From Models to Pathways: A Typological Study of Interdisciplinary Postgraduate Education in Industry-Background Higher Education Institutions

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Abstract: Training postgraduate students in interdisciplinary subjects is crucial for the comprehensive reform of postgraduate education in China. However, existing research has largely focused on the macro-level design of training models, paying insufficient attention to the meso-level element of 'training pathways' and lacking differentiated analyses of pathways for various types of interdisciplinary programs. This study examines institutions that were directly affiliated with either the former Ministry of Metallurgy or the former China National Nonferrous Metals Industry Corporation. Using a classification framework comprising four types of interdisciplinarity - theory aggregation, theory community, practice aggregation, and practice community - derived from two dimensions, the mode of knowledge generation and the mode of knowledge interaction, this research systematically identifies the corresponding postgraduate training pathways for each type. The findings suggest that the 'theory-aggregation' type is most appropriate for interdisciplinary student recruitment pathways, the 'theory-community' type for curriculum integration pathways, the 'practice-aggregation' type for project-driven pathways, and the 'practice-community' type for platform-based collaborative pathways. These pathways are effective through a mediating mechanism of 'training objectives-training competencies-training outcomes', moderated by boundary conditions such as institutional development level and regional gradients. This study reveals the underlying mechanisms of interdisciplinary postgraduate training pathways, offering practical guidance for industry-backed universities and providing references for policy formulation.

Keywords: Industry Background; Multi-Type; Interdisciplinary; Postgraduate Training; Training Pathways

1. Research Background

1.1 The Contemporary Imperative of Interdisciplinary Education in Industry-Specific Universities

Interdisciplinary integration provides a powerful impetus for universities to transcend conventional thinking and achieve significant progress in disciplinary development and talent cultivation. It has become a frequent theme in higher education reform and a focal point for institutional growth [1]. The National Medium- and Long-Term Education Reform and Development Plan (2010–2020) explicitly calls for universities to optimize the structure of academic disciplines, program types, and educational levels, and to promote interdisciplinary integration. Cultivating postgraduate students in interdisciplinary fields is a global trend in graduate education reform and a critical step in deepening comprehensive reform and enhancing the quality of postgraduate education in China [2]. In 2020, the Ministry of Education officially recognized “Interdisciplinary Studies” as China's 14th academic discipline, prompting numerous universities to establish interdisciplinary research institutes and create “special zones” for disciplinary development and talent cultivation. From the initial calls by scholars in 1985 to formal government recognition in 2020, interdisciplinary studies have evolved from scattered, spontaneous efforts into a national systemic strategy [3].

Against this macro-level backdrop, a key question emerges: How can different types of universities effectively cultivate interdisciplinary postgraduates based on their unique characteristics? Universities with strong industry backgrounds, such as those directly affiliated with the former Ministry of Metallurgy and the former China National Nonferrous Metals Industry Corporation, have significantly different disciplinary traditions, industrial linkages, and resource endowments from comprehensive universities. Consequently, their choices of training pathways for interdisciplinary programs should diverge accordingly. In the current historical context, how these universities with strong industry backgrounds leverage their strengths to address the challenges of interdisciplinary training is important not only for their own development but also for the strategic planning of talent development for key industries at the national level.

1.2 A Shift in the Approach to Research on Interdisciplinary Postgraduate Education

Academic research on interdisciplinary postgraduate training has converged around three key areas of study.

The first concerns the connotations and development of interdisciplinarity itself. The term 'interdisciplinary' was first introduced by the American psychologist Woodworth in 1926 to describe research activities that transcend a single disciplinary scope. Studies show that among the 466 scientists who won Nobel Prizes in the natural sciences during the 20^(th) century, 41.63% had interdisciplinary backgrounds, highlighting the importance of interdisciplinary knowledge structures in cultivating top talent [4]. Wang divides the evolution of interdisciplinarity into four stages: the incubation stage (scientific differentiation and sporadic related research); the development stage (accelerated knowledge growth, gradually perfected theoretical systems and initial talent cultivation); the stabilisation stage (theoretical systems are largely complete and the discipline enters the national academic catalogue); and the adjustment stage (expansion and differentiation of the disciplinary scale and structure) [5].

The second line of inquiry focuses on case studies of domestic and international training practices. Scholars have examined practices at leading universities, including Tsinghua University, Zhejiang University, Peking University, Harvard University, and Stanford University. Studies indicate that factors such as the discipline-based departmental organization of universities abroad, inertia in existing academic evaluation mechanisms, the mentor-dominated model, and the practical difficulties faced by graduate students all constrain interdisciplinary graduate training [6]. Tian et al. found that Stanford's SHIPS doctoral program has the following interdisciplinary features: a “problem + interdisciplinarity” dual drive conceptually; a “home discipline + interdisciplinarity” matrix integration knowledge-wise; a “solid foundation + strong thinking” complementary embedding curricularly; and an “internal synergy + external linkage” resource aggregation support-wise [7]. Research also reveals that most universities have fully recognized the importance of interdisciplinarity in enhancing research vitality and expanding disciplinary directions [8]. Xu et al. analyzed interdisciplinary program setups in 42 'Double First-Class' universities and found that China's interdisciplinary practices in graduate education generally meet the practical demands of interdisciplinary development. This is reflected in the establishment of the supporting role of 'enabling disciplines' and in their playing a leading role in long-distance, cross-disciplinary integration [9].

The third line of inquiry involves the theoretical construction of training models. Yang et al. elaborated on the types and configurations of interdisciplinarity from a knowledge-based perspective [10]. Wang et al. emphasize that interdisciplinarity's vitality lies in its continuous 'crossing', requiring openness to society as a whole to gain collaborative support for problem solving [11]. Using QCA on 112 interdisciplinary postgraduate training cases from 'Double First-Class' universities, Wang et al. constructed a three-dimensional framework ('knowledge, institution, organization') and found that interdisciplinary research fields and cross-disciplinary faculty allocation are necessary conditions. They also identified three training models: organization-supported, platform-guaranteed, and evaluation-guided [12].

A review of the existing literature reveals that prior studies have laid a solid foundation for this research, but several issues merit further exploration. Firstly, most existing results focus on the macro-level construction of 'training models' for interdisciplinary postgraduates, paying insufficient attention to the meso-level element of 'training pathways'. A training model concerns the overall architecture of the education system, whereas a training pathway focuses on the specific routes and methods for achieving training objectives. These two levels are analytically distinct, and the latter requires more detailed examination. Secondly, current research lacks a differentiated focus on various types of interdisciplinary programs. Few studies examine training pathways by type, limiting the applicability of research conclusions across different types of universities. Based on these considerations, this study aims to complement existing research by adopting a multi-type industry background perspective and focusing on training pathways for interdisciplinary postgraduates.

2. Concept Definition and Typology

2.1 Core Concept: Training Pathways for Interdisciplinary Postgraduates

A training pathway for interdisciplinary postgraduates is a systematic route designed to achieve the educational objectives of interdisciplinary programs. It comprises a combination of institutionalized key elements, including admissions and selection, curriculum design, research training, mentorship, practical experience, and evaluation mechanisms. Unlike a 'training model', which concerns the overall architecture of the education system, a 'training pathway' focuses on the specific routes and methods for realizing educational goals. The two operate at different analytical levels.

Drawing on practical explorations by universities in China and abroad, three basic pathways currently predominate in interdisciplinary postgraduate education: The interdisciplinary student recruitment pathway (recruiting students from different disciplinary backgrounds at the admissions level). The curriculum integration pathway involves integrating multidisciplinary knowledge through systematic course-level curriculum design. The project-driven pathway engages students in real research or practical projects, allowing them to learn and apply interdisciplinary knowledge in authentic contexts.

2.2 Classification: Four Ideal Types of Interdisciplinary Research

Different types of interdisciplinary programs require different training pathways. Therefore, constructing a typology is the first step in pathway analysis. Professor Yang identified the core dimension of interdisciplinary fields as the generation and exchange of knowledge, which are crucial to their establishment and development [10]. Mode of knowledge generation: theoretical vs. practical. The theoretical approach involves producing knowledge centered on traditional disciplines, with peer review within the academic community being the main evaluation method. In contrast, the practical mode refers to problem -centered knowledge production that emphasizes social impact and employs diverse evaluation criteria. Mode of knowledge interaction: aggregation vs. community. The aggregation mode refers to multiple disciplines converging into a highly focused research area, which resembles “valleys of convergence.” The community mode refers to multiple disciplines forming several parallel fields that are linked by shared elements, resembling “plateaus of undulation.”

Crossing these two dimensions yields four ideal types of interdisciplinarity, as shown in Table 1.

Table 1. Four Ideal Types of Interdisciplinarity and Characteristics

Type	Mode of Knowledge Generation	Mode of Knowledge Interaction	Core Characteristics	Representative Fields
Theory-Aggregation	Theoretical	Aggregation	Independent conceptual system, stable research paradigm, tight academic community	Biochemistry, Physical Chemistry
Theory-Community	Theoretical	Community	Heterogeneous branches, limited dialogue across branches but shared paradigm	Environmental Science & Engineering
Practice-Aggregation	Practical	Aggregation	Problem-oriented, integration of multidisciplinary knowledge to form solutions	Clinical specialties
Practice-Community	Practical	Community	Systemic problem orientation, multidisciplinary and multi-sectoral collaboration	Sustainable Development, Smart Cities

These four types differ significantly in terms of their disciplinary foundation, mode of knowledge integration, and evaluation criteria. Based on this typology, the study focuses on universities that were directly affiliated with either the former Ministry of Metallurgy or the former China National Nonferrous Metals Industry Corporation. It adopts an analytical framework consisting of the following steps: 'type identification', 'pathway matching', 'mechanism analysis', and 'application of recommendations'. This framework is used to uncover the underlying mechanisms of interdisciplinary postgraduate training pathways by type.

3. The Current Landscape of Interdisciplinary Training at Industry-Background Universities

This study focuses on the 22 universities that were directly affiliated with the former Ministry of Metallurgy and the former China National Nonferrous Metals Industry Corporation. In-depth interviews were conducted with 14 individuals from two or three representative universities. Drawing also on literature and publicly available data, the study examines the overall situation of interdisciplinary postgraduate training at these institutions.

The investigation reveals three characteristics of interdisciplinary postgraduate training in these institutions. Firstly, interdisciplinary program development is gradually advancing. Most of the surveyed universities have established at least one interdisciplinary program, expanding from their traditional strengths into fields such as materials, the environment, and artificial intelligence. Secondly, multiple training models are being explored. Some universities adopt interdisciplinary admissions policies, some strengthen curriculum system development, and others rely on major research projects to drive interdisciplinary training. Thirdly, industry-education integration is a distinct feature. The majority of surveyed universities have established joint training bases with industry partners, demonstrating a solid foundation for university–industry collaboration.

Significant differences in interdisciplinary training exist across the eastern, central, and western regions, as well as in their levels of institutional development and policy support intensity. Universities in the eastern region enjoy relatively favorable conditions, while those in the central region have distinctive features based on their traditional strengths. Those in the western region have made positive progress with policy support. Universities with more doctoral programs and those receiving policy support have developed more rapidly. Disciplines and programs must be oriented towards national strategies, regional industries, and talent needs, implementing a structural restructure that combines 'upgrading existing programs, creating new ones, and phasing out obsolete ones' [13].

The investigation also identifies five key issues in interdisciplinary postgraduate training at industry-focused universities. Firstly, disciplinary barriers remain. Cross-department course selection and cross-disciplinary mentoring still face institutional obstacles. Secondly, the interdisciplinary curriculum system is weak. Some universities remain at the level of 'patchwork' course offerings and lack courses that genuinely reflect interdisciplinary integration. Thirdly, the development of mentor teams lags behind. The number of mentors with interdisciplinary backgrounds is limited, and dual-mentor systems are costly to coordinate. Fourthly, industry–education integration is insufficient. Industry participation in curriculum development, program design, and practical guidance is limited. Fifthly, the evaluation mechanism is inadequate. Evaluation criteria remain dominated by academic publications, paying insufficient attention to practical skills and cross-disciplinary collaboration.

4. Identification and Matching of Differentiated Training Pathways

4.1 'Theory-Aggregation' Type: Interdisciplinary Student Recruitment Pathway

This type of interdisciplinarity focuses on knowledge integration and forms a highly specialized research area. This type of interdisciplinarity is best suited to an interdisciplinary student recruitment pathway, which admits students from diverse disciplinary backgrounds. Implementation requires flexible admission policies, remedial courses tailored to students' needs, and an atmosphere that encourages cross-disciplinary exchange. For universities with an industrial background, traditional disciplines such as metallurgical, physical chemistry, and ferrous metallurgy already have interdisciplinary characteristics. Recruiting students with backgrounds in chemistry, physics, and materials science can help to drive innovation. The metallurgical physical chemistry program at Northeastern University, for example, focuses on recruiting students from multiple disciplinary backgrounds and is a typical model of interdisciplinary training.

4.2 'Theory-Community' Type: Curriculum Integration Pathway

The theory-community type of interdisciplinarity comprises several relatively independent yet interconnected branches. This type of interdisciplinarity is best suited to the curriculum integration pathway, which uses systematic curriculum design to help students develop an integrated knowledge base. Implementation may include a 'core courses + branch courses + frontier lectures' system, cross -branch elective requirements, and modular course combinations. Typical examples include materials science and engineering, and environmental science and engineering. For example, the materials science and engineering program at the University of Science and Technology Beijing covers several branches, including materials physics, materials chemistry, and materials processing. The program has established a modular curriculum system and offers frontier lectures, effectively supporting graduate students' cross-branch knowledge integration.

4.3 'Practice-Aggregation' Type: Project-Driven Pathway

Practice-aggregation interdisciplinarity focuses on specific practical problems, integrating multidisciplinary knowledge to form solutions. This approach is best suited to a project-driven pathway, where students learn and apply interdisciplinary knowledge through research or industrial practice, based on faculty research projects or real-world problems. Implementation can include conducting cross-disciplinary research projects under faculty supervision, encouraging university–industry cooperation, offering project-based courses, and establishing mechanisms to evaluate project outcomes. Engineering practice projects and key technology development projects undertaken in collaboration with industry are effective vehicles for this approach. For instance, the 'Heavy Metal Pollution Control' research program at the School of Metallurgy and Environment at Central South University draws on expertise in metallurgy, environmental science, and chemical engineering. Graduate students participate directly in industry-cooperative projects, and most graduates go on to work in environmental or metallurgical industries, engaging in research and development.

4.4 'Practice-Community' Type: Platform-Based Collaborative Pathway

The practice-community approach to interdisciplinarity tackles complex systemic issues and necessitates multidisciplinary and multisectoral collaboration. It works best with the platform-based collaborative pathway, which brings together cross-disciplinary teams to integrate resources. Implementation requires establishing interdisciplinary research centers, forming cross-disciplinary mentor teams, constructing shared laboratories and practice bases, and exploring mechanisms for awarding cross-disciplinary degrees. This pathway is suitable for fields such as green low-carbon metallurgy, smart mining, and intelligent manufacturing. For instance, the 'Green Low-Carbon Metallurgy' interdisciplinary platform at Kunming University of Science and Technology brings together resources from the fields of metallurgy, energy, the environment, materials, and automation. The platform has established a research center, formed mentor teams, built shared laboratories, and set up practice bases in cooperation with enterprises. The platform director noted that the platform-based collaborative pathway brings together multidisciplinary resources and develops talent with systemic thinking.

4.5 Choosing among the Four Pathways

Choosing between these four training pathways requires considering several factors. Disciplinary tradition provides the foundation, with strong disciplines serving as the starting point for interdisciplinarity. Faculty resources are also key to success, with different pathways imposing different demands on mentors' capabilities. Platform resources provide material support, including laboratories and research centers. Industry linkages offer real-world problem contexts for practice-oriented interdisciplinarity, providing external impetus. Universities should base their choices on their own resources and seek the best match among these four factors, rather than unquestioningly imitating others.

5. Analysis of the Underlying Mechanisms of Training Pathways

5.1 The Mediating Mechanism of 'Training Objectives – Training Competencies – Training Outcomes'

Training objectives serve as the logical starting point. Different types of interdisciplinarity have different training objectives. The theory-aggregation type focuses on cultivating academic talent with a strong theoretical foundation and the ability to conduct original research. The theory-community type focuses on cultivating compound talents with broad knowledge and the ability to integrate across branches. The practice-aggregation type focuses on cultivating applied talents with problem-solving skills and technical application abilities. The practice-community type focuses on cultivating strategic talent with systemic thinking and cross-sectoral collaboration skills.

Training competencies are the mediating variable that connects training objectives and outcomes. These include knowledge integration, problem solving, innovative thinking, and cross-sectoral collaboration. The core competencies required vary by type. The theory-aggregation type relies primarily on knowledge integration. The theory-community type relies on a combination of knowledge integration and cross-sectoral collaboration. The practice-aggregation type relies mainly on problem-solving. The practice-community type relies on systemic thinking and cross-sectoral collaboration.

Training outcomes reflect the extent to which training objectives are met, including academic innovation, practical application, and career development. Different types of interdisciplinarity emphasize different dimensions of outcomes.

5.2 The Moderating Role of Boundary Conditions

The mediating mechanism is moderated by boundary conditions. Universities with more doctoral programs and a longer history tend to have stronger faculty and better research platforms, allowing the mediating mechanism to function more fully. In terms of regional differences, universities in the eastern region have extensive external cooperation, facilitating the development of problem-solving competencies for practice-oriented interdisciplinarity. In contrast, universities in the central and western regions have unique advantages in specific industrial fields, thereby supporting the development of knowledge-integration competencies for theory-oriented interdisciplinarity. In terms of policy support, universities that receive it gain advantages in resource investment and institutional innovation. In terms of industry characteristics, universities from different industry backgrounds have strengths in specific fields, influencing the choice of interdisciplinary types and the design of training pathways.

5.3 Construction of an Integrated Theoretical Model

Based on the above analysis, this study has constructed an integrated model of the underlying mechanisms of interdisciplinary postgraduate training pathways (see Figure 1).

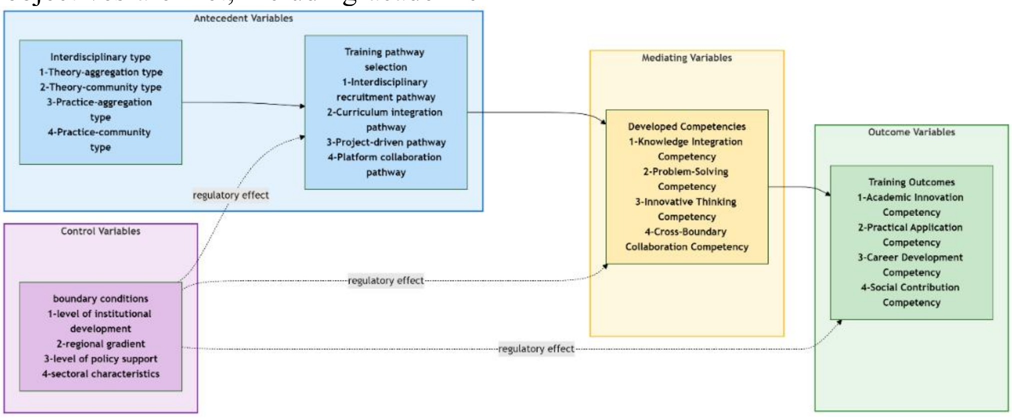

Figure 1. An Integrated Model of the Underlying Mechanisms of Interdisciplinary Postgraduate Training Pathways

The antecedent variables in the model are the type of interdisciplinarity and the chosen training pathway. The mediating variable is training competencies. The outcome variable is training outcomes. The moderating variable is the boundary conditions. The core hypothesis is that training pathways affect training outcomes through the mediating role of training competencies, which is moderated by boundary conditions. Different types of interdisciplinarity are suited to different training pathways, and the transmission mechanisms of mediation vary accordingly.

6. Conclusions and Outlook

This study focuses on universities that were directly affiliated with either the former Ministry of Metallurgy or the former China National Nonferrous Metals Industry Corporation. It constructs a framework of 'type identification → pathway matching → mechanism analysis → application of recommendations' and draws the following conclusions.

First, a typological framework of interdisciplinarity is established. Based on the mode of knowledge generation (theoretical versus practical) and the mode of knowledge interaction (aggregation versus community), interdisciplinarity is classified into four types: theory-aggregation, theory-community, practice -aggregation, and practice-community. These four types differ significantly in their disciplinary foundations, knowledge integration, and evaluation criteria.

Second, the matching relationship between training pathways and interdisciplinary types is revealed. The theory-aggregation type is best suited to the interdisciplinary student recruitment pathway, the theory-community type to the curriculum integration pathway, the practice-aggregation type to the project-driven pathway, and the practice-community type to the platform-based collaborative pathway. Empirical evidence supports the validity of these matches.

Thirdly, the underlying mechanism of the training pathways is clarified. They are effective through the mediating mechanism of 'training objectives → training competencies → training outcomes'. Core competencies vary by type and are moderated by boundary conditions, including institutional development level, regional gradient, policy support, and industry characteristics.

Based on the above findings, three practical recommendations are proposed.

Firstly, precise positioning should be identified and accurate matching achieved by building type-adapted training pathways. Universities should base their efforts on their disciplinary traditions and industrial strengths, clearly identifying the types of interdisciplinarity they wish to prioritize. Those with strengths in metallurgy, materials, and mining could focus on theory-aggregation and theory-community types. Those oriented towards green, low-carbon development and intelligent manufacturing may concentrate on the practice-community type. They should then select the corresponding pathway: interdisciplinary student recruitment for theory-aggregation, curriculum integration for theory-community, project-driven for practice-aggregation, and platform-based collaborative for practice-community.

Secondly, a competency-based approach and systematic design should be adopted to build an integrated training system. Training plans, curricula, practical experiences, and evaluation mechanisms should be designed around core competencies. Differentiated evaluation standards should be set according to type: theory-oriented types should emphasize academic innovation and knowledge integration, while practice-oriented types should focus on problem-solving and practical application. Dynamic monitoring and feedback mechanisms should be established to continuously improve training quality.

Thirdly, promote industry-education integration and institutional synergy by establishing a multi -stakeholder guarantee mechanism. Make the most of the natural industry linkages of universities with an industry background by involving industry experts deeply in curriculum design, practical training, and thesis supervision, and by jointly establishing laboratories and practice bases. Simultaneously, reform faculty evaluation to include contributions to interdisciplinary teaching and industry-education integration. Improve the cross-disciplinary mentorship system and refine supporting policies, including those related to student status management and degree conferral.

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