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Developing professional capital through technology-enabled university-school-enterprise collaboration: an innovative model for C-STEAM preservice teacher education in the Greater Bay area

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Abstract

Purpose – Preservice teacher (PST) professional development programs are crucial for cultivating high-quality STEAM teachers of the future, significantly impacting the quality of regional STEAM education. The Guangdong-Hong Kong-Macao Greater Bay Area, as a region of cross-border cooperation, integrates the resources and advantages of Guangdong, Hong Kong, and Macao, possessing rich cultural heritage and innovative capabilities. Transdisciplinary Education for Cultural Inheritance (C-STEAM) is an effective approach to promoting educational collaboration within the Greater Bay Area, facilitating the integration of both technological and humanities education. This study aims to develop a Technology-Enabled University-School-Enterprise (T-USE) collaborative education model and implement it in the Greater Bay Area, to explore its role as a support mechanism in professional development and its impact on C-STEAM PSTs' professional capital.

Design/methodology/approach – Adopting a qualitative methodology, the study interviewed PSTs who participated in a C-STEAM teacher education course under the T-USE model. Thematic coding is used to

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analyze their knowledge acquisition, interaction benefits with community members, and autonomous thinking and decision-making in theoretical learning and teaching practice.

Findings – The findings show that the T-USE model significantly enhanced the PSTs' human capital, including teaching beliefs, knowledge, and skills. In terms of social capital, PSTs benefited from collaboration with PST groups, university teaching teams, in-service teachers, and enterprises, though challenges such as varying levels of expertise among in-service teachers and occasional technical instability emerged. For decisional capital, the T-USE model provided opportunities for autonomous thinking and promoted teaching judgment skills through real teaching challenges and scenarios. Reflective practice activities also supported PSTs' professional growth.

Originality/value – This study reveals the effectiveness and internal mechanism of the T-USE model in C-STEAM PST training, offering significant theoretical and practical references for future PST education.

Keywords C-STEAM education, Professional capital, Preservice teachers, University-School-Enterprise collaboration

Paper type Research paper

1. Introduction

With the rapid advancement of science and technology in the 21st century, profound changes have occurred in socio-economic models and occupational structures. In this transformative era, STEAM education, integrating Science, Technology, Engineering, Arts, and Mathematics, has emerged as an effective approach for cultivating students' 21st-century skills and core competencies, representing an innovative trend in international curriculum reform (Zhan and Niu, 2023). However, in the learning environments where STEAM curricula are developed in various regions, there exists a phenomenon of excessive imitation of Western curricula, which cannot be closely integrated with existing curriculum systems. To address this issue and promote the localization of STEAM education, Zhan *et al.* (2022a) proposed a form of STEAM education based on Chinese indigenous culture, referred to as C-STEAM.

Like STEM education, the key to implementing high-quality C-STEAM education lies in the teachers. Professional development programs for preservice teachers are crucial in nurturing future educators, equipping them with interdisciplinary teaching knowledge, skills, and attitudes essential for adapting to formal teaching roles(Chai, 2019). However, the complexity of C-STEAM education is not only evident in the integration of STEM disciplines, real-world orientation, and project-based learning (English, 2016; Erdogan *et al.*, 2016; Lau and Jong, 2022), but also in the challenge of combining culture with technology. Designing and implementing interdisciplinary education is particularly challenging for preservice teachers lacking practical experience (Van Ingen and Ariew, 2015; Kostiainen *et al.*, 2018).

Professional Capital theory is a crucial theoretical framework for promoting teacher professional development and effective teaching, representing a future direction in teacher education reform (Malone *et al.*, 2017, pp. 87–161). It emphasizes the importance of focusing on the knowledge foundation of the teaching profession (human capital), the opportunities for sustained support and collaboration (social capital), and the professional agency of teachers (decisional capital) (Hargreaves and Fullan, 2015). The guiding role of Professional Capital theory in preservice teacher education has been recognized by numerous researchers (Nolan and Molla, 2017; Osmond-Johnson and Fuhrmann, 2022; Witt *et al.*, 2022), However, in the field of STEAM education, there is yet to be a systematic research ecosystem. Particularly, there is a lack of in-depth discussion on how teacher education programs can support the development of professional capital among preservice teachers.

Establishing educational communities is a vital pathway to enhancing professional capital (Sergiovanni, 1998), and is equally instrumental in achieving integrated preservice and in-service training and high-quality development for STEAM teachers (Bush and Cook, 2016). Educational collaboration is a key issue in advancing coordinated and innovative development in the Guangdong-Hong Kong-Macao Greater Bay Area. Transdisciplinary Education for Cultural Inheritance (C-STEAM), targets cultural inheritance and utilizes multidisciplinary integrated STEAM education as a means to achieve this (Zhan *et al.*, 2020; Qian *et al.*, 2022). This approach contributes to the dual integration of science and humanities education in the Greater Bay Area (Zhan *et al.*, 2022c; Li *et al.*, 2023), and its effectiveness has been demonstrated in multiple rounds of practice (Huo *et al.*, 2020; Zhan *et al.*, 2021; Guan and Zhan, 2021; Yu *et al.*, 2022; He *et al.*, 2022; Lyu *et al.*, 2022; Wu *et al.*, 2022a; Wu *et al.*, 2022b; Sun *et al.*, 2023).

The University-School-Enterprise (USE) model, integrating universities, enterprises, and schools as core components, evolves from the traditional University-School (U-S) collaboration by incorporating enterprise forces into a tripartite research and education collaboration framework. The involvement of enterprises addresses the financial and resource constraints faced by universities in preservice teacher (PST) training, thereby facilitating the scaled development of STEAM education (Zhan *et al.*, 2022c). Enterprise contributions in technology and environmental support offer PSTs an innovative, practical, and interactive learning experience. This is crucial in preparing them to plan and implement educational strategies in complex real-world scenarios, thereby enriching their practical experience (Li *et al.*, 2023). However, despite the USE model being considered more flexible and operational, capable of addressing issues such as the lack of interdisciplinary educational resources for PSTs, the singularity of cooperative education models, and the disconnection of courses from reality, its applicability, sustainability, and scalability still face some practical limitations, and its true training effectiveness requires further exploration.

This study is based on the advantages and challenges of the University-School-Enterprise collaborative education model in fostering the professional capital of STEAM PSTs. Leveraging technology to optimize the training process, it proposes a technology-empowered University-School-Enterprise collaborative education model for C-STEAM PSTs. Conducted in the Guangdong-Hong Kong-Macao Greater Bay Area of China, this research employs qualitative methods to explore how this model affects the professional capital of STEAM PSTs, providing theoretical and practical references for STEAM PSTs education reform.

2. Conceptual framing

This study adopts the theoretical framework of professional capital theory proposed by Hargreaves and Fullan (2015), which views teacher professional capital as a function of teacher human capital, social capital, and decisional capital.

Human capital refers to the knowledge and skills that teachers possess and are developing through education and training, which have economic value, essentially comprising a teacher's personal competence. Teachers with strong human capital are often more familiar with the subjects they teach, understand students' cognitive patterns and diverse learning backgrounds, possess emotional resonance capabilities, know how to impart subject knowledge to students, and can creatively engage in teaching practices. In summary, teacher human capital represents the professional competence that teachers, as professional individuals, should possess. It includes the professional knowledge and skills acquired by teachers as well as their emotional attitudes and values (Hargreaves and Fullan, 2015).

Social capital can be understood as interpersonal relationships, networks, and interactions (Bourdieu, 1986). In the field of education, social capital exists within the interactions between individuals and is instrumental in fostering productive activities through the creation of a culture of communication, learning, trust, and sharing(Coleman, 1988). Hargreaves and Fullan (2015) point out that social capital refers to how the quantity and quality of social interactions among individuals affect their cognition, emotions, and identity. It encompasses the ability and nature of interactions between teachers and others, not only greatly influencing teacher human capital but also being crucial to the transformation of schools and the entire education system (Leana, 2011).

The essence of professionalism lies in the ability to make autonomous decisions in complex situations. Teacher decisional capital can be understood as a teacher's professional judgment capacity, primarily reflected in their ability to make wise decisions and judgments independently when faced with complex situations with numerous uncertainties, without relying on external factors such as lesson plans or colleagues. For example, it involves the capacity to choose and implement appropriate teaching strategies based on different educational contexts and student characteristics (Hargreaves and Fullan, 2015). Reflective practice is a crucial step in the accumulation of teacher experience, particularly concerning teacher decisional capital and the overall development of professional capital. Dialectical reflection on the practice process, guides teachers to make wiser professional judgments in their next educational actions.

If teachers aspire not only to develop their students' foundational skills but also to cultivate their higher-order competencies, having a "heart of gold" alone is insufficient. They must learn and accumulate more "professional capital" to acquire valuable knowledge and skills that enable effective teaching (Hargreaves and Fullan, 2015). C-STEAM education, with its interdisciplinary and integrative nature, poses new challenges to the professional competence and training models of preservice teachers. The professional capital theory distinguishes between human capital, social capital, and decisional capital as three distinct forms of expression, analyzing teacher professional development practices from the perspectives of individual teacher quality, teacher group quality, and teacher professional judgment ability. This framework provides critical theoretical underpinnings for this research and offers guidance for a deeper analysis of C-STEAM preservice teacher training programs.

This framework provides a key theoretical basis for this study and guides an in-depth analysis of C-STEAM PSTs training programs. Firstly, the perspective of human capital aids in a deeper understanding of the professional knowledge and skills that preservice C-STEAM teachers should possess at different stages. This ensures that preservice teachers acquire the ability to integrate interdisciplinary knowledge and apply it to teaching, providing targeted guidance for the design of training program content. Secondly, the perspective of social capital contributes to the formation of a positive interactive preservice teacher education community. Through teamwork and resource sharing, it further promotes the development of a high-quality cohort of preservice C-STEAM teachers. Finally, the perspective of decisional capital helps guide the design of reflective practice activities for preservice C-STEAM teachers. Increasing opportunities for teaching practice and teaching discussion activities, assists preservice teachers in accumulating authentic teaching experience and bridging the gap between academic teaching and practical teaching.

In summary, the professional capital theory provides a favorable theoretical framework for this research. It helps guide the design of preservice C-STEAM teacher professional development models and, from the perspectives of human capital, social capital, and decisional capital, aids in a deeper understanding of the effectiveness of this professional development model.

3. Literature review

3.1 Development of professional capital for C-STEAM preservice teachers

Professional development programs are crucial in enhancing the professional competencies of STEAM teachers, encompassing improvements in teaching beliefs, teaching knowledge, and teaching skills (Zhan *et al.*, 2022b). Although existing studies have not explored C-STEAM teacher training based on the theory of professional capital, the typical professional STEAM teacher development methods still offer valuable insights.

For instance, in the development of human capital, effective shifts in perspectives and instructional guidance can be provided to preservice teachers. This includes discussions on STEAM subject content and pedagogical knowledge (Radloff and Guzey, 2017), experiences based on specific teaching practice methods (Alangari, 2021), and enhancing preservice teachers' self-efficacy in STEAM teaching by improving their teaching beliefs (Chen *et al.*, 2021).

In terms of social capital, establishing interdisciplinary learning communities is a crucial path for the professional development of preservice teachers. This includes implementing collaborative learning among preservice teachers from different disciplinary backgrounds to facilitate the conceptualization of STEAM and its teaching practices (Berisha and Vula, 2021); fostering collaboration between STEAM preservice teachers and in-service teachers to expose preservice teachers to real-world classroom scenarios (Öztürk and Korkut, 2023; Schmid and Hegelheimer, 2014), and incorporating experts such as engineering researchers into collaborative groups to assist preservice teachers in integrating and applying multidisciplinary knowledge and skills in teaching contexts (Estapa and Tank, 2017).

Regarding decisional capital, project-based STEAM inquiry practices, and reflective learning activities are effective in developing the professional judgment capabilities of preservice teachers. Planned learning records or thematic discussions and other reflective practices can develop preservice teachers' understanding of core concepts in STEAM education and their scientific practice skills (Saribas and Ceyhan, 2015), as well as their sense of professional identity (Blackley *et al.*, 2017).

Existing professional development programs have developed some effective methods, such as combining theory with practice, cooperative learning, real-world experiences, reflective practice, and design-based learning. However, these programs still have limitations in developing preservice teachers' (PSTs) human capital (such as attitudes, knowledge, and skills for interdisciplinary teaching), social capital (like the level of cooperation in C-STEAM learning projects), and decisional capital (such as reflection on practical teaching), which hinders the overall development of PSTs' professional capital.

On one hand, although many educational reforms and studies do focus on integrated teaching methods in STEAM education, they are primarily centered on K-12 education stages and in-service teacher training (Huang *et al.*, 2022). Courses and seminars tailored for PSTs are still insufficient, making it challenging for them to demonstrate how to integrate STEM disciplines or offer opportunities to collaboratively solve real-world problems (Shernoff *et al.*, 2017). Consequently, PSTs lack sufficient STEAM learning experiences to reflect on their decisions and actions.

On the other hand, the disconnect between theoretical learning and practical teaching for PSTs still exists. This includes the academicization of STEAM content learning, where PSTs struggle to transform it into real-world-based courses (Aydin-Gunbatar *et al.*, 2018), the predominance of simulated teaching or presentation-based practices lacking dynamic, complex real teaching situations to reflect the learning outcomes of PSTs (Brown, 2017), and imbalances in power and cognitive understanding between PSTs and in-service teachers in existing cooperative models (Meschede *et al.*, 2017).

In summary, current C-STEAM PST professional development programs need further improvement in course and teaching methods. This involves developing human capital as the foundation, enhancing social capital through practice communities and professional learning communities, and continually accumulating decisional capital in areas like professional judgment and personalized development through reflective practices. This approach aims to promote the holistic development of PSTs' professional capital.

3.2 The university-school-enterprise collaboration in C-STEAM preservice teachers professional development programs

The establishment of an educational community is an important pathway for the development of teachers' professional capital (Hargreaves and Fullan, 2015). Currently, PST education communities mainly follow the university-school (U-S) model, which involves collaboration between universities and primary/secondary schools (Wang *et al.*, 2022). Alternatively, they may incorporate government and educational authorities as external driving forces, forming a university-government-school (USG) model. In this USG model, universities take the lead in conducting educational research and teaching practices, guiding the development of STEAM education in schools (Ye *et al.*, 2019).

However, the "university-school" educational community has gradually revealed some shortcomings during its development. Firstly, the collaboration between universities and primary/secondary schools often serves the purpose of meeting specific quick-fix needs (Singh *et al.*, 2013). Their interaction is primarily limited to preservice teacher education practices, lacking in-depth collaboration in areas such as curriculum, teaching, and educational research. Secondly, numerous issues in information dissemination have led to a policy-dependent relationship between the two, with a lengthy information transmission chain. This institutionalization of information policies has weakened the universities' and schools' willingness to active cooperation (Yuan and Mak, 2016). Thirdly, universities and schools struggle to establish an equal dialogue. Universities are often defined more as "guides" and "experts" rather than learning partners (Bain *et al.*, 2017).

In this context, the flexible application of the University-School-Enterprise (USE) tripartite collaboration, with universities, businesses, and schools as its core components, adds a new dynamic to STEAM education collaborative innovation within the University-Government-School (UGS) model. USE is an extension of the U-S model, incorporating the involvement of businesses in a collaborative model that integrates academia, industry, and research. The inclusion of businesses is not only a natural requirement for the scalable development of C-STEAM education but also a practical necessity for primary and secondary schools in terms of curriculum development and teaching resources (Zhan *et al.*, 2022c). Additionally, businesses can provide preservice teachers with authentic social practice scenarios, helping them plan and implement teaching in a complex world and accumulate practical experience (Li *et al.*, 2023). Therefore, when universities, primary/secondary schools, and businesses all participate in C-STEAM teacher education, the normalization of C-STEAM education in primary and secondary schools becomes more assured, creating a closer and healthier educational mutual benefit system. Hence, this model is mature, and adaptable, and can serve as a valuable reference for this study.

A lack of time and funding is the most common obstacle for schools in implementing professional capital development plans (Tong and Razniak, 2017). Businesses can act as coordinators and supporters of resources in collaborative education programs, effectively addressing issues such as insufficient resources in current C-STEAM PST professional development projects, a singular collaborative education model, and a disconnect between the curriculum and real-world applications. Simultaneously, as a practical usage model in the Greater Bay Area of Guangdong-Hong Kong-Macao for C-STEAM education collaborative development (Zhan *et al.*, 2022c), the USE model contributes to the restructuring of STEAM teacher education communities, exploring collaborative innovation education models aimed at promoting professional capital development.

3.3 Using technology to develop professional capital for C-STEAM preservice teachers

The rapid development of 21st-century digital technology has driven the integration of technology and education, making the digital transformation of preservice teacher education one of the inevitable trends in future educational reform. Leveraging technology to create more adaptive and personalized learning environments is beneficial for C-STEAM PSTs to acquire the complex knowledge and skills required for interdisciplinary education(Hwang *et al.*, 2020).

In the context of preservice teacher professional development in C-STEAM, digital technology can optimize preservice teachers' learning experiences and outcomes in the following ways:

- Firstly, By integrating rich digital teaching resources, interactive learning environments, and accompanying data analysis through online course platforms, it provides preservice teachers with a systematic repository of STEAM education learning resources (Ferri *et al.*, 2020).
- Secondly, the use of virtual simulation systems to simulate teaching practice scenarios, conduct teaching experiment simulations, create teaching resources, and engage in simulated classroom interactions, enhances preservice teachers' practical knowledge (Dieker *et al.*, 2014).
- Thirdly, by constructing a dual-teacher course platform that builds a teaching community between preservice teachers and in-service teachers, integrating dual-teacher teaching functions, and enabling collaborative education.This is achieved through recording systems, collective lesson preparation platforms, and interactive research platforms for real teaching, thereby enhancing preservice teachers' educational and teaching abilities (Zhang *et al.*, 2022).
- Fourthly, By utilizing learning analytics technology to achieve intelligent management and intelligent educational research, deep mining and analysis of preservice teacher education data, intelligent assessment and feedback, and personalized guidance based on their professional development needs (Fernández-Morante *et al.*, 2022).
- Fifthly, using generative artificial intelligence technology to enable intelligent tutoring and personalized guidance, helping preservice teachers integrate and share interdisciplinary knowledge, and generating teaching designs and templates tailored to specific topics (Kasneci *et al.*, 2023).

The organic integration of digital technology and professional development programs can enhance the learning experience and outcomes of preservice C-STEAM teachers. Within the C-STEAM preservice teacher education community, businesses can serve as strong providers of technology. For example, Finland's diverse collaborative STEAM teacher training system integrates interdisciplinary educational resources through university-enterprise collaboration, providing technical resources and environmental support for the training of preservice STEAM teachers.

Businesses offer scenarios such as science laboratories and science training camps, guiding preservice teachers from being mere observers of scientific activities to gradually becoming participants. They take on teaching roles for visiting student groups and gain rich teaching experience while guiding primary and secondary school students in interdisciplinary exploration. Additionally, businesses can initiate research projects based on activity data from laboratories. They also provide free online courses through virtual platforms, enabling preservice teachers to interact with practicing teachers, interdisciplinary experts, and university scholars on the business education platform to facilitate the sharing of professional knowledge (LUMA, 2020). The technology integration approach in Finland's university-enterprise collaborative education process serves as a model for this research.

In summary, we recognize the potential of the university-school-enterprise collaborative model and technology-enhanced learning in promoting the development of professional capital among C-STEAM PSTs. These elements are instrumental in guiding the transformation of PST training models. However, in current research, there remains a need for further exploration into questions such as how the university-school-enterprise collaborative model can effectively promote professional capital development and how technology empowers the construction of C-STEAM PSTs education communities. In light of this, this study poses the following research questions:

RQ1. What are the key elements and system components of the technology-enhanced university-school-enterprise collaborative model aimed at fostering the development of professional capital among C-STEAM PSTs?

RQ2. How does the technology-enhanced university-school-enterprise collaborative model impact the development of professional capital among C-STEAM PSTs?

4. Methodology

4.1 Participants

This study was conducted in a STEAM course at a public normal university in South China, with 36 s-year undergraduate PSTs in educational technology as participants. The average age of the participants was 19.32 years, comprising 24 females and 13 males. All of them had not participated in STEAM or C-STEAM teaching design or practice before.

4.2 Course design

The experimental course selected for this study spanned 16 weeks (2 h per week) and involved teams from universities, primary and secondary schools, and enterprises. The university teaching team consisted of 1 professor and 3 graduate student assistants. The school mentoring team comprised 16 experienced subject teachers from 7 different schools. The enterprise team included 1 education research consultant and 2 technical consultants. The course was delivered in a collaborative team format, with the 36 PSTs divided into 6 groups, each consisting of 6 members. During the course, each group of PSTs was paired with two in-service teachers.

Regarding the course content, the first Six weeks were dedicated to STEAM and C-STEAM education theory learning. This phase introduced PSTs to the fundamental concepts of C-STEAM education, including content knowledge, pedagogical knowledge, and technological knowledge. Weeks Seven to 10 focused on C-STEAM course teaching design. The university teaching team used the interdisciplinary "C-POTE" model as a guiding framework to explain teaching design methods (Li *et al.*, 2024), including Conceptual group, Problem chain, Objective layer, Task cluster, and Evidence set. After class, PSTs collaborated to complete the selection and comprehensive design of a C-STEAM course project. Each group of six PSTs jointly decided on a C-STEAM course theme, designing three sub-lessons around this theme, with two members responsible for the design and practice of the same lesson content. Their themes include: Chinese knotting, traditional bridge design, Chinese herbal medicine, dragon boat, ancient building design, as well as traditional musical instruments from different regions.

From the 11th to the 15th week, the focus shifted to C-STEAM course teaching practice. Before the official teaching, PSTs used a collective lesson preparation platform to discuss and modify their teaching design plans with the university teaching team and paired in-service guiding teachers, employing video discussion features for simulated teaching and refining the teaching process. Subsequently, PSTs conducted real-time remote teaching for paired primary and secondary school classes using an intelligent recording and broadcasting system (see Figure 1). During the PSTs' teaching sessions, a live link was generated on the interactive teaching research platform for other PSTs, the in-service guiding teacher team, the university teaching team, the enterprise research team, and other socially relevant individuals to watch and provide feedback on the teaching video. Each PST was required to complete one period of online educational practice, participate in one review session of their group's teaching, and one review session of another group's teaching, followed by writing reflective logs. In the sixteenth week, all groups presented their overall course plans and shared their experiences, engaging in thematic discussions with the university teaching team, in-service teacher team, and enterprise team, culminating in a course summary.

4.3 The technology-enabled USE model

Activity Theory focuses on actions with clear intentions or objectives and deconstructs a complete activity system into six basic elements: subject, object, community, tools, rules, and division of labor. This approach is instrumental in explaining and analyzing the complex process and outcomes of STEAM teacher professional development (Goodnough, 2018). Viewing this study's C-STEAM preservice teacher education practice project through

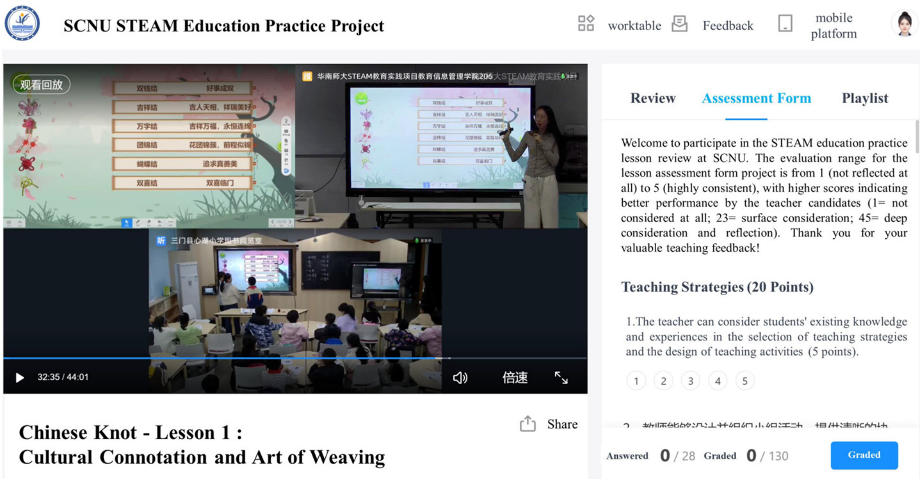


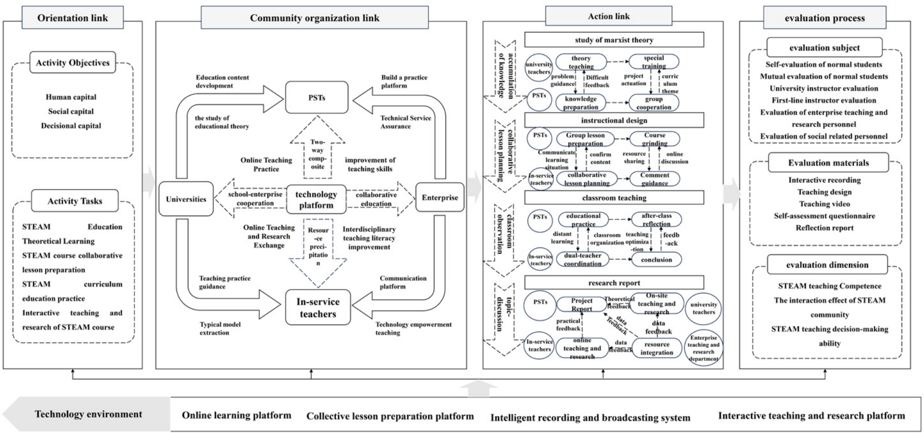
Figure 1. Online education practices for steam preservice teachers [1]

Source: Authors' own work

the lens of Activity Theory reveals that the elements of the activity system can map onto the elements of the C-STEAM education community, thereby providing explanatory power for activities within the technology-enabled C-STEAM educational practice community. Therefore, based on Activity Theory and referring to the preservice teacher education community model proposed by Wang *et al.* (2023), this study constructs a technology-enabled university-school-enterprise collaborative education model (see Figure 2). This model relies on a technological environment and is divided into several phases: orientation (defining professional development goals and tasks), community organization (building interaction models among preservice teachers, universities, enterprises, and primary and secondary school teachers), action (designing the course implementation process), and evaluation (identifying the evaluators, evaluation materials, and evaluation dimensions).

In the orientation phase of the program, the initial step was to identify the needs of the School-Enterprise Collaborative Education activity, specifically focusing on fostering the professional capital of C-STEAM PSTs. The objectives for the PST training program were then established, encompassing human capital (C-STEAM teaching attitudes, knowledge, and skills), social capital (level of interaction within the C-STEAM education community), and decisional capital (C-STEAM teaching professional judgment ability). Guided by these objectives, the tasks for community activities were delineated, aligning with the actualities and status quo of PSTs' theoretical and practical learning in C-STEAM education, with a focus on elements such as C-STEAM educational theory learning, collaborative course preparation, educational practice, and interactive teaching research.

In the organization phase of the University-School-Enterprise educational community, key individuals who could contribute to the development of PSTs' professional capital were identified, forming an educational community that included PSTs, university instructors, primary and secondary school guiding teachers, and corporate educational teams. Within this community, PSTs and their peers were the main participants, collaborating in course practices; university instructors guided and organized the activities, leading with advanced educational concepts and providing theoretical guidance; primary and secondary school teachers evaluated the feasibility of theoretical teaching and offered practical guidance, promoting the planning and progression of activities; and corporations, as coordinators and integrators, provided technological, resource, and environmental support, closely integrating the community members and offering a connected, extensive practice environment.



Source: Authors' own work

Figure 2. Technology-enabled USE collaborative education model

The action phase was the practical carrier for achieving the program's objectives, designed as a series of progressive activities that included knowledge accumulation enabled by technology, collaborative lesson preparation, classroom observation, and thematic teaching research. In the knowledge accumulation stage, PSTs accessed a wealth of STEAM teaching and case resources via an online learning platform, completing collaborative tasks and periodic knowledge assessments to build a personalized STEAM teaching knowledge map. During the collaborative lesson preparation stage, PSTs worked with peers on the collective lesson preparation platform to complete lesson plans, task sheets, and courseware designs, inviting in-service guiding teachers and university instructors for joint lesson preparation and refining teaching designs using features like lesson annotation and video discussions. In the classroom observation stage, each PST first conducted autonomous teaching using an intelligent recording and broadcasting system, then observed their own, their group's, and other groups' classroom teaching on the interactive teaching research platform, engaging in reflective practice and review sessions. In the thematic teaching research stage, based on data from collective lesson preparation and interactive teaching research, practical teaching themes were selected for discussion and exchange among PSTs, in-service guiding teachers, university instructors, corporate educational consultants, and relevant societal figures, culminating in the refinement of practical research reports.

The purpose of the evaluation phase was to monitor the process and ensure the quality of activities. Evidence-based support is a crucial measure in schools to foster the development of teachers' professional capital (Hargreaves and Fullan, 2015), aiding in the formation of PSTs' self-regulated learning and professional decision-making abilities. In the context of technology-enabled collaborative education, evaluation focused on diverse subjects providing feedback, including PSTs and their peers, university teachers, primary and secondary school teachers, corporate personnel, as well as other school teachers and societal stakeholders. Emphasis was placed on the processual nature of evaluation, utilizing technology platforms to collect and analyze data accompanying PSTs' C-STEAM educational practices, such as course participation and learning records on online course platforms, interaction data, and teaching designs from collective lesson preparation platforms, teaching recordings generated by intelligent recording and broadcasting systems, and listening and reviewing data retained on interactive teaching research platforms. Finally, PSTs' professional capital development was evaluated from multiple dimensions, including C-STEAM teaching literacy (human capital), interaction effects within the C-STEAM education community (social capital), and C-STEAM teaching decision-making ability (decisional capital).

Furthermore, the activities of the C-STEAM PST educational community unfolded within a technology-enabled learning environment. The theoretical teaching phase relied on online course platforms provided by universities, integrating predetermined C-STEAM educational materials and cases, as well as PSTs' stage-specific learning outcomes, to create a dynamic C-STEAM teaching resource repository jointly built by teachers and students. Practical teaching phases, such as teaching design, teaching practice, and thematic discussions, were conducted using technology platforms provided by corporations, including collective lesson preparation platforms, intelligent recording and broadcasting systems, and interactive teaching research platforms, accommodating and managing the interactions among PSTs, university teachers, and in-service teachers within a unified technological system.

4.4 Instrument

This study adopts an interpretivist theoretical perspective, considering reality as subjective (Crotty, 1998). A qualitative research approach is employed to emphasize the critical and decisive role of human factors in defining truth and knowledge (Nolan and Molla, 2017).

Consequently, considering the sociological foundation of STEAM educational community practice, this research utilizes qualitative methods to explore how the technology-enabled School-Enterprise Collaborative Education model serves as a mechanism to support the professional development of STEAM PSTs, aiding them in developing their professional capital during their undergraduate phase. The primary method of this research is Semi-structured interviews. Semi-structured interviews are the most commonly used interviewing technique because their structured yet flexible format allows for tailoring to the research objectives and questions, enabling a flexible and in-depth exploration of the interviewees' thoughts, feelings, and experiences (Kallio *et al.*, 2016). After all PSTs completed their teaching practices, we employed a stratified random sampling method to randomly select 10 PSTs for semi-structured interviews from the six groups, ensuring that at least one student from each group was interviewed. The PSTs were invited to reflect on their acquisition of knowledge and skills during the course, their interactions with fellow PSTs, university teachers, in-service teachers, enterprises, and other community members, as well as their autonomous thinking and decision-making in theoretical learning and teaching practice. The interview questions are listed in Table 1.

4.5 Data analysis

The data analysis employed thematic analysis (Smith, 2015), using the constructs of professional capital—human capital, social capital, and decisional capital—as the fundamental coding framework. This approach explored changes in the professional capital of STEAM preservice teachers (PSTs) before and after participating in a professional development program based on a technology-enabled University-School-Enterprise collaborative training model, as well as the reasons for these changes. The steps were as follows:

First, all interview content was preprocessed, including transcription and organization, to facilitate reading and familiarization with the interview text.

Next, the research team decomposed all interview materials and conducted open coding (the coding format for interview content was: group number + PSTs number, for example, the first PST in the first group was coded as G1-1). Key contents such as teaching confidence, practical ability, collaborative learning, resource integration, and reflective teaching were identified through line-by-line reading and repeated discussions.

No.	Question
1	Has participating in this course changed your view of STEAM teaching?
2	What gains and growth do you feel you have made in your professional skills through participating in this course?
3	What was your collaborative experience like with community members in this course? What support did you receive from the USE project during the collaboration?
4	In this course, were you able to engage in professional learning and teaching practices in a way that you liked?
5	How did you determine that your teaching plan was reasonable and feasible in this course? What support did you receive from the USE project in the process of making independent decisions?
6	What do you think was the biggest challenge in this course? Did the course design provide you with enough opportunities to try and err, along with corresponding support?

Source: Authors' own work

Table 1.
Interview question

The open codes were then meticulously reviewed, and higher-level sub-themes were integrated based on similarities and differences between codes.

Finally, these sub-themes were linked to the professional capital of C-STEAM PSTs under the University-School-Enterprise collaborative training model and categorized under the framework of human capital, social capital, and decisional capital (see Table 2).

To ensure the reliability of the analysis, cross-validation was performed. The research team members audited and verified each other's coding processes and theme extraction, enhancing the understanding of the data from multiple perspectives.

5. Results

5.1 Human capital

5.1.1 STEAM teaching beliefs. All interviewed PSTs reported that their perspectives on C-STEAM teaching changed significantly after participating in the course, with a notable enhancement in their STEAM teaching beliefs. This change manifested in several ways.

Firstly, the PSTs' attitudes toward teaching improved. They generally recognized the educational value of interdisciplinary teaching in C-STEAM education and expressed a willingness to continue learning and conducting C-STEAM teaching activities. For instance, G1-1 mentioned:

> Previously, I was exposed to segregated subject teaching and didn't understand why STEAM education integrates different disciplines. Now, I realize that C-STEAM education can help students address the fragmentation of knowledge and the disconnection of theory from practice. It can cultivate students' cultural competence and innovative competence, so I am willing to continue with C-STEAM education in the future. I find it very meaningful.

Secondly, the PSTs' confidence in teaching increased. They felt that the theoretical learning and educational practices in the course had demystified STEAM education for them, allowing them to experience the full process of C-STEAM teaching design and implementation. As G6-2 said:

> At first, I thought C-STEAM teaching would be difficult to accomplish, but after experiencing a series of activities like topic selection, collaborative lesson planning, educational practice, and thematic discussion this semester, I've gone through the complete process of C-STEAM teaching in schools. This has already accumulated good experience and confidence for me.

Thirdly, the PSTs' motivation for teaching was enhanced. They believed that the process of conducting C-STEAM education also contributed to their professional development. G1-2 mentioned:

> I feel that the C-STEAM teaching practice has enhanced my knowledge and teaching skills. STEAM education is the direction of future educational development, and C-STEAM is a more suitable way that meets the needs of Chinese education. Accumulating relevant interdisciplinary experience can enhance my professional competence. After starting formal work, I am also willing to continue conducting C-STEAM teaching.

5.1.2 C-STEAM teaching knowledge. Interviewed PSTs commonly reported an increase in their C-STEAM teaching knowledge and a deeper understanding of how to conduct C-STEAM teaching after participating in the course. The growth manifested in several ways:

- Firstly, their understanding of curriculum standards and content deepened, enabling them to recognize potential connections between multiple subjects and explore the educational value of different disciplines from an interdisciplinary perspective. As G5-2 mentioned:

Table 2.
Thematic coding process [2]

Examples of interview meaning segments	Open coding	Themes	Category
I feel that STEAM education has advantages over subject-based teaching as it can cultivate students' practical innovation abilities. I want to continue to carry out C-STEAM teaching activities in the future (G1-1)	Teaching attitude	STEAM teaching beliefs	Human capital
At first, I thought STEAM teaching would be difficult to accomplish, but the course practices this semester has already helped me accumulate the experience and confidence to conduct STEAM teaching (G6-2)	Teaching confidence		
I think this STEAM teaching practice has enhanced my knowledge reserves and pedagogical skills, and I am willing to continue STEAM teaching after officially starting work (G1-2)	Teaching motivation		
STEAM education should be carried out based on curriculum standards and textbook content. Looking at our theme'Paper Tower' about the curriculum and relevant subject textbooks, I found it relates to the stability of shapes in mathematics and model-making in engineering. Moreover, mathematics provides a theoretical and computational basis for engineering design (G5-2)	Understanding curriculum standards and textbook content	STEAM teaching knowledge	
I initially thought STEAM education only needed to include knowledge from these five subjects, but gradually, I realized through the course learning and teaching design that integrating multidisciplinary knowledge and skills is about solving real problems (G4-1)	Subject integration knowledge		
In the course, I learned more about the core knowledge related to STEAM education, especially since STEAM education needs to revolve around big concepts (G1-1)	Educational theoretical knowledge		
In the course, I mastered how to use various teaching technologies and learned how to apply technology to design rich interactive activities (G3-1)	Technology application knowledge		
My teaching design ability has improved. I now know how to break down the teaching objectives of STEAM courses and design corresponding learning activities and assessment methods around these objectives (G6-1)	Teaching Design Ability	STEAM teaching skills	

(*continued*)

Table 2.

Examples of interview meaning segments	Open coding	Themes	Category
I can create problem scenarios related to students' real-life experiences, using a series of questions and activities to help students understand knowledge (G2-2)	Teaching implementation ability		
I have realized the importance of assessment and can design clear self-assessment and peer-assessment scales for students, implementing evaluations through task sheets and classroom activities (G5-1)	Teaching assessment ability		
Group members reduced my workload and psychological burden, allowing us to work collaboratively, encourage each other, and collectively face challenges (G2-1)	Personnel support	Collaboration within PST groups	Social capital
Collaborating with PST peers in learning and practice helps me think outside the box. Our teaching design plans were determined and refined through brainstorming (G5-2)	Collective wisdom		
The course team provided many online courses related to STEAM education, as well as quality teaching cases and class recordings for our learning (G4-1)	Learning resource support	Collaboration with university	
The teacher provided an operational model for interdisciplinary teaching, giving us a clear framework to organize our teaching plans (G5-1)	Instructional theoretical guidance		
The instructor reminded us to guide students to explore scientific principles in learning activities, let students summarize the steps of making by themselves, and reminded us of activity safety (G2-1)	Teaching experience support	Collaboration with in-service teacher	
The instructor helped us rephrase the activity requirements in clearer language and followed up on each student's progress (G2-2)	Instructional practice guidance		
The educational consultant from the company invited teachers from local famous teacher studios to listen to and critique our classes, providing suggestions for modifications (G3-1)	Social resource support	Collaboration with enterprises	
The remote teaching platform and interactive research platform were very helpful for my practical learning. I could watch and learn from other PSTs' classes on the platform at any time and summarize experiences (G4-1)	Technology application guidance		

(*continued*)

Table 2.

Examples of interview meaning segments	Open coding	Themes	Category
The course theme, related teaching activities, and resources were developed by us, and I feel we had a lot of freedom and space for creativity (G6-1)	Active learning	Independent thinking	Decisional capital
Our interdisciplinary theme was not fully explained in the textbook, so we had to discern the scientific nature of the collected materials and compare data from multiple sources before integrating them (G1-1)	Critical thinking		
Our initial activity design was too complex, and after discussing it with the instructor, we realized the students couldn't complete it within the class time, so we adjusted the plan and prepared semi-finished products to send over (G2-2)	Problem-solving	Teaching judgment	
I think the biggest challenge of the course was dealing with unexpected situations in the actual classroom; many aspects were different from what we anticipated, and we had to adjust our teaching plans on the spot (G6-1)	Responding to the unpredictable		
I would watch my mock teaching videos and other PSTs' educational practice recordings, learning from successful classroom interactions and analyzing current problems I faced (G3-1)	Evidence-based reflection	Reflective improvement	
Our teaching process was determined through continuous trial and error; each discussion and mock teaching revealed new issues, but step-by-step modifications allowed us to feel our progress (G6-2)	Improvement through trial and error		

Source: Authors' own work

> In the course, I learned that C-STEAM education should be based on curriculum standards and textbooks, applying specific subject knowledge. For instance, our theme'Paper Tower'relates to both the stability of shapes in mathematics and model making in engineering, with mathematics providing theoretical and computational foundations for engineering design.

- Secondly, their knowledge of subject integration improved, understanding that C-STEAM education organically integrates knowledge and skills from multiple subjects, oriented toward problem-solving. G5-1 stated:

> Initially, I thought C-STEAM education simply needed to include knowledge from these five subjects. However, through course learning and my teaching design, I increasingly realize that the integration of multidisciplinary knowledge and skills is not simply additive, but rather needs to be based on meaningful cultural issues, with the aim of addressing real-world problems.

- Thirdly, their theoretical knowledge of C-STEAM education enhanced, their grasping core concepts and basic methods of C-STEAM education design and implementation. G1-1 noted:

> In the course, I learned more core knowledge related to C-STEAM education, like how to carry out project-based and problem-based learning methods.

However, some PSTs felt that certain theoretical knowledge they learned about C-STEAM education was not utilized in subsequent educational practices. G1-2 remarked:

> When learning about broad concepts, I found them abstract. Initially, I didn't realize these theories were meant to guide later practical phases, feeling a disconnect between theory learning and teaching design.

- Fourthly, their knowledge of technology applications improved, mastering various technological tools for teaching functions and operations, which could be used to enrich classroom activities and engage students. G3-1 said:

> In the course, I mastered the use of various teaching technologies, like timed response, line matching, photo uploads for classroom interaction, and remote teaching system operations like inviting listeners and switching scenes. I found them very practical, and they made the classroom atmosphere livelier.

5.1.3 STEAM teaching skills. All interviewed PSTs reported a significant improvement in their C-STEAM teaching skills after participating in the course, gaining a practical understanding of how to design and implement a complete STEAM lesson. The improvements manifested in various ways:

- Firstly, their teaching design skills were enhanced. They became capable of organizing and writing teaching content, objectives, implementation, and evaluation around specific themes. G6-1 explained:

> Now I know how to extract teaching content from the curriculum and textbooks. I can design teaching objectives based on the core concepts of the course, and around these objectives, plan corresponding learning activities and evaluation methods, forming a complete lesson plan.

- Secondly, their ability to implement teaching improved. They learned to facilitate active student learning through problem-driven and task-driven methods, trying out student-centered teaching approaches. G2-2 shared:

> I've learned how to ask questions effectively. Now, I can create problem situations connected to students' real lives, guiding them to actively understand concepts through a series of questions and activities, rather than relying on extended periods of direct instruction.

- Thirdly, their evaluation skills in teaching developed. They understood the importance of assessment-driven learning, enabling them to design appropriate evaluation tools and conduct evaluation activities in class. G5-1 noted:

> During theoretical learning, I only considered how to link knowledge points and advance teaching activities. But in educational practice, I realized that without an evaluation phase, I couldn't understand students' learning progress or know how to adjust subsequent teaching steps. So, I added task sheets and student evaluation scales.

5.2 Social capital

5.2.1 Collaboration with PSTs groups. All interviewed PSTs reported benefiting from collaborative learning with their PST peers, which facilitated their successful design and implementation of a C-STEAM course. On one hand, collaboration within the PST group provided personnel support, not only sharing the burden of lesson preparation and improving teaching efficiency but also offering emotional value and enhancing motivation to learn. As G2-1 explained:

> Unlike previous simulated reports, this time we had to complete a full teaching task for three class periods, making the initial preparation quite cumbersome. My group members helped share a lot of the workload and pressure. We were able to divide tasks, encourage each other, and face the challenge together.

On the other hand, collaboration with PST peers contributed to the generation of collective intelligence and the enhancement of professional literacy. G5-2 noted:

> Collaborating with PST peers helped open up my thinking. During discussions, many different ideas would emerge, and listening to others' opinions helped me avoid subjective assumptions. Our teaching design was refined through this clash of thoughts, and I believe it turned out much better than what I could have conceived on my own.

5.2.2 Collaboration with university teaching teams. All interviewed PSTs expressed that they benefited greatly from their collaboration with the university teaching team, which significantly aided in developing scientifically sound C-STEAM teaching designs and implementation plans. On one hand, the university teaching team provided extensive and coherent learning resource support, helping them form a structured understanding of C-STEAM education. As G4-1 stated:

"The teaching team provided us with online courses related to C-STEAM education, high-quality teaching cases, and classroom recordings for our learning." G2-2 also mentioned:

> The teaching team set up periodic group collaboration task sheets and provided detailed lesson plan templates, which helped me understand the knowledge and skills I should master.

On the other hand, the university teaching team offered solid theoretical teaching guidance to the PSTs and assisted and guided them throughout the entire process of teaching design and practice. As G5-1 said:

> I think the help from the teaching team was significant. Firstly, they provided an operational model for interdisciplinary teaching, giving us a clear direction for thinking. Particularly, they

helped me understand the need for clear evaluation criteria in teaching assessments. And G6-1 added:

Throughout the process, I felt the teaching team was in sync with us. They worked with us multiple times to refine the teaching process and helped us promptly with any situation we faced.

5.2.3 Collaboration with in-service teachers. The interviewed PSTs commonly expressed that through collaboration with primary and secondary school teachers, they were able to access real teaching scenarios and student learning information. The guidance from experienced in-service teachers enhanced the feasibility of their teaching plans. As G3-1 stated:

The guiding teacher gave feedback that our teaching content was too difficult and that we should consider the actual situation of the students. For example, the knowledge about circles in mathematics and mechanics in physics is not yet learned by seventh graders. G2-2 also mentioned:

The guiding teacher reminded us that too much theoretical teaching might lead to primary students losing focus. They suggested guiding students to explore scientific principles in learning activities, let them summarize the steps of making things themselves, and emphasized the importance of safety in activities.

Moreover, primary and secondary school teachers provided practical guidance for teaching to the PSTs, assisting in classroom management and the progression of the teaching process. As G2-2 said:

In our class, there were many hands-on activities. Initially, students didn't understand what to do. The guiding teacher helped us restate the activity requirements in clearer and more accurate language and followed up on each student's progress. And G5-2 added:

The guiding teacher was very proactive in managing the classroom atmosphere, encouraging student participation. Their interaction skills during the class were also very enlightening for me.

However, not all PSTs had a positive experience with their collaboration with in-service teachers. For instance, some PSTs pointed out issues like "the paired teacher did not have time to guide the teaching design" (G1-2) and "the teacher present did not participate in classroom management, leading to poor classroom discipline and wasting a lot of time" (G6-1).

5.2.4 Collaboration with enterprises. The majority of interviewed PSTs indicated that collaboration with enterprises increased their access to social resources, enabling interaction with experts from different groups. As G3-1 mentioned:

During our educational practice, the enterprise education consultant invited teachers from local famous teacher studios to observe and review our teaching, providing suggestions for improvement.

Additionally, enterprises provided technological support for hardware and software use, aiding PSTs in enhancing lesson preparation efficiency and the effectiveness of educational practice. G5-2 noted:

I found the collective lesson planning platform very convenient. My team members and I could collaborate on lesson plans and courseware design, then share it with the teaching team and front-line guiding teachers for their feedback. The platform allowed us to keep track of all comments, making it easier for us to review and revise. G4-1 added:

> I found the remote teaching platform and the interactive teaching research platform very helpful for my practical learning. I could observe and learn from other PSTs' classes on the platform anytime, summarizing experiences.

However, some PSTs reported that the effectiveness of the technological systems did not meet their expectations, hindering the teaching process, and the technical support from enterprises was sometimes delayed. G3-1 said:

> We designed many classroom interactive activities on the lesson planning platform, but they didn't work when we opened the remote teaching system. The company said it was due to a lack of synchronization between the two software, so we had to skip those activities. G4-2 mentioned:

> When I encountered a malfunction in the remote teaching system during a class, I had to contact online customer service and wait for a resolution. I was very nervous at that time, feeling that it delayed the students' learning time.

5.3 Decisional capital

5.3.1 Independent thinking. The interviewed PSTs commonly expressed that the course offered numerous opportunities for autonomous thinking. On one hand, they enjoyed considerable autonomy in the course, which enhanced their opportunities and motivation for active learning. G6-1 commented:

"We chose the course theme ourselves, and we developed the related teaching activities and resources. I feel that we had a lot of freedom and scope for creativity." Similarly, G2-2 stated:

> This wasn't just about presenting a plan, but teaching a class to students. It made me feel like a real teacher, motivating me to learn the subject knowledge and skills related to the course theme. Only after thoroughly understanding them, could I teach these contents to the students.

On the other hand, the PSTs needed to sift through, analyze, and organize information from various sources to ensure the scientific validity of their content, which increased the demand for critical thinking. For instance, G1-1 mentioned:

> Our theme involved the cultural significance of the Chinese knot, which isn't fully explained in textbooks. While researching, we found many different perspectives, so we had to compare them to choose the most scientific and well-substantiated answer to avoid misleading the students.

5.3.2 Teaching judgment. Most interviewed PSTs indicated that they had to make numerous decisions and judgments during the design and implementation of C-STEAM teaching. Before the formal teaching sessions, they encountered various unforeseen issues in the lesson plan design and mock teaching stages, which required them to find solutions on the spot. For instance, G2-2 mentioned:

> The activity we initially designed was too complex. After discussing with the guiding teachers, we realized that the students couldn't complete it within the class time. So, we had to readjust our plan urgently and prepare semi-finished products to be sent over.

Furthermore, during the actual teaching, PSTs also faced many unexpected situations that they hadn't anticipated, necessitating on-the-spot adjustments and changes in teaching pace. G6-1, when discussing the biggest challenge, they faced, said:

> I think the biggest challenge of the course was dealing with sudden occurrences in the actual classroom. For example, when I invited students to participate in an interactive game, they

> couldn't click on the screen to operate. So, I had to switch strategies temporarily, asking students to verbalize while I assisted in the operation, which still achieved the knowledge testing effect.

However, not all PSTs were able to make timely and reasonable teaching judgments and adjustments, leading to some negative emotions. G1-1 expressed:

> The students' reactions were different from what I expected. It seemed like they were not interested in engaging with me. There were times when I had to ask and answer my questions, which felt somewhat awkward. G2-1 also mentioned:

> The students were too excited during the hands-on activity and didn't stop even when the time was up. My reminders from a distance were ineffective, causing us to rush through the subsequent parts of the lesson without much detail.

5.3.3 Reflective improvement. The interviewed PSTs commonly reported that their teaching plans and materials underwent at least three iterations, completed through continuous reflection and improvement. On one hand, they were able to promptly identify issues in their current teaching designs based on a wealth of pedagogical and learning evidence. As G1-2 stated:

> The teaching team and in-service teachers provided us with detailed feedback on our lesson plans via the collaborative planning platform, and they also held regular video-based pedagogical discussions with us. We used these feedback materials for further group discussions and reflections, which helped us refine our lesson plans and teaching materials. Similarly, G3-1 mentioned:

> I would review my mock teaching videos, as well as the official teaching practice recordings and peer review data from other PSTs, to analyze if I was facing similar issues in my teaching.

On the other hand, the PSTs summarized their experiences through continuous trial and error, forming and implementing improved plans. G6-2 shared:

> Our teaching process was defined through constant trials. Every discussion and practice session revealed new problems, but we could distinctly feel our progress as we modified our plans step by step. We had prepared several sets of plans in advance, so we were not nervous when it came to the actual practice. Moreover, G4-1 added:

> I tried several methods to encourage students to answer questions, like positive guidance or direct calling, but none were very effective. Eventually, I added a group competition element to the class, which significantly increased student engagement. We continued to use this method in other lessons in our group.

6. Discussion

6.1 Human capital

Overall, participation in courses based on the T-USE model has developed the human capital of C-STEAM PSTs, primarily in areas such as teaching beliefs, teaching knowledge, and teaching skills.

In terms of teaching beliefs, all interviewed PSTs reported that their attitudes, confidence, and motivation toward C-STEAM teaching improved after participating in the course. This is reflected in a greater endorsement of the value of C-STEAM education, confidence in conducting C-STEAM teaching, and a desire to continue engaging in C-STEAM education. This change in belief primarily stems from the T-USE model providing PSTs with a series of structured C-STEAM education training phases, including team formation, theoretical learning, topic selection, design, implementation, pedagogical research, and presentation. PSTs personally experienced the operability and effectiveness of C-STEAM education throughout the course, which altered their perceptions and attitudes toward C-STEAM teaching. Establishing their own successful experiences, observing and learning from others' success, collaborating with experts, and having opportunities for continuous learning of new knowledge and skills are the primary sources for developing preservice teachers' teaching beliefs (Bandura *et al.*, 1999; Nolan and Molla, 2017). The T-USE model provided ample resources and opportunities for PSTs in these four areas.

In terms of teaching knowledge, all interviewed PSTs reported a deeper understanding of C-STEAM education's subject knowledge, interdisciplinary integration, educational theories, and technological applications. This advancement can be attributed to two primary reasons. First, the T-USE model provided a systematic framework for C-STEAM theoretical learning and inquiry-based activities. The university teaching team developed the "C-POTE" framework and collaborative tasks embedded with inquiry questions. This structured knowledge system and inquiry activities helped PSTs grasp the basic concepts of disciplines and interdisciplinarity, as well as the pedagogical knowledge for multi-disciplinary integration (Nadelson and Seifert, 2017). Second, the T-USE model combined design learning with cooperative learning, encouraging PSTs to collaborate on designing teaching tasks and activities based on interdisciplinary themes and real student needs. Such methods facilitated the transformation of theoretical knowledge into practical knowledge for PSTs (Pak *et al.*, 2020; Bush and Grotjohann, 2020). However, some PSTs noted that certain theoretical knowledge was not applied in subsequent teaching practices, indicating a disconnect between theory and practice that added to their cognitive complexity. The possible reason for this was the continued academic orientation in the training of university PSTs, making it challenging for some teaching theories to be applied in primary and secondary schools (Teo and Ke, 2014). In the implementation of the T-USE model, universities and schools guided PSTs separately, with a lack of interaction between them.

In terms of teaching skills, all interviewed PSTs expressed improvement in areas like teaching design, implementation, and evaluation after participating in educational practice. The T-USE model provided PSTs with the opportunity to experience the complete process of C-STEAM teaching as in-service teachers do, organizing them to collaboratively design and implement a structured C-STEAM course in a project-based learning manner. The collective lesson preparation platform and intelligent recording environment set up by enterprises created realistic research and teaching scenarios for PSTs. This experience-based approach enabled PSTs to directly confront challenges and situations they might encounter in teaching, applying, and developing teaching skills in practice (Luo *et al.*, 2017; Bush and Grotjohann, 2020).

6.2 Social capital

In the T-USE model, the development of PSTs' social capital is primarily reflected in their interactions with members of the educational community. Overall, these interactions enhanced their learning efficiency and course effectiveness but also presented varying degrees of challenges.

PSTs generally reported significant benefits from collaborating with their PST peer groups, gaining personnel support and collective wisdom, which enhanced their learning efficiency and the final course outcomes. In the early stages of the T-USE model, PSTs were required to form learning communities to collaboratively tackle the task of designing and implementing C-STEAM courses. Clearly defined common goals and challenging real-world tasks fostered knowledge-sharing and problem-solving among group members. Active interaction and communication with peers helped them achieve higher levels of accomplishment, consistent with existing research (Estapa and Tank, 2017; Bush and Grotjohann, 2020).

Furthermore, collaboration with the university teaching team provided PSTs with a wealth of learning resources and theoretical guidance. Constructive feedback from expert mentors helped PSTs establish a structured knowledge and skill system and generate scientifically sound teaching plans (So *et al.*, 2019). The T-USE model also integrated a collective lesson preparation platform and an interactive teaching platform, offering a more convenient and interactive cooperative environment enabled by technology. This technological integration facilitated more timely guidance from the university teaching team to the PSTs, enhancing the frequency and depth of their collaboration.

In their collaboration with in-service teachers, the PSTs' feedback varied. Some PSTs felt that working with these teachers provided them with valuable firsthand teaching experience and helped them complete their teaching practice more smoothly. However, other PSTs felt that in-service teachers only provided "a classroom" and "some students," without actively participating in the design and implementation of the STEAM course, and were not available to help when needed. In this collaboration, in-service teachers, serving as practical mentors and model educators, can offer guidance based on real teaching experiences, helping PSTs understand the realities of future formal teaching jobs (Sá and De Almeida, 2016). However, the in-service teachers' perspectives on C-STEAM education, their attitudes toward collaboration, and their teaching proficiency can all impact the effectiveness of their collaboration with PSTs (Estapa and Tank, 2017; Herro and Quigley, 2017; Willegems *et al.*, 2017), which may be a primary reason for the differences in feedback.

Furthermore, not all PSTs were able to engage in equal and effective dialogue with in-service teachers. On one hand, in-service teachers are busy with their regular duties and might resist additional commitments required for educational collaboration projects (Cochran-Smith and Lytle, 2015, p. 40). On the other hand, PSTs might feel apprehensive about the "authority" of in-service teachers, hindering proactive communication with them. As some PSTs mentioned, even in online discussions, they still felt pressure (G5-1) and fear of not performing well (G2-2) when facing experienced in-service teachers. Therefore, they tended to seek help from groups with lower hierarchical relationships(Burbank and Kauchak, 2003), such as group members or course assistants, which also led to closer interaction with PST peers or university teaching teams. This highlights the importance of establishing effective communication mechanisms within educational communities.

In their collaborations with enterprises, all interviewed PSTs expressed that enterprises provided them access to abundant technological resources and social support, enhancing their learning experience and efficiency. In the T-USE model, enterprises supplied advanced technological tools and resources, such as collective lesson preparation platforms, smart recording systems, and interactive teaching research systems. These resources helped PSTs to master digital-age lesson preparation and teaching methods and gain practical experience working in digital teaching environments. Additionally, the social resource networks of the enterprises expanded the learning environment for PSTs, offering them opportunities to interact with other experts. This cross-disciplinary social exposure aids PSTs in building professional networks, comprehensively understanding career trends, and establishing connections with resources they may need in their future professional life (Li *et al.*, 2023).

While the technological support and social resources provided by enterprises broadened the opportunities for the professional development of PSTs, there were still some limitations. For instance, some PSTs mentioned issues such as unstable technological tools and delayed support services from enterprises, which hindered their teaching effectiveness (G3-1) and led to negative learning emotions (G4-2). Therefore, the quality and sustainability of the collaboration with enterprises are key factors affecting the effectiveness of the T-USE model. This implies the need to establish stable and mutually beneficial relationships with enterprises, ensuring timely updates of technology and resources to meet the specific needs and challenges of C-STEAM education.

6.3 Decisional capital

In the T-USE model, the development of decisional capital in PSTs is reflected in their ability to make independent decisions or judgments during the C-STEAM teaching design and implementation process. This includes autonomous thinking, pedagogical judgment, and reflective improvement.

The T-USE model provides PSTs with ample opportunities for autonomous thinking. On the one hand, the "knowledge accumulation" and "collaborative lesson planning" phases require PSTs to autonomously choose C-STEAM course themes, design teaching activities, and develop resources, creating a space for active learning. On the other hand, since the C-STEAM course content and activities are self-developed and put into real educational practice, PSTs must engage in critical thinking when searching for and integrating interdisciplinary resources, and assessing the accuracy and applicability of information. T-USE offers a combination of active learning and critical thinking, enabling PSTs to have strong autonomy and flexibility in their learning, which can promote the development of decision-making skills, consistent with existing research (Beck and Kosnik, 2002; Rawles, 2016).

Moreover, by providing real teaching challenges and scenarios, the T-USE model encourages PSTs to make and execute teaching judgments. In designing and refining teaching plans, PSTs must make scientific and feasible judgments about teaching content, activities, and resources, analyze and solve existing problems to meet students' real learning situations and ensure effective implementation of teaching practice. During the teaching implementation, PSTs will face many unpredictable situations, forcing them to adapt based on students' live feedback. In these T-USE C-STEAM education practice activities, PSTs need to flexibly apply their knowledge and make adaptive adjustments based on actual circumstances, which is also confirmed in existing research as a necessary condition for developing decision-making abilities (Schwartz and Sharpe, 2010). However, good teaching judgment skills require extensive experience accumulation and grow over time with practice (Hargreaves and Fullan, 2015), so PSTs at the beginning of their professional learning may inevitably encounter difficulties.

Furthermore, the T-USE model offers PSTs a variety of reflective practice activities, considered an important way to develop decisional capital (Hargreaves and Fullan, 2015). Firstly, T-USE provides opportunities for evidence-based teaching reflection. In the "collaborative lesson planning" phase, PSTs need to report and refine teaching plans with university and front-line teachers through multiple rounds. In the "class observation" phase, PSTs review their teaching processes and watch other PSTs' teaching recordings on the interactive teaching research platform, and self-reflect based on collective lesson preparation and interactive teaching research data. Secondly, T-USE reserves opportunities for iterative planning, allowing PSTs to continuously experiment and summarize experiences in practice, and form and implement improvement plans, enhancing professional proficiency. The evidence supports and iteration space provided by T-USE can develop PSTs' reflective improvement abilities, helping them make informed decisions.

7. Conclusion

This study aims to establish a technology-enabled university-school-enterprise collaborative education model and assess its impact on the professional capital development of C-STEAM PSTs, providing a theoretical and practical reference for C-STEAM PSTs' educational reform. The results indicate that this model enhances three aspects of C-STEAM PSTs' professional capital development, strengthening teaching beliefs, knowledge, and skills, benefiting from interactions within the educational community, and enhancing professional judgment capabilities in C-STEAM education.

The technology-enabled university-school-enterprise collaborative education model targets the development of PSTs' professional capital, forming a community for PSTs' educational practice, and integrating resources for technology-enabled C-STEAM education practice. During implementation, it emphasizes a combination of theoretical learning and educational practice, providing PSTs with opportunities for design learning and collaborative learning, as well as scaffolding based on real experiences. This allows them to participate in the entire process of C-STEAM education, thus developing their beliefs, knowledge, and skills in C-STEAM teaching (human capital). At the same time, the model creates a broader and more cohesive community through technological platforms, allowing PSTs to access human capital from peers, university expert teachers, in-service school teachers, and educational enterprise personnel. Interactions and collective intelligence developed in this way promote the growth of their social capital and further enhance their human capital. Real educational contexts and reflective practices help PSTs build decisional capital, supported by evidence from technology platforms, aiding them in making informed decisions.

However, some limitations of this model were also identified, such as the lack of interaction between universities and schools, insufficient collaboration between PSTs and in-service teachers, and instability and delays in enterprise support. Additionally, the development of decisional capital requires longer-term and more sustainable professional development programs. Moreover, our study's results may be influenced by the limited number of participants, being restricted to graduate students in educational technology, and the short duration of the experiment. Therefore, future research needs longer experimental periods, more adaptive learning activity designs, and more diverse participant groups to establish effective educational models for high-quality C-STEAM PSTs.

Notes

1. Figure 1 presents the online educational practice scene and the lesson evaluation form in the interactive teaching and research platform for normal students. It comprises three signal channels: the real-time teaching screen of the PSTs (top right), the PSTs' courseware screen (top left), and the live student audience screen (middle bottom). Members of the educational community access the platform via a live stream link to watch the PSTs' teaching recordings. The comprehensive evaluation of the PSTs' STEAM education practice is conducted by considering both teaching and learning dimensions. The teaching dimensions include teaching strategies, teaching content, teaching implementation, teaching evaluation, classroom culture, and technology application. The learning dimensions focus on cognitive development, classroom participation, and technology application.
2. Table 2 presents only a portion of the PSTs' interviews as an example of the coding process.

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