3D Technologies in Teacher Education: Reflections and Didactic Potential

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Abstract: This paper presents findings from a qualitative study conducted within a university-level course on technical education for pre-service teachers. The course was innovatively enhanced by integrating the topic of 3D modelling and printing (3DMP), with a focus on exploring its educational applications in the context of school teaching. The aim of the study was to analyze how future teachers perceive and reflect on the use of 3D technologies in education. Students participated in hands-on training using Tinkercad and learned the basic operation of 3D printers. They were also introduced to examples of how 3DMP can be applied across different school subjects, such as mathematics, science, and technology education. As a final project, students worked in small groups to design a 3D model, print it, and develop a detailed methodological plan for its use in the classroom. The collected data included project documentation, lesson proposals, and students' written reflections, which were analyzed through qualitative content analysis. The results indicate a generally positive perception of 3D technologies among pre-service teachers. Students appreciated the creative and interdisciplinary possibilities of 3D modelling, while also critically reflecting on technical and didactic challenges. Many participants highlighted the motivational potential of 3D printing for young learners and its usefulness for visualizing abstract or complex content in an accessible way. This study contributes to the growing body of research on educational technology in teacher preparation by emphasizing the need for meaningful, practice-oriented integration of digital tools. It also points to the importance of developing technological-pedagogical thinking in future educators, fostering both innovation and critical awareness in their professional development.

Keywords: 3D Printing, Teacher Education, 3DMP, Tinkercad, Educational Technology.

1. Introduction

The integration of emerging technologies into teacher education has become an increasingly important area of focus in the digital era. As classrooms evolve to include digital tools, educators must be prepared not only to use technology effectively but also to understand its pedagogical implications (Koehler and Mishra 2009; Tondeur et al. 2017). This is particularly relevant in the context of initial teacher education (ITE), where the foundations of professional identity and instructional reasoning are being formed. Despite the growing emphasis on digital competence, many teacher education programmes still offer limited opportunities for students to engage with hands-on, creative, and design-oriented technologies (Instefjord and Munthe 2017).

3DMP have gained increasing attention as innovative tools in education. Their capacity to visualise abstract concepts, support spatial reasoning, and foster learner engagement has been widely recognised (Ford and Minshall 2019; Lavicza et al. 2023; Trust and Maloy 2017). In school settings, 3D technologies can be used across disciplines—from mathematics and science to geography, arts, or special education—yet their use by teachers remains relatively rare (Bull et al. 2015). Introducing such tools in pre-service training may not only expand teachers' technical skillsets, but also stimulate constructivist thinking, multimodal design, and inclusive pedagogical strategies (Piaget 1973; Papert 1980).

While prior research has explored the use of 3D modelling in STEM education and design-based learning (Beauchamp 2016), comparative insights into how future teachers from different educational cultures approach 3D technologies are still lacking. There is a need to examine how pre-service teachers conceptualise and implement 3DMP within diverse didactic frameworks, and how this reflects their evolving pedagogical thinking. This paper presents findings from a comparative qualitative study involving two groups of pre-service teachers—one from Slovakia and one from Austria—who participated in a university course integrating 3DMP. The aim of the study was to analyse students' final projects, including their 3D models, written documentation, and reflections, in order to identify key thematic patterns in their didactic design, use of technology, and pedagogical reasoning.

By comparing the outputs of the two groups, this study seeks to contribute to the growing body of research on technology-enhanced teacher education, with a particular focus on the creative and critical use of digital fabrication tools. The findings offer insights into how pre-service teachers conceptualise educational technologies in different contexts, and what this reveals about their emerging professional identities.

2. Theoretical Background

The integration of 3DMP into teacher education requires a theoretical framework that connects digital competence with pedagogical reasoning. In this study, three conceptual lenses are used to inform the analysis: the TPACK framework, constructivist learning theory, and the 5E instructional model. Together, they provide a foundation for interpreting how pre-service teachers conceptualise, design, and reflect on 3D-based educational tools.

2.1 Technological Pedagogical Content Knowledge (TPACK)

The Technological Pedagogical Content Knowledge (TPACK) model (Koehler and Mishra 2009) describes the dynamic interplay between teachers' knowledge of content, pedagogy, and technology. In the context of 3D modelling, pre-service teachers are required to blend technical skills (e.g., understanding software, working with the printers) with pedagogical strategies (e.g., student engagement, instructional scaffolding) and curricular content (e.g., mathematics, science). This framework offers a valuable lens for assessing how students reflect on the role of digital tools in their didactic planning and implementation (Chai, Koh, and Tsai 2013; Voogt et al. 2013).

2.2 Constructivism and Inquiry-Based Learning (5E Model)

Secondly, the study draws on constructivist learning theory, which emphasises active, learner-centred knowledge construction. In line with Piaget (1973) and Vygotsky (1978), educational applications of 3D modelling are particularly suited to constructivist practices, as they encourage exploration, manipulation, and co-construction of meaning through artefact creation (Resnick 2006). When pre-service teachers design tools with learners in mind, they often reveal their understanding of how knowledge emerges from interaction, context, and sensory experience.

To further conceptualise the design and sequencing of learning activities, the study references the 5E instructional model—Engage, Explore, Explain, Elaborate, Evaluate (Bybee et al. 2006)—widely used in science and technology education. This model aligns well with 3D-based instructional design, as it encourages inquiry-driven learning and facilitates a structured yet flexible environment for experimentation. The model also supports the analysis of how students anticipate learner needs, plan task sequences, and evaluate learning outcomes.

2.3 Digital Fabrication and the Educational Potential of 3D Printing

Digital fabrication, particularly through 3DMP, is increasingly recognised as a transformative tool in education. It allows learners to move from abstract concepts to tangible artefacts, thus bridging cognitive and sensory experiences (Blikstein 2013). In teacher education, 3D printing has been explored not only as a technical skill but also as a means to foster design thinking, creativity, and interdisciplinary problem-solving (Martinez and Stager 2013; Tejera et al. 2025).

The educational value of 3D printing lies in its potential to support inquiry-based, hands-on learning experiences that are aligned with constructivist pedagogies. When pre-service teachers engage in the creation of 3D learning objects, they are challenged to consider learner needs, curricular goals, and didactic strategies in an integrated way. Moreover, the process of translating educational ideas into printable forms reinforces spatial reasoning, iterative thinking, and material awareness (Lavicza et al. 2023; Marshall and Harron 2018).

From a pedagogical standpoint, digital fabrication promotes both cognitive engagement and motivation, especially in STEM-related subjects. Research has shown that the use of 3DMP in schools can enhance understanding of abstract or invisible phenomena, support differentiated instruction, and increase student agency (Bull et al. 2015). For future educators, learning to design and justify the use of 3D tools within authentic teaching scenarios is a valuable step toward technological-pedagogical fluency.

This study adopts the perspective that digital fabrication is not merely an add-on to educational technology curricula, but a pedagogically rich environment in which pre-service teachers can develop and articulate their didactic identities. The integration of 3D printing within teacher preparation provides a lens for examining how future educators conceptualise innovation, practicality, and learner-centred instruction.

These three frameworks not only informed the creation of the initial qualitative codebook, but also supported the interpretation of students' choices, reflections, and design rationales. Together, they provided a theoretical structure for analysing the interplay between technological tools, didactic thinking, and learner engagement, which lay at the core of this comparative study.

3. Methodology

3.1 Research Questions

This study was guided by three research questions aimed at understanding how pre-service teachers from two educational contexts engage with 3DMP in their professional preparation:

- **RQ1:** How do pre-service teachers from Slovakia and Austria conceptualise and engage with 3D technologies in the design of educational tools?
- **RQ2:** How do pre-service teachers from both contexts integrate constructivist learning principles when designing teaching activities involving 3D-printed artefacts?
- **RQ3:** In what ways do Slovak and Austrian pre-service teachers reflect on the practical feasibility of using 3D models in real classroom settings, including considerations of learner engagement, accessibility, and logistical constraints?

These questions align with the theoretical framework of the study (TPACK, constructivist learning theory, and the 5E model) and provided the analytical lens for interpreting the qualitative data collected from students' projects and reflections.

3.2 Research Design

The study employed a comparative qualitative research design to explore how pre-service teachers from two European universities conceptualise and apply 3DMP in the context of classroom practice. The aim was to analyse students' design artefacts, didactic rationales, and written reflections to identify patterns in their technological-pedagogical thinking.

3.3 Participants and Context

The participants were two cohorts of pre-service teachers enrolled in university courses focused on technical and digital education—one at a Slovak university (n = 20), and one at an Austrian university (n = 27). Both courses were conducted during the 2024/2025 academic year and featured a practice-oriented approach to integrating 3DMP. The Slovak course was part of a broader educational technology module; the Austrian course was an elective seminar within the teacher education program.

All participants received training in Tinkercad, explored educational use cases of 3DMP, and were guided through the basics of 3D printing workflows. As part of their final course assignment, students worked in small groups to:

(a) design a 3D printable educational object,
(b) develop a written methodological plan for classroom use, and
(c) reflect on the didactic value and challenges of 3D technologies in education.

3.4 Data Collection and Types of Student Outputs

The data corpus consisted of a total of 18 group projects (8 Slovak, 10 Austrian), which included:

- Technical documentation of the 3D models (images, schematics, .stl files),
- Written teaching scenarios and lesson plans,
- Open-ended written reflections (1–2 pages per group).

All materials were collected in digital format and anonymised prior to analysis. The data were rich in descriptive, procedural, and evaluative content, allowing for in-depth thematic interpretation.

3.5 Development of the Codebook

To analyse the collected data from both the Slovak and Austrian groups of pre-service teachers, a qualitative content analysis approach was applied. A joint codebook was developed as a conceptual and analytical tool to identify recurring themes, didactic reasoning, and patterns in students' 3D model designs, lesson planning, and reflective writing.

The development of the codebook followed a hybrid strategy that combined both deductive and inductive procedures. Deductive codes were drawn from three interrelated theoretical frameworks:

- the **TPACK framework** (Technological Pedagogical Content Knowledge; Mishra and Koehler 2006),
- the **5E Instructional Model** (Bybee 1997),
- and **constructivist approaches** to learning and teaching (Piaget 1973; Vygotsky 1978; Papert 1980).

These frameworks informed the initial conceptual categorisation, allowing the researchers to anticipate key areas such as technological fluency, pedagogical intention, and inquiry-based learning.

At the same time, inductive codes emerged from a close reading of the actual student materials, including group reports, lesson plans, and written reflections. Codes were formulated to capture not only technological and pedagogical dimensions but also students' reflections on feasibility, motivation, and learning design.

The final codebook was constructed through iterative testing and refinement across both national groups. It was designed to be flexible enough to accommodate differences in language, educational context, and design choices, while remaining consistent in its core structure and interpretive focus.

The codebook includes four main thematic categories:

1. **Didactic Orientation** (Pedagogical-Content Layer) – focusing on subject-specific goals, interdisciplinary use, visualisation support, and motivational potential.
2. **Technological Engagement** (Technological Layer) – covering tool mastery, technical challenges, and collaborative aspects of using 3D technologies.
3. **Constructivist Learning Design** (Constructivist Layer) – identifying students' reflections, learning-by-doing experiences, and didactic planning strategies.
4. **Practical Implementation Reasoning** – reflecting concerns about classroom realities, feasibility, and innovation proposals.

Each category includes 2–4 subcodes, accompanied by **operational definitions and authentic examples** from student work. This structure enabled a nuanced yet consistent interpretation of the artefacts and written narratives, and supported the comparative analysis of pedagogical thinking across the two cohorts.

The complete version of the codebook is presented in **Tables 1–4**, with subcategories and illustrative excerpts from the data.

Table 1: Didactic Perspective (Pedagogical-Content Layer)

Code	***Label***	***Definition***	***Example (from data)***
PCK-GEO	Geometric Content	Clearly defined goal related to teaching geometry	"The model helps pupils visualise different types of triangles."
PCK-INT	Interdisciplinary Integration	Connecting the 3D tool with other school subjects (e.g. history, science, arts)	"We will use the medieval castle model in history lessons."
PCK-VIS	Visualisation Support	The tool helps visualise abstract or complex content	"It helps pupils imagine what crossing the tens boundary means."
PCK-MOT	Motivational Effect	Highlights learner engagement, excitement or enjoyment	"The children were excited about printing something themselves."

Table 2: Technological Perspective (Technological Layer)

Code	***Label***	***Definition***	***Example (from data)***
TK-USE	Tool Mastery	Describes the process of using Tinkercad, slicers or printers	"We had to resize the model in Tinkercad."
TK-PROB	Technical Difficulties	Technical issues or challenges with software, printing or modelling	"We had to reinstall the software – our file didn't save."

TK-COLL	Technical Collaboration	Collaboration in technical aspects of the work	"One of us did the modelling, the other searched for inspiration."

Table 3: Learning and Reflection (Constructivist Layer)

Code	***Label***	***Definition***	***Example (from data)***
CON-EXP	Learning through Exploration (5E: Explore)	Pupils engage in experimentation, discovery or hands-on trial	"The children discovered which parts fit together by trying them."
CON-REF	Reflection by Student Teachers	Reflections on teaching practice or digital tool use	"I realised not everything can be turned into a 3D model effectively."
CON-DES	Didactic Task Design	Description of how the learning activity was intentionally designed	"We made sure pupils would touch the model first before solving tasks."

Table 4: Implementation and Practical Reasoning

Code	***Label***	***Definition***	***Example (from data)***
IMP-REAL	Real-World Constraints	Time limits, class size, material needs, feasibility	"With 20 pupils in the class, I don't think we can finish this in one lesson."
IMP-INOV	Innovation and Improvement Ideas	Suggestions for how to enhance, adapt or expand the activity	"I would also use this tool in speech therapy."

3.6 Analytical Strategy

The analysis followed a qualitative content analysis approach (Mayring 2014; Schreier 2012), combining deductive and inductive coding strategies. Deductive categories were derived from the theoretical frameworks introduced in the previous section—namely TPACK (Koehler and Mishra 2009), constructivist pedagogy (Piaget 1973; Vygotsky 1978), and the 5E model (Bybee et al. 2006). Inductive codes emerged through close reading and iterative examination of student texts and artefacts.

The student outputs were diverse in both form and function. The designed 3D models included didactic tools such as geometric manipulatives, anatomical structures, interactive puzzles, ecological dioramas, and symbolic artefacts for narrative-based instruction. These were often accompanied by illustrative images, schematics, and STL files prepared for 3D printing. Each model was conceptually framed within a detailed methodological plan, in which students justified its pedagogical relevance, integration into specific subject areas (e.g., mathematics, natural science, language education), and its alignment with intended learning outcomes.

In addition to the physical artefacts and teaching scenarios, each group submitted a written reflection in which they discussed their creative and technical process, challenges encountered, and perceived educational value of their project. These reflections were particularly rich in metacognitive insights and pedagogical reasoning.

The coding process was conducted using manual annotation and supported by matrix-based categorisation and thematic synthesis. Codes were applied collaboratively and cross-validated across cases to ensure consistency, analytical rigour, and fidelity to the original meanings expressed by participants.

4. Findings

This section presents the results of the qualitative content analysis of final course assignments created by pre-service teachers from Slovakia and Austria. The analysis followed the thematic categories derived from the joint codebook and focused on students' pedagogical thinking, technological engagement, and reflections on feasibility. Findings are presented separately for each national group, followed by a comparative thematic synthesis.

4.1 Slovak Student Group

The analysis of submissions from Slovak pre-service teachers revealed consistent patterns across four thematic domains: didactic orientation, technological engagement, constructivist learning design, and practical reasoning. Students demonstrated a strong alignment with curriculum goals, particularly in mathematics and geometry. Their 3D models often served to support spatial reasoning, number sense, or shape recognition. Interdisciplinary extensions were also present, such as historical models or phoneme tools for literacy instruction. In their reflections, students frequently emphasised the motivational potential of 3D-printed artefacts, attributing learner excitement to the novelty and interactivity of the tools—even though these assumptions were largely anticipatory rather than based on classroom experience.

In terms of technological engagement, Slovak students actively used Tinkercad and slicers, showing competence in basic modelling operations. Several groups documented technical challenges such as calibration errors, print failures, or filament issues. Collaboration during modelling was common, with teams distributing tasks efficiently. However, deeper pedagogical reflection on the use of digital tools was limited, suggesting a focus on functional rather than integrative use of technology (i.e., more TK than TPK).

From a constructivist perspective, many groups designed activities that invited pupils to manipulate and explore the 3D artefacts. Their lesson plans included clear sequences and scaffolding strategies, promoting discovery and hands-on learning consistent with the "Explore" phase of the 5E model. Some students reflected on their own learning process, noting moments of insight or unexpected challenge during the task.

Practical reasoning was present in most reflections, particularly in relation to time constraints, equipment access, and pupil readiness. Some students adapted their original designs to make them more feasible or suggested alternative uses across different subjects or learner populations (e.g., special education). These reflections indicate an emerging awareness of classroom realities and a willingness to balance creativity with pragmatism.

4.2 Austrian Student Group

The Austrian pre-service teachers produced outputs that reflected a strong focus on learner diversity, sensory engagement, and inclusive design. The analysis revealed four key thematic areas aligned with the joint codebook, yet the orientation and emphasis often differed from the Slovak group.

Many projects were developed with attention to accessibility and imaginative learning. Models included tactile globes for visually impaired students, 3D numerals for children with dyscalculia, or artefacts that combined cultural and ecological content. Interdisciplinary thinking was prominent, with connections across geography, biology, and arts. While links to specific curricular goals were less explicit, students articulated broader developmental intentions such as motor skills development or emotional engagement.

Technological aspects were generally underdeveloped in students' reflections. Although all groups used 3D software (usually Tinkercad), few described the modelling or printing process. There was little mention of slicing, calibration, or design revisions. This suggests either a shift in instructional focus towards pedagogical goals, or limited student ownership of the technical process. As a result, Technological Knowledge (TK) was present at a basic level, but TPK thinking remained implicit.

Despite minimal formal lesson planning, the submitted materials frequently showed strong constructivist tendencies. Most models invited manipulation, assembly, or play—supporting exploratory and multisensory learning. Students often described their tools as "fun," "interactive," or "engaging," relying on their assumed motivational value. Activities supported discovery-based learning, aligning with the "Engage" and "Explore" phases of the 5E model, even if the terminology was not explicitly used.

Reflections on feasibility focused less on classroom logistics and more on affective outcomes. Students emphasised enjoyment, inclusion, and learner-centredness, often proposing cross-curricular or therapeutic applications. Practical constraints such as time or resources were rarely discussed, but many submissions suggested a belief in the transformative potential of material and sensory learning experiences.

4.3 Comparative Thematic Synthesis

A cross-case comparison of the Slovak and Austrian student groups revealed shared pedagogical intentions, yet also highlighted divergent orientations shaped by context and emphasis.

4.3.1 Didactic Orientation

Slovak students tended to align their 3D models with curriculum-based goals, especially in mathematics and science. Their designs often included explicit learning objectives and step-by-step lesson planning. In contrast, Austrian students focused on inclusivity and learner engagement. Their projects frequently targeted diverse needs—such as visual impairments or dyscalculia—and emphasised cross-curricular connections and sensory learning. While less anchored in formal curriculum, their outputs reflected a broader developmental perspective.

4.3.2 Technological Engagement

Slovak students showed stronger engagement with the technical aspects of 3DMP. Their reflections often included challenges with slicing, design revisions, or collaboration during the modelling process. Austrian students, while competent users of design tools, rarely commented on the technical workflow. Their focus remained on pedagogical intent, suggesting a product-oriented rather than process-oriented view of technology use.

4.3.3 Constructivist Learning Design

Both groups embraced constructivist principles, though expressed differently. Slovak students structured their scenarios with didactic sequencing, aligning with inquiry-based learning phases. Austrian students, on the other hand, designed artefacts that promoted free exploration, play, and sensory engagement, often without rigid instructional framing. Their learning designs leaned toward learner autonomy and emotional connection.

4.3.4 Implementation Reasoning

Slovak reflections often addressed logistical feasibility—time constraints, class size, or material limitations. Austrian students rarely discussed such constraints but instead reflected on motivational potential, inclusion, and learner diversity. Their reflections revealed an aspirational mindset, focusing on engagement and affective outcomes over operational planning.

Slovak students demonstrated a more structured, curriculum-aligned, and technologically reflective approach, indicative of growing professional reasoning within known educational parameters. Austrian students revealed greater openness to innovation, emotional engagement, and inclusive design, even if less focused on classroom logistics. These complementary perspectives suggest that effective teacher preparation can benefit from a balance of technical precision and empathetic, learner-centred creativity.

5. Discussion

This study explored how pre-service teachers from Slovakia and Austria engaged with 3DMP as part of their teacher education coursework. Guided by three research questions, the findings illustrate how students conceptualised the pedagogical role of 3D technologies, integrated constructivist learning principles, and reflected on the feasibility of using such tools in actual classrooms. The discussion situates these findings within the four analytical categories and links them to prior research and theoretical frameworks relevant to technology-enhanced teacher education.

5.1 RQ1: Conceptualising and Engaging with 3D Technologies in Educational Design

The first research question addressed how pre-service teachers conceptualised and engaged with 3D technologies in designing educational tools. The findings revealed different emphases between the two national contexts, reflecting broader patterns in teacher education cultures and curricular traditions.
Didactic Orientation: Slovak students largely embedded their 3D models within specific curricular areas, particularly mathematics and science, aligning their designs with structured learning objectives. This is consistent with previous studies showing that novice teachers often view technology as an extension of existing curriculum frameworks rather than a transformative medium for new forms of learning (Koehler and Mishra 2009; Chai et al. 2013). In contrast, Austrian students displayed more interdisciplinary thinking, using 3D tools to design resources that spanned multiple subjects or addressed diverse learner needs, such as tactile maps for visually impaired pupils. This approach resonates with Trust and Maloy (2017), who argue that digital technologies can foster broader, inclusive pedagogical practices when teacher education creates space for flexible and creative use.

Technological Engagement: Slovak students frequently documented their technical workflow, reflecting a procedural engagement with design tools and the challenges of 3DMP. This aligns with Voogt et al. (2013), who highlight that developing technological-pedagogical content knowledge (TPACK) requires explicit opportunities for teachers to reflect on how technology functions and interacts with pedagogy. Austrian students, while successfully using the technology, focused less on technical aspects and more on the artefacts' imaginative or communicative value. Their treatment of technology as a creative medium echoes Bull et al. (2015), who suggest that digital fabrication can support meaning-making and narrative design in education. However, the absence of technical reflection suggests a potential gap in building integrated TPACK knowledge, where technology understanding remains implicit rather than consciously articulated.

These findings underline that pre-service teachers' engagement with 3D technologies is shaped not only by individual skills but also by the pedagogical framing of coursework. Slovak outputs reflect a curriculum-driven and process-oriented mindset, whereas Austrian outputs suggest a more learner-centered and expressive orientation, albeit with less focus on technical reasoning. This echoes Tondeur et al. (2017), who emphasise that institutional contexts strongly shape how future teachers develop their digital competence and pedagogical reasoning.

5.2 RQ2: Integration of Constructivist Learning Principles in 3D-Based Teaching Activities

The second research question examined how students embedded constructivist learning principles into their designs. Findings highlighted constructivist orientations in both groups, but with distinct levels of structure and learner agency.

Constructivist Learning Design: Slovak students generally developed step-by-step instructional plans, emphasising guided discovery and structured scaffolding. These designs reflect the "Explain" and "Elaborate" phases of the 5E instructional model (Bybee et al. 2006), ensuring clear pathways for concept acquisition. Such approaches align with research suggesting that novice teachers often prefer structured methods to manage uncertainty in new pedagogical environments (Tondeur et al. 2017).

Austrian students, on the other hand, designed open-ended, exploratory tasks that encouraged learners to manipulate artefacts freely, experiment, and co-construct knowledge. These scenarios align with Piaget's (1973) notion of active exploration and Papert's (1980) constructionist vision of learning-by-making, where tangible artefacts foster personal meaning-making and creativity. This approach also mirrors Resnick's (2006) argument that digital fabrication supports playful experimentation and non-linear larning paths.

The contrast between guided and exploratory designs highlights a tension documented in previous studies on technology integration: pre-service teachers often oscillate between structured, teacher-led activities and more open, learner-driven models (Beauchamp 2016). This may reflect their own prior schooling experiences, differing emphases in national curricula, and varying levels of confidence in facilitating inquiry-based learning. Both approaches have pedagogical merit, but teacher education must help students understand how to balance structure with opportunities for autonomy, particularly when leveraging new technologies that invite experimentation.

5.3 RQ3: Reflections on the Practical Feasibility of Using 3D Models in Real Classroom Settings

The third research question explored how pre-service teachers reflected on the feasibility of implementing 3D-based activities in authentic classroom contexts. The findings revealed two complementary dimensions of feasibility reasoning.

Practical Implementation Reasoning: Slovak students frequently considered operational constraints—lesson time, equipment availability, class size—and proposed concrete adaptations to make activities manageable. This pragmatic focus aligns with findings by Instefjord and Munthe (2017), who note that teachers' digital competence is strongly shaped by perceived barriers in school environments. Such reasoning illustrates the beginnings of professional thinking that seeks to balance innovation with classroom relities.

Austrian students focused more on the motivational and inclusive potential of 3D artefacts, considering how these tools could enhance learner engagement, accessibility, and participation for diverse learners. This reflects Bull et al. (2015), who highlight the role of technology in promoting equity and inclusion, and suggest that some students conceptualised feasibility not only as logistical but also as affective and social viability.

Both forms of reasoning demonstrate that pre-service teachers understand that technology integration is not purely a technical decision but involves pedagogical, organisational, and relational dimensions (Koehler and Mishra 2009). The findings point to the need for teacher education programmes to support students in bridging aspirational visions of engagement and accessibility with operational realities of time, resources, and institutional constraints.

5.4 Implications for Teacher Education

The comparative analysis of Slovak and Austrian students' projects suggests several implications for the design of teacher education programmes seeking to integrate 3DMP effectively.

1. **Balancing Technical and Pedagogical Reflection:** Teacher preparation should explicitly foster TPACK development by prompting students to reflect not only on their pedagogical intentions but also on how technological processes shape design outcomes (Voogt et al. 2013). This ensures that 3D modelling is not treated as a mere functional task or a black-boxed process but as part of informed instructional reasoning.
2. **Integrating Curriculum Alignment with Accessibility:** The Slovak group demonstrated strong curriculum-linked designs, while Austrian students emphasised inclusion and multisensory engagement. Combining these orientations can help future teachers design tools that are both content-rich and equitable (Trust and Maloy 2017), addressing the dual mandate of relevance and diversity in education.
3. **Strengthening Constructivist and Inquiry-Based Pedagogies:** 3D modelling naturally supports constructivist learning, but students displayed varying degrees of openness and scaffolding. Programmes should link design activities explicitly to frameworks like the 5E model (Bybee et al. 2006), helping pre-service teachers understand how to structure exploratory, learner-driven experiences while maintaining conceptual clarity (Resnick 2006; Papert 1980).
4. **Bridging Aspirational and Operational Thinking:** Opportunities for testing, iterating, and adapting designs in authentic or simulated classroom settings can help future teachers reconcile creative aspirations with practical limitations (Instefjord and Munthe 2017). Such experiences strengthen their ability to plan realistic, scalable uses of emerging technologies.
5. **Promoting Cross-Cultural Perspectives in Teacher Education:** The contrasts observed suggest that national or institutional contexts shape pedagogical reasoning about technology. Collaborative, international design experiences could broaden students' conceptions of how digital tools can serve different educational purposes (Tondeur et al. 2017), fostering more flexible and reflective professional identities.

Overall, this study shows that integrating 3DMP in teacher education stimulates multiple dimensions of pedagogical thinking. Students demonstrated creativity and sensitivity to learners' needs, but their designs revealed varying emphases on curriculum alignment, technological reasoning, constructivist openness, and practical feasibility. These variations reflect both individual and contextual factors and align with broader literature on the complex, situated nature of developing digital competence in initial teacher education (Koehler and Mishra 2009; Tejera et al. 2025; Tondeur et al. 2017).

Embedding digital fabrication in pre-service training holds promise not just for technical skill acquisition but for cultivating a deeper understanding of how technologies shape teaching and learning. To fully leverage this potential, teacher education must provide structured opportunities for reflection, experimentation, and cross-contextual dialogue, preparing future teachers to integrate emerging technologies in ways that are pedagogically sound, inclusive, and feasible within real classroom conditions.

6. Conclusion

This study explored how pre-service teachers from Slovakia and Austria engaged with 3DMP in a university-level educational technology course. Through a comparative qualitative analysis of student-created teaching tools, reflections, and design documentation, the research identified four key thematic areas: didactic orientation, technological engagement, constructivist learning design, and practical implementation reasoning.

The findings reveal both shared and context-specific patterns. Slovak students demonstrated a strong focus on curricular alignment, structured lesson planning, and explicit reflection on technological processes. Austrian students, in turn, emphasised inclusive design, sensory engagement, and learner motivation, often with less attention to technical or logistical details. These differences point to the diverse pedagogical orientations and cultural priorities present within teacher education across contexts.

Despite these contrasts, both groups showed promising levels of creativity, empathy, and educational insight. Their 3D models reflect the potential of digital fabrication technologies to support active, hands-on, and

meaningful learning experiences. Importantly, students across both groups were able to connect digital tools with their developing teacher identities—whether through structured planning or intuitive exploration.
The study contributes to the growing body of literature on educational technology in initial teacher education by demonstrating how 3D technologies can be leveraged not only as tools for instruction but as catalysts for pedagogical thinking. The comparative perspective offers valuable insights for programme designers, suggesting that combining structured instructional strategies with open-ended, learner-centred creativity may yield the most impactful results. Future research may further explore longitudinal impacts on classroom practice or investigate collaborative, cross-cultural design experiences among pre-service teachers.

7. Ethics Declaration

All participation was voluntary, with informed consent obtained in line with recognised ethical guidelines and the institutional requirements of the authors' universities for research involving human participants.

8. AI Declaration

During the preparation of this paper, the authors utilised the ChatGPT language model developed by OpenAI to enhance academic English through improvements in clarity, coherence, and stylistic consistency. All AI-assisted content was critically reviewed and substantively revised by the authors, who take full responsibility for the final text and its scholarly content.

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