looking perspective. Major national engineering projects can provide a practical context in which government, universities, and industry jointly translate strategic priorities into educational content.

For example, universities and enterprises could jointly develop training standards and curricula, while real engineering problems encountered in industry could be incorporated into course content and used to inform students' thesis topics. Such arrangements would create opportunities for knowledge to be developed across organisational boundaries and would allow broad strategic priorities to be translated into concrete educational programmes and teaching practices.

The central task is to move from strategic consensus to knowledge consensus. Agreement on broad strategic priorities is insufficient if stakeholders do not also share an understanding of what should be taught and learned. Such agreement provides a

foundation for subsequent practical training, institutional coordination, and resource integration to operate as part of a coherent educational process (Gulikers et al., 2025).

5.3.2. Connecting resources to learning through institutional coordination

The findings suggest that resources become educationally meaningful only when they are embedded in processes that connect different forms of expertise. The presence of shared platforms, facilities, or other resources does not, in itself, ensure effective collaboration. What matters is how these resources are connected to educational purposes and how the knowledge and expertise of different actors are brought into the learning process.

This has particular relevance in the context of digital and technological change. Engineering talent development increasingly depends not only on access to physical infrastructure, but also on access to data, research knowledge, engineering problems, and innovation contexts. Digital platforms can therefore serve as spaces for connecting university research with enterprise data and real-world applications. Their value lies less in the resources they accumulate than in their capacity to create meaningful connections among these otherwise dispersed forms of knowledge and expertise (Albats et al., 2025).

Such connections require institutional arrangements that link resource provision with participation in the educational process. University–industry platforms, experimental facilities, and engineering centres can be integrated into specific stages of talent development, while university and industry mentors can share responsibility for defining problems, guiding practical work, and assessing learning. Establishing these

connections would help shift resources from being treated as inputs to being used as part of an integrated learning process. In this sense, the implementation challenge is not simply how to provide more resources, but how to create the organisational conditions under which existing resources can be effectively mobilised for learning and development (Khan et al., 2026).

5.3.3. Building governance as a process of continuous coordination

Collaborative governance has the strongest direct association with training outcomes in the model ($\beta = 0.574$), highlighting the importance of governance not as a fixed institutional arrangement, but as an ongoing process of coordination. This distinction is particularly important when the knowledge required for engineering innovation is distributed across disciplines, organisations, and sectors.

Three implications follow from this finding. First, collaboration requires continuing opportunities for stakeholders to negotiate priorities, responsibilities, and differences in interpretation. Regular interaction among government, universities, and industry can provide a basis for coordinating their different interests and forms of expertise, while clearer procedures for addressing disagreement can reduce reliance on informal coordination.

Second, governance needs to extend across the full educational process. Rather than treating collaboration as a set of arrangements established at the beginning of a programme, institutions can use continuous monitoring and feedback to connect goal setting, knowledge development, practical learning, assessment, and subsequent adjustment. A cycle of goal setting → implementation → coordination → evaluation

→ feedback and adjustment can therefore provide a basis for maintaining alignment as educational and technological conditions change.

Third, such governance needs to remain responsive to changes in engineering knowledge and industrial practice. Curricula, practical activities, and assessment criteria should not be treated as fixed outputs of an initial agreement. Instead, they can be periodically revisited as new technologies emerge, engineering problems evolve, and the expertise required of future engineers changes. Governance thus becomes a means of maintaining the connection between evolving external demands and the internal processes of education.

Taken together, these implications suggest that the central challenge of multi-stakeholder engineering education is not simply the mobilisation of additional resources, but the integration of knowledge and expertise across organisational boundaries. Resources acquire educational value when they are connected to shared learning processes; collaboration becomes effective when different forms of expertise are coordinated through continuing governance; and training goals become meaningful when they are translated into knowledge and practices that can be jointly enacted by different stakeholders.

5.4. Concluding implications

The findings provide a broader perspective on how engineering talent development can respond to emerging technological and societal challenges. Rather than viewing government–university–industry collaboration primarily as a mechanism for matching graduates to existing industrial needs, the evidence points towards a more dynamic

model in which different actors jointly shape the knowledge, practices, and capabilities required for uncertain and evolving engineering contexts.

The Chinese reform examined in this study provides a distinctive setting in which to observe this process. Its significance lies not simply in the institutional form of the National Institutes for Excellent Engineers, but in the way the reform attempts to connect national strategic needs, academic knowledge, and engineering practice. The findings suggest that such connections depend on two linked processes: the translation of broad strategic priorities into shared knowledge and the coordination of distributed expertise through governance.

This perspective shifts attention from whether organisations participate in collaboration to how their knowledge and expertise are made mutually accessible, interpretable, and actionable. For engineering talent development, effective collaboration therefore depends less on the accumulation of institutional resources than on the capacity to create connections among different sources of expertise and to continually adapt these connections as knowledge and technological conditions change.

More broadly, the study suggests that developing talent for emerging technological fields requires an approach that goes beyond adapting education to established occupational demands. It calls for educational arrangements capable of bringing together disciplinary knowledge, engineering practice, strategic priorities, and emerging technological possibilities. Such an approach can support a shift from resource sharing towards knowledge integration, and from one-time institutional

coordination towards continuous collaborative learning and adaptation.

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Figure legends

Figure 1. Model of Government-University-Enterprise Collaborative Talent Development in National Institutes for Excellent Engineers

Figure 2. Path Diagram of the Mediation Model

Note. ***$p < 0.001$

Data availability

The materials supporting the findings of this study, including Research data, Research instruments, Descriptions of the research procedures, are available in the supplementary files submitted with this manuscript for editorial and peer review.

Competing interests

The authors declare no competing interests.

Ethical statements

This study was reviewed and approved by the Ethics Committee of Beijing University of Technology (Certificate No. BJUTCOM-202611-001, dated 11 November 2026). The research was conducted in accordance with the applicable institutional ethical requirements and relevant regulations. Informed consent was obtained from all participants prior to their participation in the study.

Author contributions

Conceptualization, S.Q.; methodology, S.Q. and M.N; formal analysis M.N. and S.Q.; investigation, S.Q. and M.N.; writing—original draft preparation S.Q. and M.N; writing—review and editing, M.N.,Y.Y. and X.R.; visualization, S.Q., M.N. and P.J. All authors have read and agreed to the published version of the manuscript.