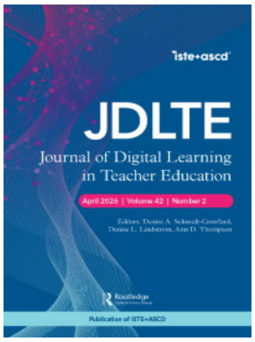

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Moving beyond tools: Experiential learning, reflection, and TPACK in a 3D modeling and printing course

Mathias Tejera[a,b], Viviana Aharonian[a], Cecilia Russo[b] and Zsolt Lavicza[a]

[a]Linz School of Education, Johannes Kepler University Linz, Austria; [b]Departamento de Innovación y Emprendimientos, Universidad Tecnológica, Uruguay

ABSTRACT

In this mixed-methods study, we use preservice teachers' reflections as windows into their learning to teach with technology. Thirty-seven reflective essays, from a 3D Modeling and Printing course for preservice mathematics teachers, were coded for TPACK dimensions and reflective depth. Patterns show that technological and pedagogical references were frequent, while content was less common and tended to appear in combination with other dimensions. Deeper reflection is aligned with stronger TPACK, particularly in relation to concrete lesson plans. The study offers concise design guidance—prioritize content goals, structure PCK-oriented reflection, and require lesson-level enactment—to advance integrated, curriculum-relevant uses of technology.

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Experiential learning; TPACK; reflection; 3DMP; teacher education

Introduction

A persistent challenge in teacher education is supporting preservice teachers (PSTs) in moving from learning a digital tool to teaching with it in pedagogically meaningful, discipline-connected ways. This study contributes to the broader conversation on technology in education by illustrating how a theory-informed, design-based intervention can support that kind of integration through iterative course design (Buss et al., 2018; Wan & Ivy, 2021).

3D modeling and printing (3DMP) offers a particularly revealing context for this challenge. As programs respond to calls for technology-rich learning environments, 3DMP has been introduced in teacher education—often within mathematics or STEAM modules—because it can make ideas tangible and enable creative production (Rodriguez et al., 2018; Wan & Ivy, 2021). These initiatives frequently generate high engagement and support PSTs in developing new technical capabilities.

At the same time, research suggests that 3DMP coursework can drift toward tool proficiency and production workflows while giving comparatively less attention to pedagogy and content integration (Song, 2018; Tejera et al., 2026). This concern aligns with evidence that PSTs may initially hold limited notions of maker education, which can constrain pedagogical potential unless explicitly reframed through coursework (Cohen et al., 2018). From a TPACK perspective, effective integration requires coordinated development across technological, pedagogical, and content knowledge, rather than growth in technology knowledge alone (Mishra & Koehler, 2006). Intentionally designed programs can strengthen PSTs' TPACK by positioning technology use in relation to lesson design, student thinking, and disciplinary goals (Buss et al., 2018).

CONTACT Mathias Tejera mathias.tejera@jku.at, mathias.tejera@utec.edu.uy Linz School of Education, Johannes Kepler University Linz, Altenberger Straße 69, Linz 4040. Austria.

Prior studies highlight both the promise and the persistent challenges of embedding 3DMP into teacher education. On the promise side, 3DMP can make abstract mathematical concepts tangible and foster creativity and problem-solving (Chien & Chu, 2018; Turgut & Uygan, 2015), and hands-on activities have been associated with engagement, spatial reasoning, and confidence with technology (e.g., Ng et al., 2022; Song, 2018; Ulbrich et al., 2024). On the challenge side, integration is often constrained by limited access to hardware and materials, steep learning curves within tight program schedules, and difficulties aligning projects with curriculum standards and assessment practices (Song, 2021; Tejera et al., 2026). These conditions underscore the need for deliberately designed courses that provide scaffolding and connect 3DMP work to pedagogically sound, curriculum-relevant uses. In line with this view, reports recommend progressions from learning the machine toward student-generated models aligned with disciplinary goals (Wan & Ivy, 2021), and structures that sustain PST engagement with digital fabrication over time (Rodriguez et al., 2018).

To address these needs, our team engaged in an Educational Design Research (EDR) process to develop and refine a 3DMP course for preservice mathematics teachers. The course design was informed by evidence from a systematic review of 3DMP in teacher education (Tejera et al., 2026) and by lessons learned in three prior pilot iterations. Grounded in the TPACK framework (Mishra & Koehler, 2006) and an adapted version of the experiential learning cycle (Kolb, 2015), the course aimed to rebalance the technical, pedagogical, and content dimensions of integrating 3DMP. We aligned key learning activities with an adapted cycle of concrete experience, reflective observation, conceptualization, and pedagogical experimentation to ensure that hands-on 3DMP tasks were coupled with reflection and application to mathematics teaching contexts. In line with program models that have enhanced participants' TPACK (Buss et al., 2018), our design sequenced experiences so that PSTs progressed from tool proficiency toward lesson-level integration. The course also addressed common barriers by providing technical support and curricular guidance to balance limited teacher readiness and curriculum misalignment (Song, 2021; Tejera et al., 2026). Situated within an EDR framework (Bakker, 2018), each iteration was treated as a cycle of analysis, (re)design, implementation, and evaluation intended to refine a sustainable model for technology-rich teacher education. Reflection was leveraged as part of that cycle, consistent with evidence that structured reflection shapes what teachers learn from experience and how it informs action (Petko et al., 2017).

In this study, we position PST narratives as windows into enactment by analyzing 37 post-course reflections in which PSTs recounted experiences, challenges, and takeaways. These reflections were elicited through guiding prompts aligned with course objectives and analytic frameworks (described in the Methods), supporting participants in reflecting on both tool use and pedagogical application. We mapped participants' reflections to the course's intended objectives and design principles to examine coherence between design intentions and outcomes as perceived by the students, focusing on the extent to which technological, pedagogical, and content learning was realized in practice and on gaps or unanticipated outcomes. Findings indicate growth in integrated knowledge alongside areas for improvement, including stronger curriculum alignment and additional technical scaffolding. Beyond mathematics and 3DMP, the design logic and analysis speak to other content-specific technologies where teacher education must counterbalance "tool-first" momentum by making content-linked learning goals and pedagogical uses explicit.

Theoretical framework

Our course design drew on two complementary frameworks: TPACK to define what PSTs should learn (the coordinated development of technological, pedagogical, and content knowledge), and Kolb's Experiential Learning Cycle to structure how they would learn it (iterative cycles of experience and reflection). A third lens, Kember's four levels of reflection, provided an analytic scheme for visualizing the depth of PSTs' written reflections. Below, we outline each framework and specify how it informed the design, implementation, and analysis.

Technological pedagogical content knowledge (TPACK)

TPACK conceptualizes the knowledge teachers need to integrate technology into instruction (Mishra & Koehler, 2006). Building on Shulman's Pedagogical Content Knowledge, TPACK distinguishes core domains—Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK)—and the intersections among them (PCK, TCK, TPK), culminating in fully integrated TPACK. In a 3DMP context, TK refers to operating printers, using modeling software, and managing digital-fabrication workflows; PK involves designing and enacting effective pedagogies for technology-rich lessons (e.g., project-based work, inquiry tasks); and CK concerns anchoring activities in subject matter concepts (e.g., solids, transformations, measurement). Meaningful integration occurs in the overlaps: TCK when 3D models function as epistemic tools; TPK when teachers orchestrate time, resources, and classroom routines around fabrication; and PCK when task design anticipates student thinking and aligns pedagogical goals with representations and scaffolds. The goal is actionable TPACK—lessons where CK, PK, and TK work in concert to advance learning (Mishra & Koehler, 2006; Tejera et al., 2026; Wan & Ivy, 2021).

Prior work cautions that digital-fabrication courses can overemphasize technical operation at the expense of pedagogy and mathematics (Buss et al., 2018; Song, 2018; Tejera et al., 2026). We therefore targeted all TPACK components simultaneously and embedded 3DMP within mathematics didactics from the outset, avoiding technology-in-isolation. To maintain the design's visibility to PSTs and coherence across activities, we specified a hierarchical set of objectives aligned with the framework (Figure 1). The base level comprised three foundations: (1) anchor every activity in explicit mathematical content (CK); (2) expand a repertoire of instructional strategies and lesson structures (PK); and (3) develop technical proficiency and confidence with 3DMP tools (TK). Intermediate goals mapped to pairwise intersections: anticipate student thinking and align tasks to goals (PCK), leverage technology as an epistemic tool to deepen mathematical ideas (TCK), and manage technology-enhanced workflows (TPK). A capstone objective at the top required PSTs to plan and justify integrated, goal-oriented lessons that balanced mathematical aims, pedagogical strategies, and technological affordances (TPACK). Concrete exemplars of such progressions in mathematics-focused teacher education (e.g.,

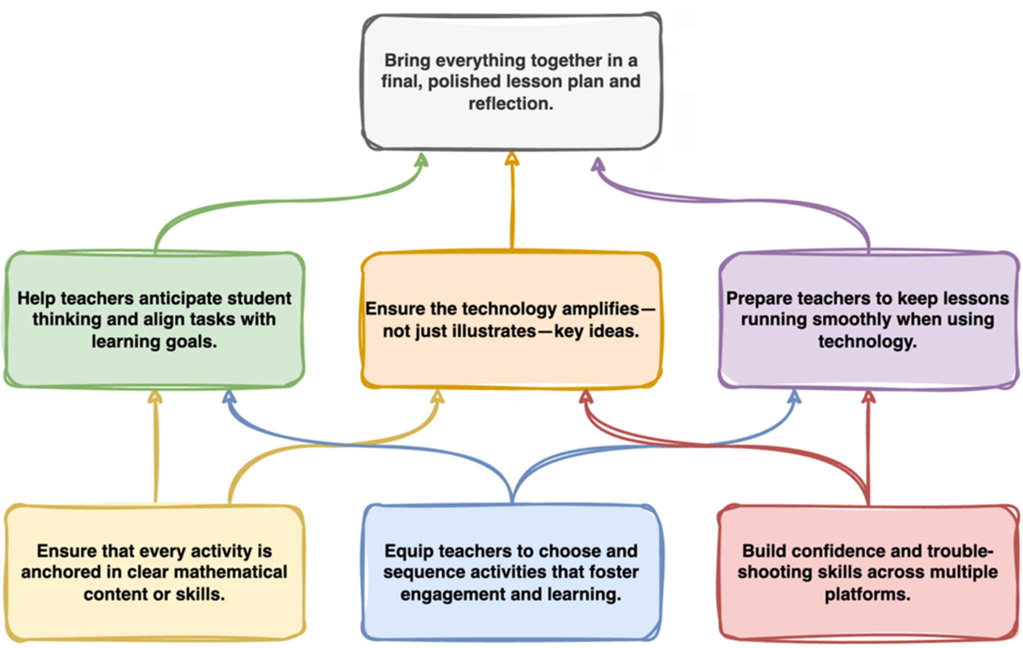

Figure 1. Progression of multi-level course objectives based on TPACK dimensions.

Jablonski, 2023; Nolla et al., 2024; Wan & Ivy, 2021) served as design anchors for tasks and modeling prompts.

This TPACK-aligned structure served dual purposes: it guided course construction and provided the analytical lens for coding PSTs' reflections. By connecting every unit of analysis to named components, we could later examine whether and how the intended integrations appeared in PSTs' written accounts.

Adapted Kolb's experiential learning cycle

Kolb's cycle conceptualizes learning as an iterative movement through Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation (Kolb, 2015). It aligns with teacher education because it mirrors how teachers learn through practice: doing, reflecting, theorizing, and re-trying. It also aligns with calls for active, authentic technology learning (Ng et al., 2022). We used Kolb's learning cycle to sequence the pathway from tool proficiency to integrated lesson design and to position reflection where it would best consolidate learning (Buss et al., 2018; Petko et al., 2017).

We adapted two elements for our context. First, we relabeled the fourth phase as Pedagogical Experimentation to emphasize that PSTs apply learning by designing, critiquing, and revising lesson ideas, rather than merely using the technology. Second, we placed short, structured reflection prompts after hands-on work and at the lesson-design stage to help PSTs articulate mathematical goals, pedagogical ideas, and the epistemic role of technology—following evidence that the structure and focus of reflection influence outcomes (Petko et al., 2017). Each 3DMP module then enacted a mini-cycle: mathematically rich 3DMP tasks (Concrete Experience) → individual and collaborative debriefs (Reflective Observation) → targeted theory and research integration (Abstract Conceptualization) → design or refinement of a teachable artifact (Pedagogical Experimentation). This design scaffolded practical skills and theory-informed understanding in tandem and repeatedly pressed toward integration rather than isolated knowledge (Figure 2).

Furthermore, the Kolb structure was aligned to the TPACK objectives. Early concrete work cultivated CK, PK, and TK; reflection and conceptualization supported the development of PCK, TCK, and TPK; and pedagogical experimentation targeted the capstone TPACK outcome (integrated lesson planning). This alignment kept learning experiential and conceptually grounded, creating moments in which reflection could mediate movement from "using a tool" toward "teaching with a tool for mathematical ends."

Kember's four-levels of reflection

To analyze the reflective depth in PSTs' writing, we used Kember's four-level scheme, which distinguishes between habitual action (non-reflection), understanding, reflection, and critical reflection (Kember et al., 2008). This scheme builds on the Reflective Thinking Questionnaire (Kember et al., 2000). The framework is widely used in teacher education to examine reflective journals and course essays because it aligns with the intention to develop reflective practitioners (Özüdoğru, 2021) and resonates with the view of reflection as a professional disposition that links theory and practice (Petko et al., 2017; Schön, 1983).

In our study, Kember's model served two purposes. First, it supplied a consistent scale for coding reflective depth across texts, enabling comparisons with the TPACK-aligned codes without privileging one domain. Second, it provided a theoretical warrant for treating reflection as more than narration: as a process through which PSTs test assumptions, connect concrete 3DMP experiences to pedagogical and mathematical reasoning, and, at the highest levels, reconsider their understanding of what constitutes effective technology integration in mathematics teaching. Coding each paragraph by Kember's levels allowed us to differentiate between description of

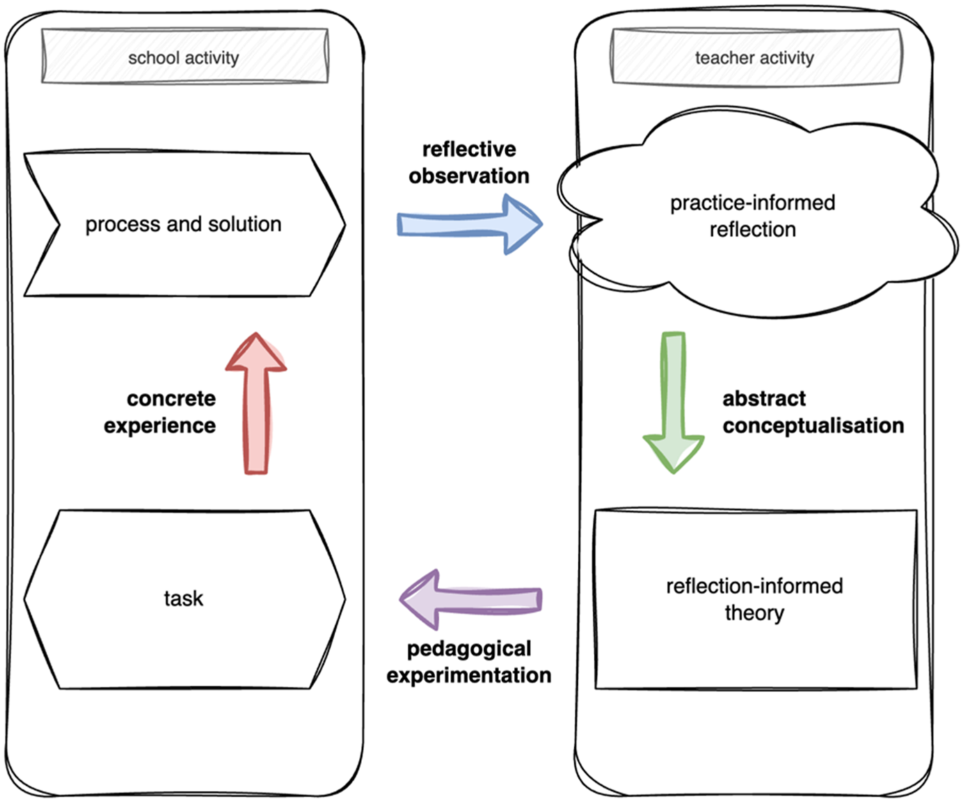

Figure 2. Experiential learning model adapted for 3DMP integration in teacher education.

activity, conceptual uptake, pedagogically connected reasoning, and transformative stance-taking about technology-rich instruction.

Taken together, the three frameworks play distinct but coordinated roles. TPACK specifies the targets of knowledge integration; Kolb structures the process by which PSTs encounter, reflect on, and apply those targets; and Kember provides the metric for how deeply PSTs reason about their experiences. Designing with TPACK and Kolb made integration explicit and recurrent throughout the course; analyzing with TPACK-aligned principles and Kember allowed us to examine how those design intentions were reflected in PSTs' narratives. This integrated theoretical frame underpins the methods and findings that follow.

Materials and methods

Research questions

Guided by the theoretical framework presented above, we explore PSTs' experiences through their reflections in our 3DMP course, answering two primary research questions:

1. What characterizes the depth and focus of preservice mathematics teachers' reflections on a TPACK-informed, experiential 3D Modeling and Printing course?
2. In what ways do preservice teachers describe their understanding of integrating technology, pedagogy, and content in mathematics teaching?

We pose these questions in light of a consistent finding in the literature: teacher education should intentionally coordinate technology, pedagogy, and content rather than privileging tool proficiency in isolation (Chien & Chu, 2018; Mishra & Koehler, 2006; Ng et al., 2022; Song, 2021; Tejera et al., 2026). Prior work also demonstrates that structured designs and reflection tasks are essential for developing TPACK, particularly in the form of sequenced experiences that transition PSTs from technical operation to lesson-level integration (Buss et al., 2018) and reflective prompts that shape the learning derived from these experiences (Petko et al., 2017). Prior reports similarly underline the need for contextually meaningful, curriculum-aligned enactments of technology (Harris & Hofer, 2017). By examining PSTs' narratives as windows into enactment, we connect design intent to perceived outcomes, tracing where integrated TPACK consolidates and where it requires further support.

Context and participants

We conducted the study in an elective 3DMP course for preservice mathematics teachers at a public university in Austria, during the winter semester of 2024–2025. The course ran in three parallel groups. Of the 40 enrolled preservice teachers (PSTs), 37 voluntarily submitted individual reflections, which constitute the dataset. Participants were 21–28 years old and at varied points in their preparation, from the seventh semester of the bachelor's program to the third semester of the master's program. This heterogeneity was intentional to capture how learners at different stages engaged with the course design. The course itself emerged from an educational design research process, informed by a recent systematic review (Tejera et al., 2026) and insights from multiple prior iterations.

Data collection

Data were collected exclusively through post-course, individual reflection papers (500–1000 words) written in response to a common prompt. The prompt asked PSTs to (a) identify key learnings from the course (technical, pedagogical, and/or personal), (b) explain their relevance for future mathematics teaching, and (c) describe specific course moments or activities that shaped their learning and their understanding of integrating technology, pedagogy, and content. Reflective writing was chosen to reveal nuanced beliefs and experience-near insights characteristic of teacher education contexts (Harris & Hofer, 2017; Özüdoğru, 2021; Schön, 1983), and to make visible how participants connected hands-on 3DMP experiences to pedagogical application and curriculum-relevant goals. The prompt was designed to align with the course objectives and analytic frameworks (TPACK and the adapted experiential learning cycle), and refined across three prior pilot iterations. To establish face validity, the author team reviewed the prompt for clarity and construct alignment and iteratively refined it based on feedback and observed misunderstandings in earlier implementations. All reflections were anonymized, participation was voluntary, and informed consent was obtained before data collection.

Data analysis

Data and unit of analysis

The dataset consisted of 37 individual reflection papers written by preservice mathematics teachers at the end of the course. Each reflection consisted of several paragraphs that described participants' experiences and learning. The paragraph served as the unit of analysis. A pilot sub-paragraph segmentation did not improve precision; we retained paragraphs.

Coding framework and scales

The codebook was derived from the course objectives and mapped a priori to TPACK domains/intersections to keep analysis aligned with intended learning. Each paragraph was coded on a

0–3 scale for the seven dimensions and on a 0–3 reflection scale (Kember's four levels); higher values indicate deeper presence or reflection. After calibrating on three reflections, we formalized three rules: (1) when TPACK is coded, additional dimensions are added only if one domain is clearly predominant; (2) CK is reserved for mathematical content (non-mathematical content noted but not scored); and (3) coding is performed strictly at the paragraph level.

Coding procedure

Two coders applied and refined the shared codebook in stages. First, they jointly calibrated on three reflections to align interpretations and finalize rules. In Round 1, both independently coded nine reflections (ICR computed on eight due to a segmentation error). A calibration meeting then refined anchors and boundary examples. In Round 2, five additional reflections were independently coded to verify improved reliability. After the thresholds were met, coders divided the remaining texts with periodic overlap (every 7th reflection) to monitor drift. Discrepancies were resolved immediately, with a third reviewer as needed. Table 1 summarizes the workflow.

Intercoder reliability

Reliability was assessed at the unit level using percent agreement and Cohen's κ. Acceptable thresholds were defined a priori as ≥ 80% agreement and κ ≥ .70, consistent with conventional benchmarks for substantial agreement (Landis & Koch, 1977).

The first independent round yielded diagnostic results, with agreement ranging from 75% to 98% across dimensions, and weighted κ values between 0.46 (TCK) and 0.89 (CK). After calibration, in Round 2, we achieved stable reliability, exceeding the thresholds (mean agreement = .86; mean weighted κ = .74).

During the central phase, every seven reflections were double-coded to monitor coder drift; all drift checks maintained κ ≥ .70. Any discrepancies were discussed and resolved through consensus before producing the final coded dataset.

Illustrative examples

To enhance transparency in how codes were applied, Table 2 presents representative excerpts illustrating the range of evidence used to determine coding levels across dimensions. Each example corresponds to a particular intensity level (0–3) and is paired with its operational definition from the objective-aligned, TPACK-mapped codebook. These excerpts serve as interpretive anchors, clarifying how evaluative judgments were made when identifying evidence. Including concrete cases follows mixed-methods content analysis guidance (e.g., Fereday & Muir-Cochrane, 2006) and strengthens rigor by illustrating how abstract categories were applied to authentic PST reflections.

Including these interpretive anchors also contributed to coder calibration, as the shared reference points were used during reliability discussions to verify boundary judgments and prevent conceptual drift over time.

Table 1. Calibration and reliability workflow.

Stage	Reflections (N)	Modality	Purpose	Outcome
Joint calibration	3	Together	Align interpretations and formalize rules	Rules finalized
Independent Round 1	8	Independent	Diagnostic reliability check	Refinement targets identified
Calibration meeting	—	Discussion	Review disagreements and clarify examples	Anchors refined
Independent Round 2	5	Independent	Verify improved reliability	Thresholds reached
Central phase	21	Split + overlap + discussion	Monitor drift to sustain reliability	Consensus dataset

Table 2. Operational definitions and example excerpts.

Dimension	Operational definition	Level (0–3)	Example excerpt
CK (Content Knowledge)	Explicit mathematical ideas or skills anchoring the activity	0	"The course on 3D printing was an enriching experience that provided me with a deeper understanding of this technology and its applications in the field of education."
		2	"It demonstrated its potential to enhance students' spatial reasoning and …"
PK (Pedagogical Knowledge)	Instructional strategies, lesson structures, pedagogical reasoning	1	"the supportive approach created a comfortable atmosphere that made it easier for me to engage with the content."
		3	"And that's exactly what I want to pass on to my students: the courage to try, the patience to persist, and the joy of creating something meaningful."
TK (Technological Knowledge)	Hands-on competence and confidence with 3D modeling or printing tools	1	"At first the slicer software was confusing."
		3	"Gaining a deeper understanding of the technical tools involved allow me to create more complex and refined designs."
PCK	Anticipating student thinking; aligning tasks to learning goals	2	"I think that math teachers should know about a lot of different ways to explain one and the same topic, as it is our job to discover und display the various ways to learn different topics, to enable every student to truly understand the mathematical contents which they have to learn."
TCK	Using technology as a cognitive tool to deepen mathematical ideas	3	"This technology enables to bridge abstract concepts and tangible outcomes. For instance, they can calculate dimensions, areas, or volumes, and then bring their calculations to life through 3D models."
TPK	Managing technology-enhanced workflows, time, and collaboration	2	"To avoid finishing all models outside class time, it is crucial to know how to adjust the printing time appropriately."
TPACK	Coherent integration of CK, PK, and TK in lesson design	3	"other thing I found valuable was learning how to integrate 3D-printed objects into a lesson plan. It's not just about printing something interesting – it's about using it in a way that supports learning."
Reflection (Kember-based)	Depth of reflection from habitual (0) to critical (3)	0	"Completing the course was a very enriching and exciting experience for me."
		1	"I realized how the old knowledge came back, and I was able to work independently the next time. Nevertheless, we continued to work as a team and benefited from our shared knowledge."
		3	"Reflecting on this course shows me how much I have learned not only technically, but also didactically. The course made me realize how important it is to be open to new technologies and methods, even if they seem complicated or challenging at first."

Note. The complete set is provided in the supplementary materials.

Analytical approach

We first produced descriptive summaries (means, medians, distributions) to characterize the prevalence and depth of each dimension. Treating the scales as numeric for description is standard practice for bounded ordinal ratings, providing an interpretable profile of emphasis across codes.

To examine how integration relates to reflection, we cross-tabulated TPACK by Reflection and reported column proportions (distribution of TPACK within each reflection level). Column normalization makes patterns comparable independent of marginal base rates, which is essential given the observed sparsity in some levels. We complemented this with Spearman rank correlations (ρ) between Reflection and each dimension, as rank-based measures are appropriate for ordinal variables and are robust to non-normality (Agresti, 2013).

To characterize co-occurrence among dimensions, we reduced each code to binary presence (>0). We computed two complementary indices for every pair: the Jaccard index to quantify overlap under sparsity, and the phi coefficient (φ) from 2×2 tables to capture association controlling for marginal prevalence (Agresti, 2013). Reporting both avoids misinterpretation when pairs have high overlap but modest φ (common codes) or low overlap but sizable φ (selective co-presence).

Finally, we generated a participant-level view by averaging paragraph scores within each reflection (per participant). We visualized the mean reflection versus the mean TPACK, using Spearman's ρ as a descriptive robustness check of the unit-level pattern after aggregation.

Ethical considerations

Participation in the study was voluntary, and all participants provided informed consent, with their data anonymized. Methodological rigor was ensured through dual, independent coding, iterative calibration, periodic drift checks, and documented operational rules and examples. All data is openly available in OSF.

Results

Guided by the course's TPACK-aligned objectives, the findings examine how PSTs described and reflected on learning in our 3DMP course. Using paragraphs as the unit of analysis, we coded 231 paragraphs from 37 reflections on 0–3 scales for the seven objective-aligned dimensions and the reflection scale (Kember et al., 2008). The quantitative pattern mirrors the design yet exposes imbalances: technological and pedagogical emphases (TK, PK, TPK) dominate, whereas content-linked categories (CK, PCK, TCK) are less frequent and usually co-occur rather than stand alone. Higher reflective depth aligns with more integrated references to TPACK, with the richest integrations clustering around concrete lesson-planning passages. We illustrate each tendency with purposefully selected quotations. Summary statistics appear in Table 3; the TPACK–Reflection relation is shown in Figure 3; and dimension co-occurrences in Table 4. A brief participant-level view concludes the section, confirming corpus-level trends, highlighting individual heterogeneity, and identifying opportunities to enhance content-focused reasoning and sustained integration.

Technological and pedagogical emphases dominate; content-linked codes are comparatively sparse. Dimension means were highest for TK and PK, followed by TPK and TPACK; content-linked codes were less frequent (Table 3).

The following passage illustrates the TK/PK prominence: concrete tool knowledge and teaching intent are foregrounded. At the same time, explicit mathematical content is limited, consistent with the much lower CK/PCK/TCK means.

> I am so happy that I enrolled to this course as I gained several insights on how to utilize 3D printers for my mathematics lessons or STEAM lessons. In terms of technical skills, I learned some new things such as that there are different types of supports, I can select when I want to print my object. Usually, I just selected

with or without support when printing. Moreover, I also learned that certain filaments could be used to make the object glow in the dark. I have more understanding on the limitations of the tools such as Tinkercad and GeoGebra to create 3D objects. From a collogue, he introduced me another tool "shapr3D" that can be used easily to construct 3D object.

Reflection concentrates at levels 1–2; higher reflection coincides with higher TPACK. Reflection counts were 0 ($n = 13$), 1 ($n = 59$), 2 ($n = 149$), 3 ($n = 10$), with a mean of 1.675 ($N = 231$). Figure 3 shows a graded pattern: at Reflection = 0–1, TPACK = 0 dominates; at Reflection = 2–3, TPACK = 2–3 becomes common. A unit-level Spearman test confirmed a positive association ($\rho = .323$, $p < .0001$, $N = 231$).

The following excerpt exemplifies a paragraph scoring higher on Reflection while simultaneously articulating integrated references to TPACK, mirroring the top right cells in Figure 3.

These skills are significant for my future teaching because they equip me with tools to make learning more interactive and lasting. Mathematics can often feel too abstract and disconnected from reality, especially for students who struggle to see its relevance in their everyday life. Although we learn about that, I really hate to force myself to come up with reasons for students why they have to learn something, that really won't have a big relevance in their future. Incorporating 3D printing into lessons offers a way to bridge this gap.

Table 3. Means by dimension.

Dimension	Mean
TK	0.693
PK	0.576
TPK	0.563
TPACK	0.485
TCK	0.190
PCK	0.061
CK	0.035
Reflection	1.675

Note. Reflection is rescaled to 0–3. All other rows are objective-aligned TPACK dimensions on the same 0–3 scale.

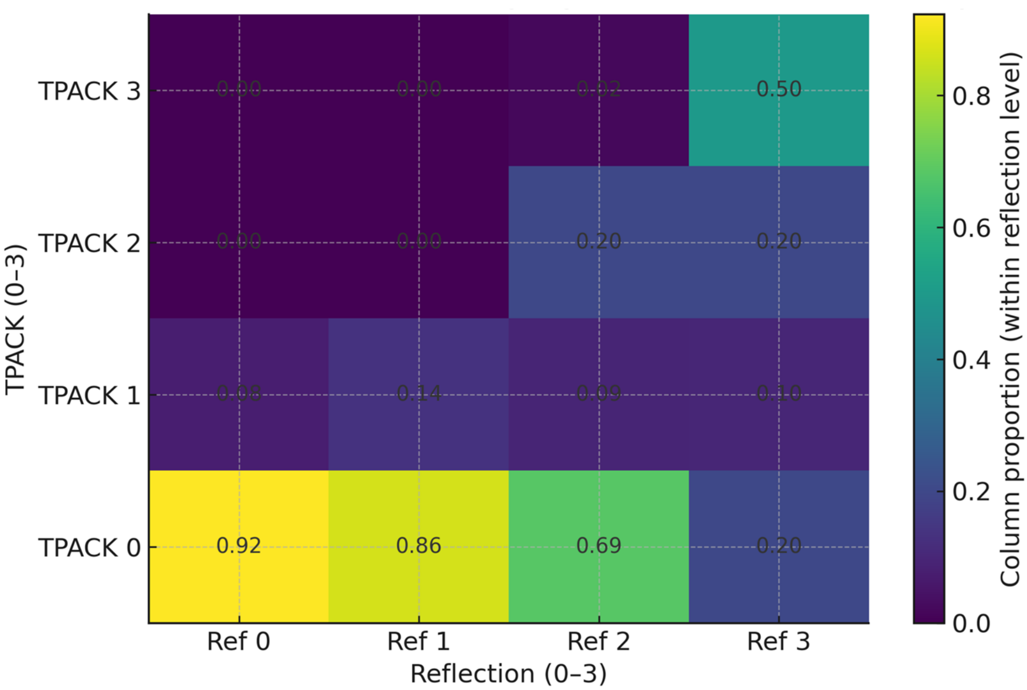

Figure 3. TPACK × reflection heatmap.

Table 4. Co-Occurrence among dimensions (illustrative pairs covering most prevalent dimensions for φ and jaccard).

Pair	Phi (φ)	Jaccard
TK—TPK	**0.240**	**0.380**
PK—TPK	0.046	0.266
CK—PCK	**0.460**	**0.300**
CK—TCK	**0.303**	0.133

Notes. Values are computed on presence (>0) per unit. Jaccard captures the overlap of co-present paragraphs (0–1), while φ reflects association controlling for marginal prevalence (−1 to +1).

For instance, creating hands-on projects where students design and print models could help them better understand and appreciate concepts like volume, symmetry, or transformations.

As shown in Table 2, when content appears, it tends to co-occur with pedagogical or technological reasoning; classroom workflow co-occurs with technology. Presence-based co-occurrence shows dense overlap for TPK–TK (Jaccard = 0.380), with moderate overlaps for PK—TPK (0.266) and PK—TK (0.257). By association (phi), the strongest pairs were CK—PCK (φ = .460), CK—TCK (φ = .303), and TPK—TK (φ = .240). In other words, content statements typically surface in tandem with pedagogical reasoning about students or with technology-supported conceptualization, while classroom organization frequently correlates with technical practice.

The following passage illustrates TCK (technology as a vehicle for working with mathematical representations), showing the CK—TCK association.

> One specific activity that stood out was a task where we had to create a scaled model of the building. This involved taking measurement of the building, scaling it down, and designing the model in GeoGebra. Once the virtual model was complete, we prepared it for printing using PrusaSlicer and then the final 3D version got printed out for us.

Here, content-related ideas arise within technological and pedagogical frames—consistent with CK appearing alongside PCK—TCK rather than standing alone (Table 2).

> When we started the project work, I was inspired by the ideas of others and saw that 3D printing could be implemented in maths lessons in many ways. I thought that the possibilities had already been exhausted in the beginners' course and hardly saw any options for new ideas. But then I realised again how stuck you are in your own knowledge and creativity. In my eyes, 3D printing was more for visualising geometric and trigonometric relationships. It was a tool that I could use to make the subject matter accessible. But I couldn't imagine using 3D printing in other mathematical subject areas. Fortunately, the course and my colleagues were able to convince me otherwise. They presented some ideas in other areas that I really liked.

The following excerpt illustrates the frequent TPK—TK pairing (classroom organization with technical practice), as indicated by the most substantial overlap.

> This course didn't just equip me with technical and pedagogical skills; it also reminded me how fulfilling it can be to step out of my comfort zone, to experiment, and to grow through hands-on experiences. And that's exactly what I want to pass on to my students: the courage to try, the patience to persist, and the joy of creating something meaningful.

Integrated TPACK appears less frequently; when present, it tends to refer to lesson planning. Although TPACK is not the dominant domain overall (Table 3), when present, it often centers on coherent planning:

> One of my favorite parts of the course was the project. We had to design and print an object that could be used in a math lesson. My team made a tool for teaching combinatorics to younger students and created a full lesson plan for it. This project gave me the chance to think deeply about how to combine hands-on activities with theoretical learning… It's not just about printing something interesting – it's about using it in a way that supports learning.

Descriptive, low-integration segments remain common, echoing the lower-left region of the TPACK × Reflection heatmap.

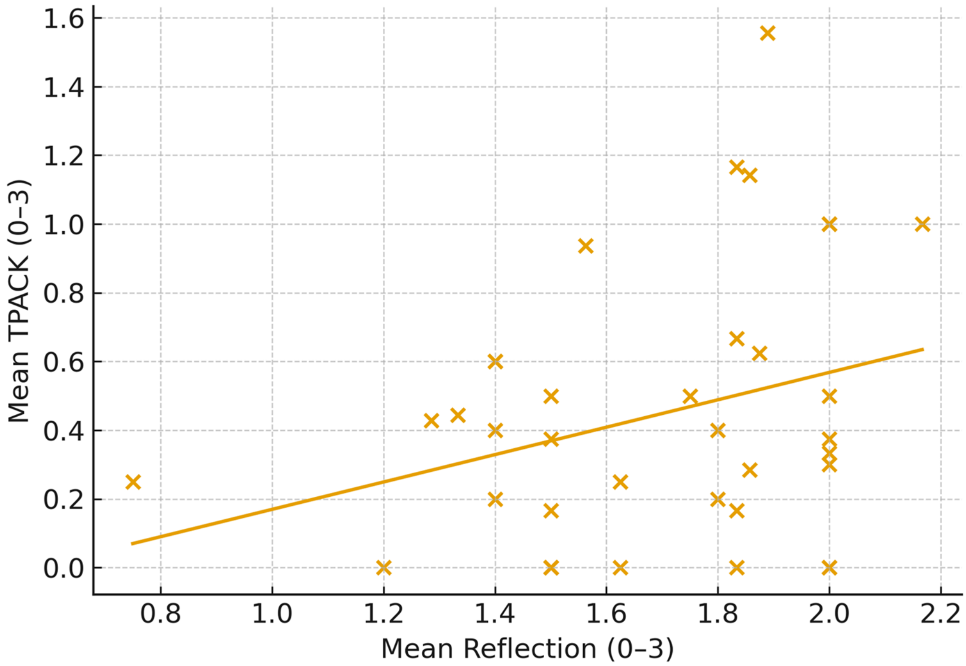

Figure 4. Reflection vs TPACK scores per participant.

> The course enabled me to acquire both basic theoretical knowledge about the functionality and possibilities of 3D printing in the context of school and mathematics and to gain practical experience and knowledge in the creation and implementation of my own projects.

The participant-level view replicated the general-level tendencies: most participants' mean TK/PK/TPK were below 1.0, and TPACK was lower still, indicating that these constructs are occasional rather than pervasive across entire reflections. A participant-level Spearman correlation between the mean Reflection and the mean TPACK showed a positive, non-significant trend ($\rho = .247$, $p = .140$, $n = 37$), consistent with the general level association but weaker when considered within-person. Figure 4 shows a modest upward trend between the mean Reflection and the mean TPACK, with considerable dispersion; most participants maintain a low mean TPACK across the range of reflections. In contrast, a smaller group with higher reflection (≈1.7–2.1) reaches higher TPACK means (≈0.8–1.6). Notably, CK rarely appeared alone; when present, it tended to co-occur with PCK or TCK, a pattern mirrored in several participant profiles.

Together, these results show (a) a strong TK/PK/TPK emphasis relative to CK/PCK/TCK, (b) a graded association between reflective depth and integrated references to TPACK, (c) content appearing in tandem with pedagogical or technological reasoning, and (d) TPACK emerging most clearly around lesson-planning.

Discussion

In this study, we examined PTSs' written reflections as windows into how a TPACK-informed, experientially sequenced 3DMP course was experienced. Across 231 coded units from 37 reflective essays, quantitative patterns echoed the course design while revealing imbalances: technological and pedagogical emphases were most prevalent, whereas content-linked reflections were comparatively sparse and, when present, tended to co-occur rather than stand alone. Notably, higher reflective depth was associated with richer, more integrated references to TPACK, with the most robust instances clustering around lesson-planning passages. Together, these findings suggest that experiential sequences and structured reflection can help PSTs move beyond tool operation toward purposeful integration (Buss et al., 2018; Harris & Hofer, 2017); however, the content dimension requires more deliberate support. This tension has implications not only for 3DMP but also for other emerging, content-specific technologies introduced in teacher education.

The TK/PK/TPK dominance aligns with well-documented patterns in technology courses, in which technical confidence and classroom workflow are easier to articulate than content aims (e.g., Ng et al., 2022; Song, 2018). Our results align with calls to integrate technology with pedagogy and content, rather than treating it in isolation (Harris & Hofer, 2017; Tejera et al., 2026). At the same time, we see encouraging signs of integration where tasks explicitly required lesson design: these were the moments when PSTs most often connected 3DMP to mathematical goals and student thinking. Supporting recommendations from teacher-education research (Buss et al., 2018; Wan & Ivy, 2021), positioning technology as an epistemic aid to disciplinary understanding rather than a display medium. For mathematics teacher education specifically, this emphasizes the importance of anchoring tool use in explicit mathematical learning goals and anticipated student reasoning, rather than treating technology as an add-on.

The content-lean profile (low CK, PCK, TCK) is consequential. In several cases, content ideas emerged only when anchored to tangible design briefs (e.g., scaling, measurement, geometric properties) or when reflection prompts triggered anticipatory PCK (Petko et al., 2017; Rodriguez et al., 2018). This pattern suggests an instructional design implication rather than a simple deficit: content integration appears to be "pulled" by tasks and prompts that make disciplinary elements unavoidable. In practical terms, that means (a) building 3DMP projects around non-trivial mathematical goals, (b) requiring explicit statements of those goals within lessons, and (c) using reflection prompts that press for the mathematical "why" of the print, not just the "how" of the workflow. Such scaffolds are consistent with program models that have strengthened preservice teachers' TPACK trajectories over time (Buss et al., 2018) and with reports emphasizing progression from learning the machine to designing student-generated models aligned with curricular aims (Wan & Ivy, 2021). More broadly, the same design logic applies when teacher education introduces other tools with strong "novelty" (e.g., sensors, simulations, AR/VR, or media production): content-linked objectives must be made explicit in the task structure, not left implicit.

The observed association between reflective depth and TPACK is also informative. At the unit level, deeper reflection co-occurred with higher TPACK scores; at the participant level, the trend persisted but was less pronounced. This asymmetry suggests that reflection, by itself, is not a guarantee of integration; it matters what the reflection is about and when it is prompted in the learning cycle (Kolb, 2015; Petko et al., 2017). TPACK integration appears essential, aligning with evidence that prompt design and peer interaction shape what reflection accomplishes in teacher education (Petko et al., 2017). In short, reflection appears to function best here as a means to press toward integration, rather than just as a metacognitive add-on. This reinforces a practical implication for teacher educators: reflection tasks should be designed as instructional scaffolds, not only as end-of-course summaries.

Finally, the co-occurrence analysis clarifies where integration is already strong. More substantial overlap between TK and TPK is unsurprising in fabrication contexts; more interesting are the co-appearances of CK with PCK and TCK. Where content does enter the narrative, it tends to do so in relation to student understanding or technology-mediated conceptualization (Harris & Hofer, 2017). This pattern suggests an actionable route to strengthen the content strand: foreground mathematical representations and student thinking as the reasons to print, rather than just the contexts in which printing occurs.

Implications for course design

Findings point us to three concrete recommendations:

1. Content-first tasks: Frame projects around explicit content targets (e.g., optimization, measurements, solids of revolution), require goal statements, and assess the epistemic contribution of the artifact (TCK), not just its quality (TK).
2. PCK-focused reflection: Embed short, structured prompts at key moments that ask PSTs to anticipate student thinking, misconceptions, and representations, and to justify how the technology advances those aims (PCK/TPACK).
3. Lesson-level enactment: Keep the capstone as a full lesson design (or micro-teaching) to draw integration; pair it with rubrics that weight CK/PCK/TCK alongside TK/TPK to counterbalance the default emphasis on tools and workflow.

These recommendations align with the broader teacher education literature, which advocates for the intentional and contextually meaningful integration of novice teachers working with emerging technologies (Harris & Hofer, 2017; Rodriguez et al., 2018; Wan & Ivy, 2021). They also translate to teacher education beyond mathematics and 3DMP: when introducing any emerging technology, programs may need to counterbalance "tool-first" momentum by assessing content-linked learning aims, designing tasks that require disciplinary justification, and using rubrics that make integration visible.

Limitations

This is a single-context study using post-course reflections; we did not observe classroom enactments or assess student learning. Coding, though calibrated and reliable, remains interpretive. The corpus is modest, and content coverage may reflect prompt emphasis as much as participant understanding. Future work should triangulate with lesson artifacts, micro-teaching observations, and follow-up interviews.

Conclusion

PSTs' narratives provide a nuanced picture of what matters when learning to teach with 3DMP. Experiential sequences and structured reflection helped many students move beyond tool operation toward lesson-level coherence; however, content-specific reasoning remained sporadic unless explicitly scaffolded. Designing for epistemic uses of technology, centering curricular goals, and prompting PCK-rich reflections appear key to strengthening integration. More broadly, the study contributes a mixed-methods approach for visualizing the balance among TPACK dimensions and their intersections in authentic coursework, offering practical insights for programs seeking to foster TPACK with emerging technologies.

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Authors' contributions

CRediT: **Mathias Tejera**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Viviana Aharonian**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing; **Cecilia Russo**: Formal analysis, Investigation, Writing – original draft, Writing – review & editing; **Zsolt Lavicza**: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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Notes on contributors

Mathias Tejera is a lecturer and researcher at JKU and UTEC. He teaches in the mathematics teacher education program at JKU and in UTEC's postgraduate program in educational technology. His work examines teacher knowledge and the integration of technology in mathematics teaching, with a focus on design-oriented, practice-based coursework and digital fabrication. He collaborates with schools and university partners to connect curriculum aims with innovative tools and reflective teacher learning, and contributes to open, replicable research workflows.

Viviana Aharonian is a mathematics teacher and researcher at JKU focused on teachers' reflective practices and the affective domain in technology integration and interdisciplinary approaches. She contributes to research projects in teacher education, studying how structured reflection, collaboration, and authentic tasks shape the learning of preservice and in-service teachers. Her current interests include designing reflection prompts and analytic approaches that illuminate how emotions, beliefs, and professional identity interact with technology-enhanced pedagogy in mathematics and STEAM contexts.

Cecilia Russo is a lecturer and researcher at UTEC's postgraduate program in educational technology. Her work centers on innovative approaches to teaching, game-based learning, and teacher education, with emphasis on designing and studying practice-oriented experiences that connect digital tools to curricular goals. She participates in multiple research projects on teacher professional development, collaborating with schools and communities to create sustainable, scalable models for technology-rich instruction and to document actionable strategies for classroom implementation.

Zsolt Lavicza is a professor at the Linz School of Education (JKU) whose scholarship spans mathematics and STEAM education, technology integration, and teacher professional development. He leads international collaborations that link research, teacher learning, and classroom innovation, and has published widely on how digital tools can support conceptual understanding, classroom orchestration, and curriculum design. His recent work emphasizes design-based approaches to educational practices, utilizing emerging technologies, and fostering research-practice partnerships across educational systems.

ORCID

Mathias Tejera http://orcid.org/0000-0002-9826-966X
Viviana Aharonian http://orcid.org/0009-0001-7644-8958
Cecilia Russo http://orcid.org/0000-0002-4513-6812
Zsolt Lavicza http://orcid.org/0000-0002-3701-5068

Data availability statement

The datasets, analysis and code used for the current study are available at https://osf.io/b2jdq/overview?view_only=438c7a0e010e48009853cd73b4a01e8e

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