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Conceptualizing Digital Professional Competence Development via Project-Based Software Engineering in Collaborative Digital Environments: A Theoretical Framework with Pilot Empirical Evidence

Ibroximbek Mirsaidov
University of Business and Science, Uzbekistan
Xurshidbek Xamrayev
xamrayevbek96@gmail.com

University of Business and Science, Uzbekistan
A□zamjon Aliyev
University of Business and Science, Uzbekistan

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Abstract

Digital professional competence is now one of the key learning outcomes of higher education programs for the preparation of future specialists of software-intensive areas. Although there are general orientations, like DigCompEdu and TPACK, that offer a general guide, there is still no integrated theoretical–methodological account of the development of this competence through authentic software design activities in collaborative digital environments, and there are still few empirical validations of such accounts.

This study (1) proposes a conceptual framework that integrates the most recent developments in digital competence theory, project-based software engineering pedagogy and computer-supported collaborative learning, and (2) offers empirical support in the form of a preliminary study with future digital specialists.

A two-track methodology was employed. First, a narrative synthesis of the most recent peer-reviewed literature (2018–2026) was first performed to create a seven-dimensional construct and a hypothesized pathway model containing seven propositions (H1–H7). Second, a quasi-experimental pretest–posttest pilot study was performed with N = 80 undergraduate computing students, who participated in a 20-day intensive project-based software engineering intervention in a collaborative digital environment based on the Git version control system. Digital professional competence was evaluated by a self-report questionnaire (DPCQ-28) with 28 items and by seven tasks (0–100 rubric).

For all seven dimensions, there were significant pre-to-post gains (mean gains ranged from 12.91 to 15.75 points on a 0–100 scale), all paired-samples comparisons were significant after Holm correction (all $p < .001$), and all effect sizes were large (Cohen's $d = 2.07–2.44$). There were 21 pairwise correlations between the posttest dimensions, all of which were moderate to strong and significant ($r = 0.55–0.77$, all $p < .001$). All seven hypothesized pathways were supported by standardized path coefficients (0.55–0.77, all $p < .001$), with digital communication being the strongest path ($\beta = 0.77$). Six qualitative themes converged with the quantitative results.

Digital professional competence is considered as a pedagogically grounded and developmentally organized construct. The preliminary findings from the pilot study are supportive of the seven dimensions of the architecture and of the proposed developmental trajectory, and warrant a full-scale confirmatory study. Implications for curriculum design, faculty preparation, and assessment in higher education are discussed.

1. Introduction

Digital transformation has changed the definition of a competent professional in the 21st century in higher education. Future specialists in software engineering, computer science, and applied computing are now expected to be able to not only master domain content, but also to be able to work effectively in digitally mediated, distributed, and collaborative work environments. Digital professional competence

has become a key learning outcome of modern higher education curricula, moving from a peripheral to a core part of the learning process (Vuorikari et al., 2023; Kiianovska, 2025).

This is a pressing issue, given two converging developments. First, the rapid diffusion of cloud-based platforms, generative AI, learning analytics, and immersive technologies has increased the technical surface that future specialists need to traverse (Ruiz Rodríguez et al., 2025; Kiianovska, 2025). Second, in the software-intensive professions, the current professional practice is more and more organized around the project work that is carried out in collaborative digital environments, and the success of which requires the simultaneous mobilization of technical, communicative and analytical skills (Vo Doan Yen Nhi & Le Thai Minh Long, 2026; Hamidi, 2025).

Although much scholarly research has been devoted to the subject, there are three interrelated gaps. First, although digital competence is not a single competence but a complex of competencies (Pedaste et al., 2023; González-Mujico, 2024), much of the empirical literature continues to measure digital competence as a set of skills using self-report instruments. Second, conceptual frameworks have tended to focus on either the technological dimension or the pedagogical dimension, but not on how the two dimensions interact in situated activity in collaborative digital environments (Nuraina et al., 2025; Mishra & Koehler, 2006). Third, while project-based and inquiry-based learning are highly recommended as means of developing digital competence, there is still no theoretical–methodological account of project-based software engineering as a developmental mechanism, nor sufficient empirical evidence of how multiple competence dimensions co-develop in project-based learning (Hamidi, 2025; Kiianovska, 2025).

The present paper addresses these gaps through a two-track contribution. The first track is conceptual: we integrate recent developments in three converging traditions — digital competence theory, project-based software engineering pedagogy, and computer-supported collaborative learning —, and present the interconnections among these traditions in a set of theoretically grounded propositions. The second track is empirical: we offer preliminary evidence from a 20-day pilot study with future digital specialists, which tests the multidimensional architecture of the construct and the hypothesized developmental pathway. The paper is guided by three research questions:

RQ1. What is digital professional competence and how can it be understood as a multi-dimensional construct that is cultivated in project-based software engineering in collaborative digital environments?

RQ2. What theoretical–methodological mechanisms can be identified that underlie the process of digital professional competence development of future specialists in such environments?

RQ3. How well does the empirical evidence from the pilot support the proposed multidimensional construct and hypothesized pathway relationships among the dimensions?

The paper has three contributions. In theory, it builds on a seven-dimensional model of digital professional competence that combines informational, communicative, collaborative, analytical,

technical and creative aspects. Methodologically, it outlines a multilevel developmental pathway based on project-based software engineering pedagogy and empirically evaluates the preliminary structure of this pathway. In practice, it provides a framework for curriculum development, faculty development, and evaluation in higher education programs for future digital specialists. The rest of the paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the conceptual framework; Section 4 describes the two-track methodology; Section 5 presents conceptual and empirical results; Section 6 discusses implications; and Section 7 concludes with limitations and future directions.

2. Literature Review

2.1. Digital Professional Competence as a Multidimensional Construct

The notion of competence in digital environments has undergone significant changes in the last 20 years. The initial versions focused on technical literacy and operational competence in specific tools (Kiianovska, 2025; Spirin, 2010). This idea has been broadened and extended over the years to encompass informational, communicative, collaborative, ethical, and creative aspects. The DigCompEdu framework (Vuorikari et al., 2023; European Commission, 2017) defines six domains of digital competence of educators: professional engagement, digital resources, teaching and learning, assessment, empowering learners, and facilitating learners' digital competence, with each domain having six proficiency levels (Newcomer, A1, to Pioneer, C2).

Empirical research in recent years has validated the view of digital competence as multidimensional and internally organized rather than as a single competence. In the development and validation of a school-based digital competence test, Pedaste et al. (2023) found that there are distinguishable competence dimensions that, however, can be grouped into higher-order structures. Reichert et al. (2020) also found evidence for a general dimension of digital literacy and more specific dimensions related to authentic software use. Based on these results, Vo Doan Yen Nhi and Le Thai Minh Long (2026) proposed and empirically tested a seven-dimensional model of information literacy, digital data analysis, collaborative technology use, digital communication, problem-solving with digital tools, creativity in digital projects, and technical digital proficiency, which showed that all seven dimensions are co-developed in student-centered, technology-supported learning environments.

The second significant advancement is in the area of measurement. González-Mujico (2024) suggested that in order to move forward in the field, self-assessment should be complemented with external assessment of actual performance. Porat et al. (2018) demonstrated that students' self-assessment of their digital literacy may be significantly higher than their actual ability to perform on digital tasks. The methodological developments have implications for any framework that aims to guide the development of digital professional competence in higher education.

2.2. Collaborative Digital Environments and Computer-Supported Learning

The concept of a collaborative digital environment is defined as a socio-technical arrangement where learners and professionals organize their cognitive activities through a shared digital environment, repository, communication, and computational resources. These environments are not passive spaces for activity, but rather active spaces for noticing, communicating, and producing (Hamidi, 2025). The systems thinking perspective proposed by Hamidi (2025) based on the DSRP model is useful to analyze such environments. In this view, digital competence is not an attribute of an individual, but an emergent property of the interactions between learners, tools, tasks and pedagogical structures.

Empirical studies on computer supported collaborative learning (CSCL) have always demonstrated that the learning value of digital collaboration is not the tool itself, but the quality of the communicative and coordinative interaction that is maintained through the tool. In a systematic review of technology-enhanced collaborative inquiry, Chen and Chen (2024) found that positive outcomes for content knowledge, inquiry processes, and scientific skills resulted when digital tools were purposefully connected to the stages of inquiry and activity structures. Bilici and Yilmaz (2024) showed that collaborative digital storytelling not only positively affected academic performance, but also co-regulation and narrative skills. The results highlight the importance of the pedagogical productivity of collaborative digital environments, which are activity systems that require intentional design.

2.3. Project-Based Software Engineering as a Pedagogical Vehicle

Project-based learning (PjBL) is one of the most widely researched pedagogies for the development of complex professional competencies. Sukackė et al. (2022) conducted a systematic review of PjBL, problem-based learning and challenge-based learning, and found that the following mechanisms are essential for the development of integrated competencies: active engagement with authentic problems, structured collaboration, and the creation of tangible artifacts. In the context of software engineering education, project-based learning places the learner in a long sequence of requirements analysis, design, implementation, testing, and reflection, which is similar to professional practice (Nuraina et al., 2025).

The use of TPACK (Mishra & Koehler, 2006) in project-based instruction has been a fruitful area of research. In a recent empirical study, Nuraina et al. (2025) demonstrated that prospective teachers who participated in TPACK-based projects acquired integrated competence in pedagogical, content and technological aspects. Project-based software engineering is not just PjBL, but also an introduction to the epistemology of design in the face of uncertainty in computing and software-related disciplines. Students who work on real-world projects build technical fluency, as well as higher-order skills in problem decomposition, iteration and collaborative coordination, as Gupta (2022) showed. Skliarova (2021) found similar results for project-based digital design courses that were taught online, indicating

that the developmental affordances of project-based software engineering are transferable to delivery modalities.

2.4. The TPACK–DigCompEdu Synthesis and Persisting Gaps

Recent research has started to converge towards a synthetic perspective that draws on the depth of the disciplines in TPACK and the breadth of the structures in DigCompEdu (Kiianovska, 2025; Caena & Redecker, 2019). This synthesis acknowledges that in digitally mediated professional settings, subject matter knowledge, pedagogical/methodological repertoire, and technological fluency must be mobilized simultaneously and are embedded in a multilevel developmental trajectory. The UNESCO ICT Competency Framework for Teachers (UNESCO, 2018) also describes a learning trajectory that corresponds to the DigCompEdu's levels of proficiency.

Although the above progress has been made, there are three gaps that remain which are discussed in the present paper. First, there is no clear and coherent literature that explains the structural relationships between the multiple dimensions of digital competence in project-based software engineering contexts. Second, although the general idea of multilevel progression is often highlighted, the developmental processes through which learners transition from basic to higher levels of proficiency in collaborative digital environments are not fully specified. Third, the methodology of project-based software engineering itself (as a delivery vehicle, activity system or developmental mechanism) has not been theoretically resolved or empirically tested in an integrated model.

3. Conceptual Framework and Theoretical Propositions

3.1. Definitional Foundations

The framework is based on three definitional commitments. First, digital professional competence is defined as the "whole package" of knowledge, skills, dispositions, and reflective capacities that enable a future professional to function effectively in digitally mediated professional contexts, including the productive use of information, communication, collaboration, analysis, problem solving, creative production, and technical operation. Second, project-based software engineering is defined as an authentic, extended, disciplinary practice in which learners — individually or in teams — design, build, test, and reflect on software products under conditions that closely approximate professional software engineering practice. Third, a collaborative digital environment is a socio-technical arrangement of shared platforms, communication channels, repositories, and computational tools that enable learners to coordinate their cognitive and productive activities.

3.2. Seven-Dimensional Construct

Following the empirical operationalization recently validated by Vo Doan Yen Nhi and Le Thai Minh Long (2026) and aligned with DigCompEdu (Vuorikari et al., 2023), the framework articulates digital

professional competence through seven interrelated dimensions presented in Table 1.

Table 1
Seven Dimensions of Digital Professional Competence

Dimension	Operational definition	Primary activity locus
Information Literacy (IL)	Locating, critically evaluating, organizing, and synthesizing credible digital information sources.	Requirements analysis; documentation review
Digital Data Analysis (DDA)	Organizing, visualizing, interpreting, and drawing evidence-based conclusions from digital data.	Testing; performance evaluation
Collaborative Technology Use (CTU)	Coordinating roles, contributing responsibly, and co-producing artifacts through shared digital platforms.	Version control; team workflows
Digital Communication Skills (DCS)	Communicating professional ideas clearly and persuasively through digital media and structured formats.	Documentation; technical presentations
Problem-Solving with Digital Tools (PSDT)	Selecting and using digital tools to investigate, decompose, and resolve professional problems under constraints.	Design; debugging; iteration
Creativity in Digital Projects (CDP)	Producing original, multimodal digital artifacts integrating disciplinary understanding with innovative form.	Artifact production; user-experience design
Technical Digital Proficiency (TDP)	Operating digital tools and platforms efficiently, including configuration, integration, and troubleshooting.	Tooling; environment configuration

Note. *Dimensions adapted from Vo Doan Yen Nhi and Le Thai Minh Long (2026) and aligned with DigCompEdu 2.2 (Vuorikari et al., 2023).*

3.3. Hypothesized Pathway Structure

The framework proposes that the seven dimensions are not parallel and independent but structurally related through a developmental pathway. Drawing on the empirically supported structural model reported by Vo Doan Yen Nhi and Le Thai Minh Long (2026) and consistent with the foundational role of information work in software engineering practice (Sarvary & Ruesch, 2023; Spektor-Levy et al., 2009), the framework articulates seven theoretical propositions. The proposed structural model is depicted in Fig. 1.

The seven theoretical propositions are:

P1 (H1). Information literacy positively predicts digital data analysis. Professionals who can locate, evaluate, and synthesize credible information are better positioned to interpret digital representations and draw evidence-based conclusions.

P2 (H2). Information literacy positively predicts digital communication. Evidence-based communication in software engineering contexts presupposes the ability to identify, evaluate, and integrate credible sources.

P3 (H3). Digital data analysis positively predicts problem-solving with digital tools. Analytical fluency provides the interpretive basis for selecting tools, framing problems, and evaluating candidate solutions.

P4 (H4). Digital communication positively predicts collaborative technology use. The productivity of collaborative digital work depends on the quality of articulation, negotiation, and coordination among team members.

P5 (H5). Problem-solving with digital tools positively predicts technical digital proficiency. Repeated, goal-directed engagement with digital tools under authentic constraints develops operational fluency.

P6 (H6). Technical digital proficiency positively predicts digital creativity. Operational fluency releases cognitive resources for experimentation, adaptation, and original artifact production.

P7 (H7). Collaborative technology use positively predicts digital creativity. Shared planning, peer feedback, and integration of multiple perspectives enrich the creative production of digital artifacts.

3.4. Project-Based Software Engineering as Developmental Mechanism

A key theoretical assumption of the framework is that project-based software engineering is not merely a delivery format, but rather the activity system in which the seven dimensions are simultaneously activated and continually woven together. This claim rests on three arguments. First, working in parallel across information, communication, collaboration, analysis, problem solving, creativity, and technical operation is a fundamental requirement of software engineering projects, and no single dimension can accomplish this on its own (Gupta, 2022; Sukackė et al., 2022). Second, the iterative nature of project work — planning, building, testing, reflecting, and refining — provides repeated developmental opportunities that allow weaker dimensions to be exposed and reinforced through sustained engagement (Nuraina et al., 2025). Third, in the context of collaborative digital environments, the socio-technical configuration itself functions as a developmental scaffold: shared repositories make information practices visible, communication platforms reveal articulation quality, and version-control systems materialize collaborative coordination (Hamidi, 2025).

3.5. Multilevel Developmental Trajectory

The framework follows the six-level developmental trajectory of digital professional competence as outlined in DigCompEdu (Vuorikari et al., 2023), and also elaborated by Kiianovska (2025) for mathematics educators: Newcomer, Explorer, Integrator, Expert, Leader, and Pioneer. At the Newcomer level learners show basic awareness and emerging practice; at the Explorer level they start to experiment systematically with project tools and methods; at the Integrator level they are beginning to purposefully

combine technological, methodological and disciplinary elements; at the Expert level they design coherent project workflows and select the tooling strategically; at the Leader level they guide colleagues and shape collaborative practice; and at the Pioneer level they innovate new approaches and contribute to disciplinary scholarship. Importantly, learners can be at varying levels along different dimensions, indicating the differentiated nature of their developmental pathways.

4. Methodology

This paper has a dual conceptual–empirical goal and uses a two-track methodology. Track 1 builds the conceptual framework by narrative literature synthesis; Track 2 offers preliminary empirical support by a quasi-experimental pilot study with future digital specialists.

4.1. Track 1: Conceptual Synthesis

Conceptual framework was developed using narrative literature synthesis (Snyder, 2019), which was appropriate when the objective was to synthesize constructs across overlapping, but disjoint literatures and to create a theoretically coherent account. The search for relevant and recent peer-reviewed publications (2018–2026) was conducted in the Scopus database and in other databases using the following terms: digital competence, digital professional competence, project-based learning, software engineering education, collaborative digital environments, TPACK, and DigCompEdu. Five key sources were used as starting points, and their citation histories were worked out backwards to the seminal works and forwards to the recent extensions.

Each source was broken down into key constructs and then coded to the categories of the emerging framework. Operational definitions, hypothesized relationships and reported empirical effects were given special consideration. Constructs were then mapped, highlighting points of convergence, divergence, and points of theoretical extension. The integrated model was presented in the form of formal propositions (P1–P7) and hypotheses (H1–H7) for the empirical pilot.

4.2. Track 2: Pilot Empirical Study.

4.2.1. Design

A quasi-experimental single group pretest–posttest pilot design was used. For a feasibility study, instrument refinement and preliminary evidence, the single-group design is suitable for a pilot whose main purpose is not confirmatory causal inference. The design combines the use of self-report questionnaire measures with performance-based tasks (González-Mujico, 2024) and qualitative reflection embedded in the tasks for triangulation. The 15 working days of intervention are a way of making the intensive project-based experience a compressed module or summer school.

4.2.2. Participants

A total of 80 undergraduate students (N = 80), who are students of computing, software engineering, and information technology programs at the host institution volunteered to join the program. Mean age was 20.3 years (SD = 1.3; range 18–23). The sample comprised 56 male (70.0%) and 24 female (30.0%) participants. Distribution by year of study: 25 second-year (31.3%), 39 third-year (48.8%), and 16 fourth-year (20.0%) students. Distribution by prior digital experience (self-reported): 23 low (28.7%), 42 medium (52.5%), and 15 high (18.8%). Table 2 presents a summary of the demographic characteristics.

Table 2
Demographic Characteristics of the Pilot Sample (N = 80)

Variable	Distribution
Age (years)	M = 20.3, SD = 1.3, range 18–23
Gender	Male: 56 (70.0%); Female: 24 (30.0%)
Year of study	2nd: 25 (31.3%); 3rd: 39 (48.8%); 4th: 16 (20.0%)
Prior digital experience	Low: 23 (28.7%); Medium: 42 (52.5%); High: 15 (18.8%)

4.2.3. Intervention

The participants completed a 20-day intensive project-based software engineering programme within a structured collaborative digital environment. Students in groups of 3–4 created a small but complete software product (e.g., web application, data dashboard, or API service) to solve an identified real-world problem. The shared digital space included: (a) a version control platform (GitHub); (b) an integrated development environment (VS Code); (c) a real-time communication platform (Discord); (d) a shared documentation space (Notion); and (e) issue tracking via GitHub Issues. The intervention was organized into a six-phase project cycle that addressed the seven competence dimensions: orientation and baseline (Days 1–2), requirements and analysis (Days 3–5), design and implementation (Days 6–9), testing and data analysis (Days 10–13), documentation and creative production (Days 14–16), and assessment and reflection (Days 17–20).

4.2.4. Measures

Two complementary instruments were used to assess digital professional competence. The first was the 28-item Digital Professional Competence Questionnaire (DPCQ-28) developed by Vo Doan Yen Nhi and Le Thai Minh Long (2026) and adapted for the software engineering domain, which measured self-reported confidence in the seven dimensions, each with four items and a 5-point Likert scale. Secondly, each dimension was operationalized as an actual task that was scored on a rubric of 0–100 (4 domains × 25 points) and conducted after the intervention under standardized conditions. A composite competence score was calculated for each dimension by averaging the transformed questionnaire mean (TQS = [mean − 1] / 4 × 100) and the rubric-based performance score, resulting in a 0–100 composite score for each dimension. To facilitate triangulation, a set of qualitative reflection prompts were gathered on Day 20.

4.2.5. Analysis Plan

Quantitative analyses performed included the following: (a) descriptive statistics with 95% confidence intervals; (b) paired samples t-tests (with Wilcoxon signed-ranked as a robustness check) for each dimension between pretest and posttest scores; (c) Cohen's d for paired samples with 95% confidence interval; (d) Holm correction for multiple comparisons across the seven dimensions; (e) Pearson correlations between the posttest dimensions; (f) Cronbach's α for internal consistency; (g) intraclass correlation coefficient (ICC) within a 20% double coding sample for inter-rater reliability; and (h) standardized regression coefficients for the seven hypothesized paths. As a result of the relatively small sample size, the path-model results are explorative in nature. Reflexive thematic analysis (Braun & Clarke, 2019) was used to analyse the qualitative reflections.

4.2.6. Ethical considerations

The pilot study was carried out on the basis of institutional ethical guidelines. Written informed consent was obtained after a session of information about the purpose of the study, the voluntary nature of participation, the right to withdraw at any time without consequences, and the measures taken to protect the data. Data were anonymized at collection time with participant codes (P01–P80) and the key used for linking was kept separate from the data. The study was approved by the ethics review process at the host institution.

5. Results

5.1. Pre-to-Post Changes Across Seven Dimensions

There were substantial pre-to-post gains in all seven dimensions of digital professional competence. Mean gains ranged from 12.91 points (DCS) to 15.75 points (DDA) on the 0–100 metric. The effect size (Cohen's d) was generally large (2.07–2.44) and all paired-samples t-tests were highly significant after Holm correction for multiple comparisons (all $p < .001$). The same pattern was confirmed by Wilcoxon signed-ranks tests under the non-parametric model. The complete descriptive and inferential results are presented in Table 3 and the profile of pre–post change is depicted in Fig. 2.

Table 3
Pretest, Posttest, Mean Gains, and Effect Sizes Across Seven Dimensions (N = 80)

Dim.	Pretest M (SD)	Posttest M (SD)	Gain M	t (df = 79)	p (Holm)	Cohen's d [95% CI]
IL	67.36 (8.39)	81.39 (6.96)	+ 14.03	20.29	< .001	2.27 [1.85, 2.68]
DDA	63.23 (7.35)	78.98 (6.84)	+ 15.75	21.13	< .001	2.36 [1.94, 2.79]
CTU	61.97 (8.63)	77.21 (6.87)	+ 15.24	21.1	< .001	2.36 [1.93, 2.79]
DCS	66.51 (7.45)	79.42 (6.69)	+ 12.91	18.54	< .001	2.07 [1.68, 2.46]
PSDT	69.46 (6.8)	83.09 (6.42)	+ 13.63	20.42	< .001	2.28 [1.87, 2.7]
CDP	61.1 (7.07)	76.82 (6.47)	+ 15.72	21.79	< .001	2.44 [2, 2.87]
TDP	67.11 (7.47)	81.98 (6.53)	+ 14.88	21.19	< .001	2.37 [1.94, 2.8]

Note. *IL = Information Literacy; DDA = Digital Data Analysis; CTU = Collaborative Technology Use; DCS = Digital Communication Skills; PSDT = Problem-Solving with Digital Tools; CDP = Creativity in Digital Projects; TDP = Technical Digital Proficiency. All scores on a 0–100 composite metric. p (Holm) = Holm-corrected p-value for paired-samples t-test.*

The largest gains were observed for DDA (M = + 15.75), and CDP (M = + 15.72), dimensions that are closely tied to the intensive collaborative and creative nature of project work. Notably, the finding of significant progress across all seven dimensions, rather than only a subset, is consistent with the conceptual argument that project-based software engineering mobilizes the entire competence architecture rather than only selected dimensions.

5.2. Structural Relations between Dimensions

The Pearson correlations between the seven dimensions of the posttest were all positive and ranged from r = 0.550 to r = 0.774, which are moderate to strong. The 21 pairwise correlations were all significant at the .001 level, suggesting that the dimensions are not independent subskills, but are an integrated whole. The highest correlation was found between Information Literacy and Digital Communication Skills (r = 0.774), and between Information Literacy and Collaborative Technology Use (r = 0.756), suggesting that information work is located in the upstream position of the conceptual model. The complete correlation matrix is shown in Table 4 and the correlation pattern in Fig. 3.

Table 4
Pearson Correlations Among Posttest Composite Scores (N = 80)

IL	IL	DDA	CTU	DCS	PSDT	CDP	TDP
	—	**0.740**	**0.756**	**0.774**	**0.729**	**0.643**	**0.677**
DDA	0.740	—	0.703	0.728	0.705	0.700	0.672
CTU	0.756	0.703	—	0.717	0.632	0.550	0.604
DCS	0.774	0.728	0.717	—	0.701	0.717	0.686
PSDT	0.729	0.705	0.632	0.701	—	0.678	0.627
CDP	0.643	0.700	0.550	0.717	0.678	—	0.711
TDP	0.677	0.672	0.604	0.686	0.627	0.711	—
Note. *All correlations significant at p < .001.*							

5.3. Reliability and Validity Evidence

Cronbach's α coefficient for the questionnaire dimensions ranged from 0.76 (PSDT) to 0.86 (IL), which is acceptable to good based on the conventional criterion of 0.70 for research instruments. The intraclass correlation coefficients of the 20% double coded subsample ranged from ICC = 0.80 to ICC = 0.94, which falls within the good-to-excellent agreement range (Koo & Li, 2016). The internal consistency and inter-rater reliability provide supporting evidence for the psychometric soundness of the measurement strategy in this pilot context. Both reliability measures are shown in Table 5.

Table 5
Reliability Evidence: Cronbach's α and Inter-rater ICC

Dimension	Cronbach's α (questionnaire, 4 items)	ICC (performance, 20% double-coded)
IL	0.86	0.94
DDA	0.78	0.88
CTU	0.84	0.88
DCS	0.80	0.94
PSDT	0.76	0.91
CDP	0.82	0.80
TDP	0.83	0.80
Note. *ICC computed as two-way random effects, absolute agreement, single measures.*		

5.4. Exploratory Path Analysis

Standardized regression coefficients were calculated for all the theoretically connected dimensions in order to test the hypothesized developmental pathway (H1 – H7). The sample size (N = 80) is not large enough to support a complete SEM, but regression-based path analysis does give some preliminary evidence regarding direction and magnitude of the proposed relationships. All seven hypothesized paths were positive, statistically significant ($p < .001$) and substantively large ($\beta = 0.55$ to 0.77). The best path connected Information Literacy to Digital Communication Skills ($\beta = 0.77$), which confirmed the hypothesis that the informational work offers an upstream basis for communicative work. The significant pattern of pathways through all seven hypothesized relationships supports the preliminary structural model proposed in Section 3.3. The path analysis results are presented in Table 6 and the empirical model is shown in Fig. 4.

Table 6
Standardized Path Coefficients for Hypothesized Relationships (N = 80)

Hyp.	Path	β	SE	t	p	Result
H1	IL → DDA	0.74	0.076	9.72	< .001	Supported
H2	IL → DCS	0.77	0.072	10.78	< .001	Supported
H3	DDA → PSDT	0.71	0.080	8.79	< .001	Supported
H4	DCS → CTU	0.72	0.079	9.07	< .001	Supported
H5	PSDT → TDP	0.63	0.088	7.12	< .001	Supported
H6	TDP → CDP	0.71	0.080	8.92	< .001	Supported
H7	CTU → CDP	0.55	0.095	5.81	< .001	Supported

Note. *β = standardized regression coefficient. SE = standard error. Result indicates whether the directional relationship was supported at p < .05.*

5.5. Subgroup Analysis by Prior Digital Experience

Gain scores were compared between three digital experience subgroups (Low, n = 23; Medium, n = 42; High, n = 15) to determine if there were differences in gains for students with different digital backgrounds. In all three subgroups, significant positive gains were obtained on all seven dimensions, indicating that the intervention was widely available and was not just for experienced students. Interestingly, students with low prior experience exhibited gains that were similar to or greater than those of more experienced students, especially in the collaborative dimensions (CTU, DCS); similar to what was observed in initial deficits in these dimensions leave more room for visible growth. Subgroup means of gains are shown in Table 7.

Table 7
Mean Gain Scores by Prior Digital Experience Subgroup

Dim.	Low experience (n = 23)	Medium experience (n = 42)	High experience (n = 15)
IL	+ 13.8 (5.2)	+ 14.97 (6.76)	+ 11.75 (5.57)
DDA	+ 16.52 (5.94)	+ 15.2 (7.32)	+ 16.1 (6.03)
CTU	+ 16.1 (4.49)	+ 14.62 (6.71)	+ 15.65 (8.34)
DCS	+ 13 (5.21)	+ 13.5 (6.71)	+ 11.09 (6.31)
PSDT	+ 13.02 (5.55)	+ 14.05 (5.92)	+ 13.36 (6.98)
CDP	+ 13.49 (6.53)	+ 16.04 (5.93)	+ 18.26 (7.03)
TDP	+ 13.02 (5.27)	+ 16.17 (6.34)	+ 14.11 (7.06)

Note. *Cell entries are mean gain (SD) on 0–100 metric.*

5.6. Qualitative Themes from Reflection Prompts

The Day-20 reflections were analysed thematically, a reflexive approach, which resulted in six themes that complement and build on the quantitative results. The themes are the qualitative texture that gives meaning and interpretation to the patterns identified in the quantitative analysis and give voice to the developmental processes of the participants.

Theme 1: Integrated competence development (68/80 participants). Participants mentioned that they had acquired more than one competence at a time: communication, collaboration, and technical work were mentioned as being interrelated in the context of teamwork using the Git tool.

Theme 2

Information literacy as gateway (54/80 participants). The information search and evaluation of sources in the early phase was described by many as influencing the quality of the later technical decisions, thus reinforcing the upstream aspect of information literacy.

Theme 3

Productive struggle with collaboration (49/80 participants). Participants reported that they had some initial problems with version control and team coordination, but experienced moments of breakthrough when the collaborative norms settled around Days 6–8.

Theme 4

Developing technical self-confidence (61/80 participants). The majority of participants reported that they had become confident in their troubleshooting abilities, moving from relying on others to taking matters

into their own hands, particularly during the testing and debugging process.

Theme 5

Creativity as integrative outcome (43/80 participants). In later phases, creative additions were made to the project artifact; participants generally attributed these additions to "confident technical operation" and "effective team coordination."

Theme 6

Professional relevance (58/80 participants). Participants often connected their project experiences to their anticipated professional careers, framing the collaborative digital environment as a major learning outcome.

Interestingly, Theme 1 (integrated competence development) and Theme 2 (information literacy as gateway) offer qualitative support to the two main quantitative findings: integrated structural pattern in all seven dimensions; and the upstream role of information literacy in the developmental pathway. Themes 3, 4 and 5 emphasize the productive aspect of difficulty in collaborative contexts and the temporal dimension of competence building during project phases.

6. Discussion

6.1. Theoretical Contributions

The study contributes to the theory in three ways. First, it extends the concept of digital professional competence beyond operationalizations based on discrete skills to a seven-dimensional structure with internally specified relationships, with pilot data revealing uniformly strong moderate-to-strong intercorrelations (all $r > 0.55$, $p < .001$) consistent with an integrated as opposed to additive architecture. This responds to the methodological critiques of Pedaste et al. (2023) and González-Mujico (2024). Second, it provides a developmental mechanism (project-based software engineering in collaborative digital environments) to explain how the competence dimensions are co-mobilized, and pilot evidence is provided that demonstrates significant parallel gains in all seven dimensions (all $d > 2.0$). Third, the framework combines the disciplinary depth of TPACK (Mishra & Koehler, 2006) and the structural breadth of the DigCompEdu (Vuorikari et al., 2023) and the developmental architecture of the multilevel competence models (Kiianovska, 2025), and preliminary empirical support for all seven hypothesized pathway relationships.

6.2. Empirical Findings in Context

The pattern of pre-to-post gains reported here (M gains 12.9–15.8 points; $d = 2.07–2.44$) is broadly similar to the pattern of pre-to-post gains reported by Vo Doan Yen Nhi and Le Thai Minh Long (2026) for technology-supported student-centered science learning (M gains 16.7–17.4 points; $d = 1.61–1.71$), although slightly larger in magnitude. The slightly larger effect sizes found in this pilot may be due to the

more intensive (20 days full-time vs. 8 weeks part-time), more disciplinarily focused (software engineering vs. general science), and more developmentally focused (university undergraduates vs. high school students) nature of the present intervention. The intercorrelations among dimensions (r = 0.55–0.77) and the uniformly significant pathway coefficients (β = 0.55–0.77) also align with the seven-dimensional structure reported by Vo Doan Yen Nhi and Le Thai Minh Long in a different disciplinary context, supporting the structure in a new setting.

6.3. Practical Implications

There are three practical implications. The framework recommends that future digital specialists be prepared by organizing curriculum around extended, authentic, collaborative projects, and not separate skill modules. The pilot evidence shows that such intensive integrated experiences can yield significant competence gains in all seven dimensions at once, thus favoring an integrated rather than modular curriculum architecture. The framework suggests that faculty members need to be technically proficient, as well as proficient facilitators, collaborative-environment orchestrators, and multilevel formative assessors when preparing faculty. The framework also supports the transition to multi-source competence portfolios, which include self-report indicators, performance-based tasks, and artifact evidence, measured against rubrics aligned with the seven dimensions and the multilevel trajectory for assessment.

6.4. Connections with Emerging Technologies

The framework also explains the relationship between emerging technologies such as generative artificial intelligence, learning analytics and immersive environments, and digital professional competence development. Even though the use of AI in learning analytics has been shown to have many opportunities for personalization, real-time feedback, and predictive support, as shown by Ruiz Rodríguez et al. (2025) in their systematic review of AI-enhanced learning analytics, it does not replace the competence architecture. Instead, they widen the surface area over which the seven dimensions are practiced: future experts are going to be called upon more and more to assess AI-generated information (IL), interpret outputs of algorithms (DDA), work alongside AI agents (CTU), communicate with and through AI systems (DCS), solve problems that involve human and AI judgment (PSDT), generate with AI tools (CDP), and operate in AI-enhanced environments (TDP).

6.5. Limitations

There are three principal limitations to acknowledge. First, the pilot employed a single-group design without a comparison group, which limits causal inference; the observed improvements could be attributable to the intervention, maturation, repeated testing, or a Hawthorne effect. Second, the sample (N = 80) was drawn from a single institution, limiting generalizability; cultural, institutional, and infrastructural factors may influence the implementation of the framework in other settings. Third, the path analysis was performed with standardized regression rather than full structural equation modeling, and the sample size (N = 80) is below the threshold typically recommended for confirmatory SEM; the results of the path analysis should therefore be considered preliminary rather than confirmatory. Further,

while self-report and performance-based evidence were triangulated, the seven performance tasks were not developed as a fully validated measurement instrument and require further psychometric validation in additional contexts.

7. Conclusions and Future Research

This paper introduced, and provided preliminary empirical validation for, an integrated conceptual framework for developing the digital professional competence of future specialists in the context of project-based software engineering activities in collaborative digital environments. The framework presents a seven-dimensional model of digital professional competence, seven theoretical propositions regarding the structural relationships among the dimensions, project-based software engineering as the central developmental mechanism, and a six-level developmental trajectory ranging from Newcomer to Pioneer. The results of the pilot study with 80 undergraduate computing students provided support for the multidimensional architecture (all pairwise correlations were significant at $p < .001$), the substantive impact of the intervention (all gains were significant after Holm correction and had large effect sizes), and the hypothesized developmental pathway (all seven path coefficients were positive and significant at $p < .001$).

There are three particularly promising directions for future research. First, to advance from preliminary to confirmatory evidence, a full-scale confirmatory study with a larger sample ($N \geq 200$), a matched comparison group, and pre-registered SEM testing of the H1–H7 path model is warranted. Second, cross-institutional and cross-cultural replication studies should explore the generalizability of the framework, especially in non-Western and resource-constrained settings. Third, longitudinal studies should follow competence development beyond the end of the intervention to assess retention, transfer to professional practice, and long-term progression across the six developmental levels. Taken together, these directions can help shift the field from a fragmented evidence base toward a robust, multidimensional, and pedagogically actionable science of digital professional competence development.

Declarations

Author Contribution

I.M. conceptualized the study, developed the seven-dimensional theoretical framework and the hypothesized pathway model (H1–H7), and wrote the main text of the Introduction, Literature Review, and Conceptual Framework sections. X.X. designed and implemented the pilot empirical study, including the intervention protocol and the measurement instruments (DPCQ-28 adaptation and performance rubrics), and conducted all quantitative analyses (paired-sample t-tests, Holm correction, Pearson correlations, and exploratory path analysis). A.A. conducted the qualitative data collection and reflexive thematic analysis, contributed to the Discussion and Conclusions sections, and prepared the tables and figures. All authors reviewed and approved the final version of the manuscript.

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Figures

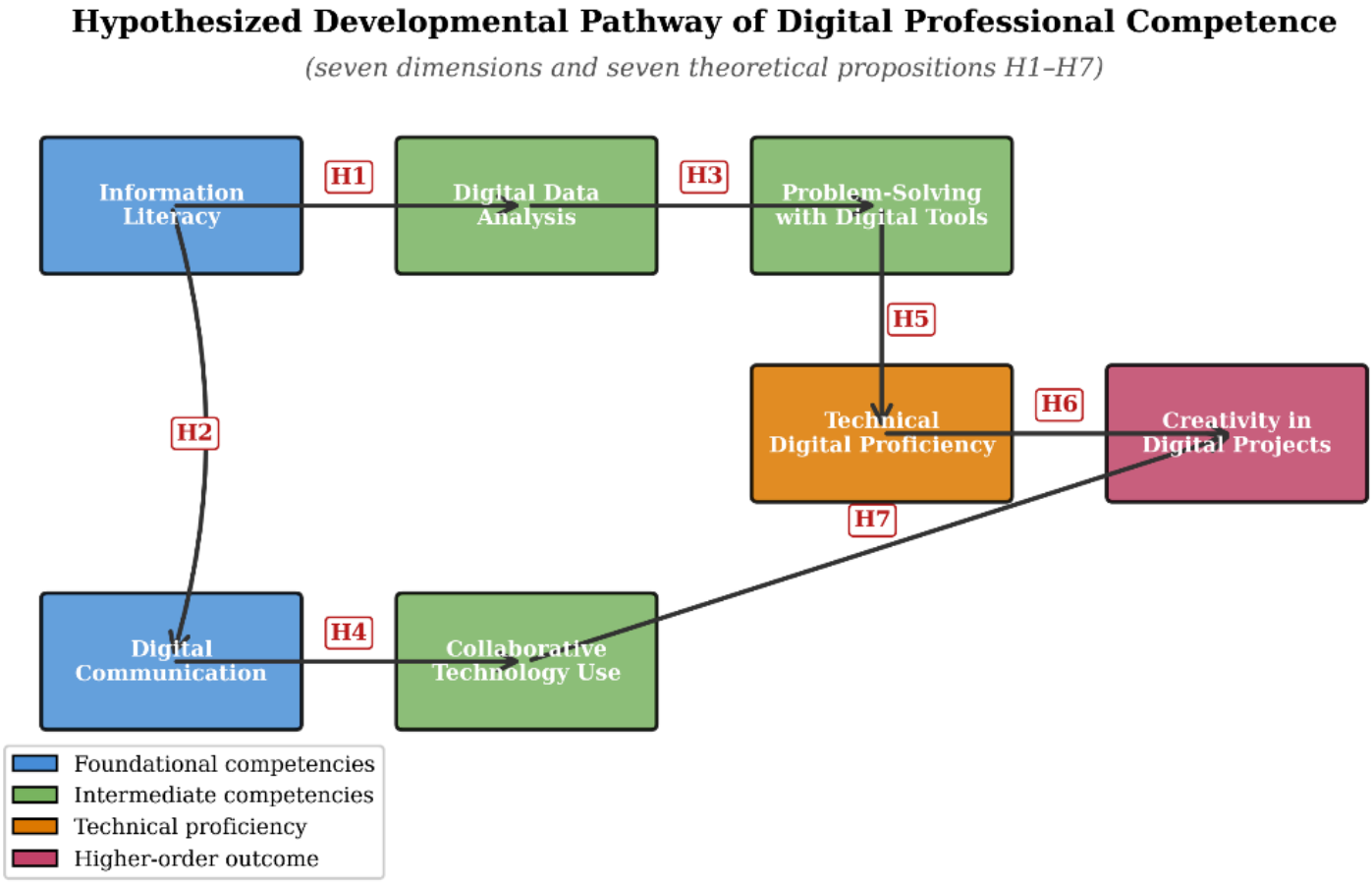
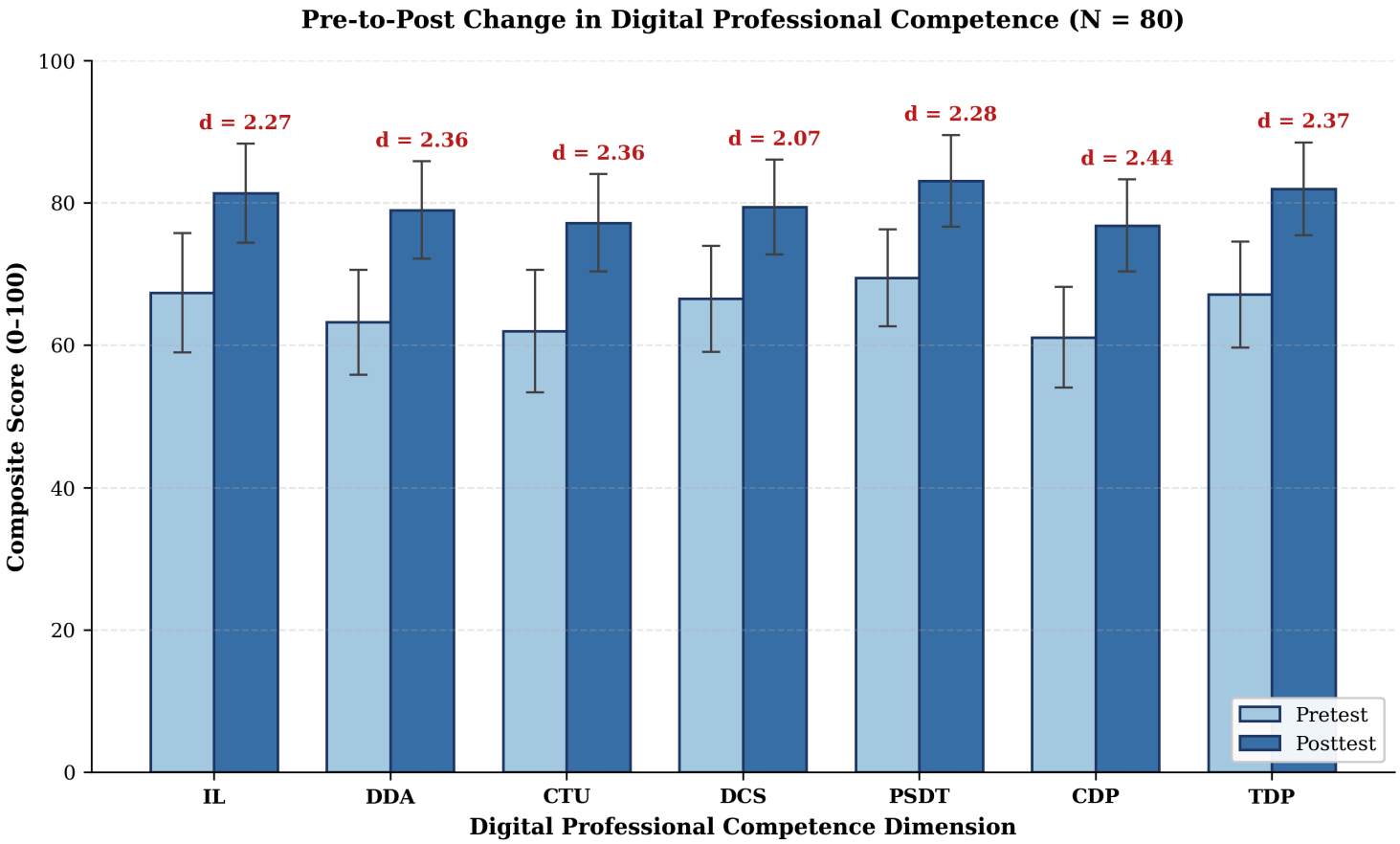


Figure 1

Hypothesized developmental pathway of digital professional competence, showing the seven dimensions and seven theoretical propositions (H1–H7). Foundational competencies (Information Literacy, Digital Communication) are positioned upstream as enablers of intermediate competencies (Digital Data Analysis, Collaborative Technology Use, Problem-Solving with Digital Tools), which in turn support Technical Digital Proficiency and the higher-order outcome of Creativity in Digital Projects.



Note. Error bars represent ±1 SD. All pre–post comparisons significant at p < .001 (Holm-adjusted).

Figure 2

Legend not included with this version.

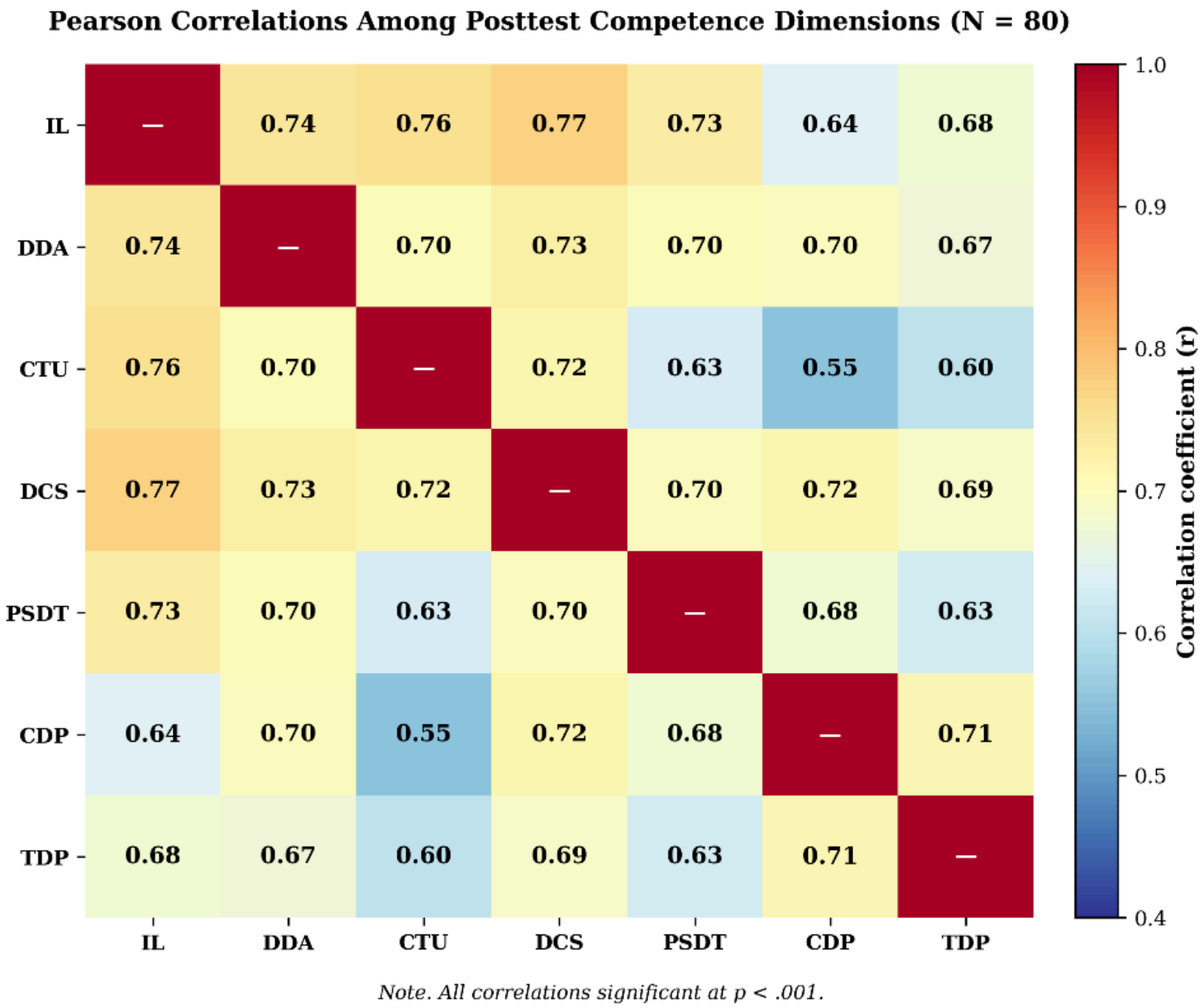


Figure 3

Pearson correlations among the seven posttest competence dimensions (N = 80) shown as a heatmap. Warmer colors represent stronger positive correlations. All pairwise correlations significant at p < .001. The figure visualizes the integrated structural pattern: dimensions co-vary moderately to strongly without redundancy, supporting the multidimensional and internally organized view of digital professional competence.

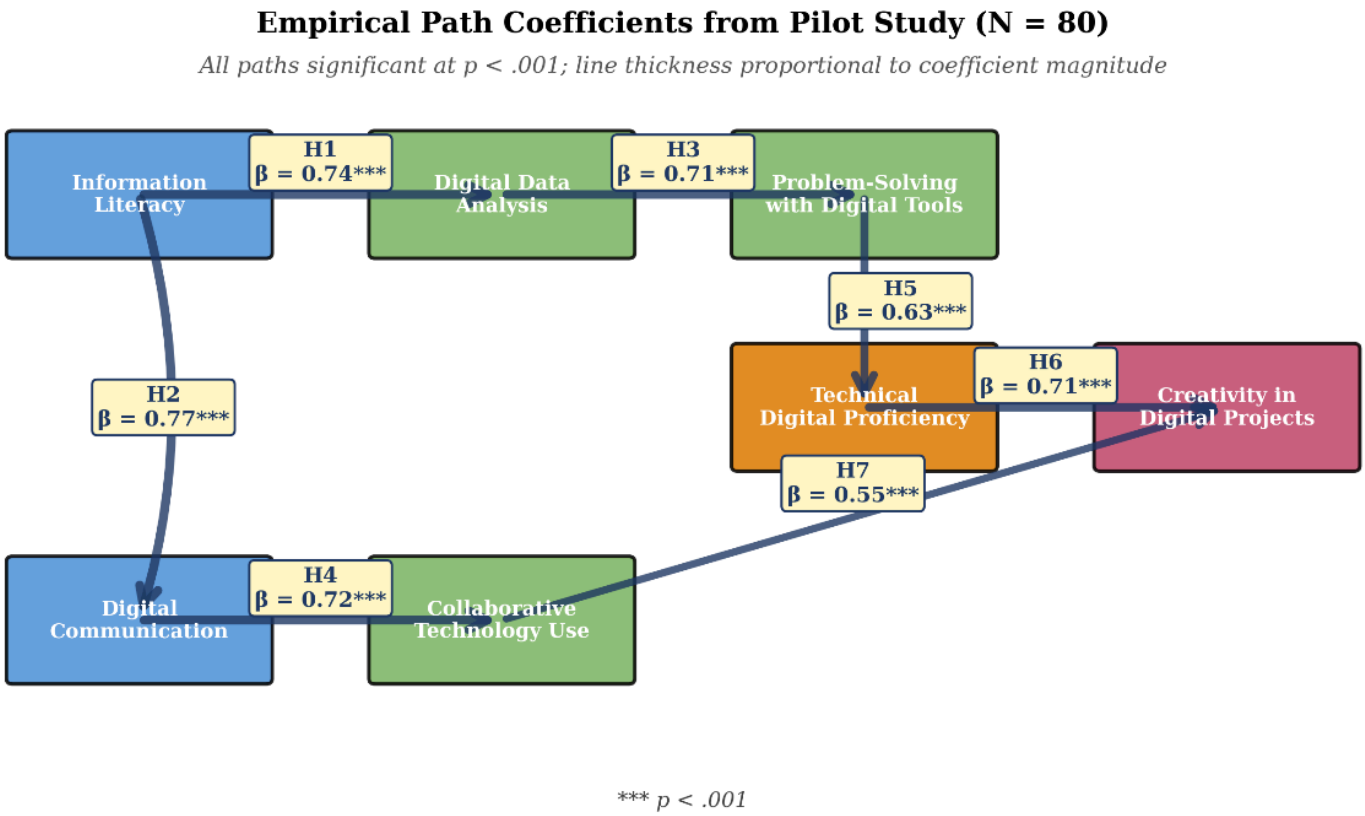


Figure 4

Empirical path coefficients from the pilot study (N = 80) overlaid on the hypothesized structural model. All seven paths (H1–H7) are statistically significant at p < .001. Line thickness is proportional to coefficient magnitude. The strongest pathway links Information Literacy → Digital Communication (β = 0.77), and the weakest of the supported pathways links Collaborative Technology Use → Creativity in Digital Projects (β = 0.55).