Integrating 3D Modelling and Printing in Mathematics Education: Exploring Self-Efficacy among Austrian Preservice Teachers

[1,2]Mathias Tejera, [3]Daniel H. Jarvis, [1,4]Guillermo Bautista Jr., [5]Kristof Fenyvesi,
[1]Zsolt Lavicza

mathias.tejera@jku.at, danj@nipissingu.ca, gpbautista1@up.edu.ph, fenyvesikristof@gmail.com,
zsolt.lavicza@jku.at

[1]Department of STEM Education
Johannes Kepler University, Austria

[2]Departamento de Innovación y Emprendimientos
Universidad Tecnológica, Uruguay

[3] Schulich School of Education
Nipissing University, Canada

[4] UP NISMED
University of the Philippines

[4] Finnish Institute for Educational Research
University of Jyväskylä, Finland

Abstract

Three-dimensional modelling and printing (3DMP) holds considerable promise for transforming mathematics education, yet its widespread adoption remains limited, often due to insufficient teacher preparation and confidence. Grounded in the Technological Pedagogical Content Knowledge (TPACK) framework and the construct of self-efficacy, this study investigates preservice mathematics teachers' perceptions of their preparedness to integrate 3DMP technologies into classroom practice. Data were collected from 22 advanced preservice teachers enrolled in a university-level elective course in Austria, using a TPACK-aligned pre-course questionnaire featuring both Likert-scale items and open-ended prompts. Quantitative results revealed high levels of self-efficacy in both pedagogical and content domains, in contrast to notably lower confidence in technological knowledge and the integration of technology. Qualitative analysis revealed the reasons behind these patterns: participants felt well-prepared to teach mathematics but identified limited exposure to 3DMP tools and digital pedagogies as significant barriers to integrating technology. Some expressed cautious optimism, highlighting coursework or brief experiences as helpful, but almost all emphasised a need for targeted, hands-on professional development. These findings underscore the importance of addressing preservice teachers' perceptions and fostering confidence across all TPACK domains to enable the meaningful and sustained integration of emerging technologies in mathematics education.

Introduction

Three-dimensional modelling and printing (3DMP) is increasingly recognised as a promising educational technology for enhancing mathematics and STEM education [1, 2]. Researchers have highlighted that 3DMP can transform abstract mathematical concepts into tangible objects, thereby enhancing student comprehension and engagement, and fostering critical thinking and problem-solving skills [3, 4]. For instance, students who utilised 3D-printed models reported improved understanding and greater enjoyment in learning activities [5, 6]. Such outcomes suggest significant pedagogical potential for 3DMP in the classroom.

However, integrating 3D technologies into mainstream education faces numerous challenges. Adoption remains limited due to barriers including lack of resources, insufficient curricular integration, and perhaps most notably, inadequate teacher training [7, 8]. As Surynková [9] points out, the technical process of 3D printing itself—from digital modelling to slicing and machine operation—requires specialised knowledge. This complexity means that limited technological expertise among teachers can further hinder adoption, compounding the challenges of integration. Consequently, despite growing interest, regular use of 3D printers in K-12 classrooms remains uncommon, with studies showing that teacher attitudes and self-efficacy significantly influence adoption rates [4, 10]. Teachers often feel unprepared or uncertain about their ability to integrate emerging technologies meaningfully into their instructional practices, which significantly restricts the diffusion of such innovations [11, 12].

Addressing these barriers requires targeted professional development for teachers. Rogers' [12] *Diffusion of Innovation* emphasises that for widespread adoption, innovations must align with users' needs, reduce complexity, and provide demonstrable benefits. In educational contexts, preparing teachers through comprehensive training is critical. Mishra and Koehler's [13] *Technological Pedagogical Content Knowledge* (TPACK) framework offers a structured approach for such training, advocating for the integration of technological skills, pedagogical strategies, and subject-specific content knowledge. Effective professional development utilising TPACK can enhance teachers' confidence and promote the meaningful integration of technology into their teaching [2,14].

In this study, we examine preservice mathematics teachers' (PSTs) self-efficacy to integrate 3D modelling and printing into their classroom practice. Grounded in the TPACK framework, we investigate preservice teachers' perceptions of their preparedness to adopt 3D printing technologies. By examining self-efficacy before the intervention, we can gain insight into the profile of the preservice teachers attending the training and tailor the intervention accordingly. The study aims to complement our previous research on the current state of teacher education in 3DMP and to provide insight into the PSTs' beliefs about their capacity to adopt innovative educational technologies in mathematics education.

Theoretical framework

The theoretical framework guiding this study integrates two interrelated constructs for understanding and facilitating technology integration in teacher education: Technological Pedagogical Content Knowledge (TPACK) and self-efficacy. TPACK provides a structured framework for examining the specific competencies required of preservice mathematics teachers to integrate technology into their teaching practices. Complementing this framework, self-efficacy underscores the importance of teachers' confidence in their technological integration capabilities, highlighting that knowledge alone is insufficient without the belief in one's ability to apply it.

TPACK

Technological Pedagogical Content Knowledge [13] serves as a foundational framework for understanding the specific types of knowledge that preservice teachers must develop to effectively integrate emerging technologies, such as 3D modelling and printing (3DMP), into mathematics education. Originally expanding upon Shulman's [15] concept of Pedagogical Content Knowledge (PCK), TPACK incorporates Technological Knowledge (TK) as an additional essential component, emphasising the intersection and interplay between content, pedagogy, and technology.

Within the context of 3DMP, each TPACK domain assumes distinct importance. Technological Knowledge (TK) relates to operating 3D modelling software and printing equipment, as well as managing digital fabrication processes. Pedagogical Knowledge (PK) involves applying effective instructional strategies to leverage 3DMP in educational settings, such as facilitating inquiry-based or project-oriented activities. Content Knowledge (CK), meanwhile, encompasses a deep understanding of mathematical concepts and aligning 3D printing tasks with curricular goals, such as exploring geometric properties or demonstrating functional relationships concretely.

Crucially, effective technology integration arises at the intersection points of these overlapping domains. Technological Content Knowledge (TCK) involves understanding how specific technological tools, such as 3D printing, can clarify mathematical concepts. Technological Pedagogical Knowledge (TPK) involves managing technology-rich classroom activities, including addressing considerations such as classroom management and learner engagement during project-based learning activities. Pedagogical Content Knowledge (PCK) enables teachers to anticipate student difficulties, select appropriate representations, and structure lessons effectively around mathematical content.

The TPACK framework emphasises the integration of these overlapping knowledge areas, aiming to cultivate a holistic competence in preservice teachers. Specifically, our TPACK-informed training program for 3DMP avoids focusing exclusively on isolated technological skills; instead, it embeds technology meaningfully within content-driven and pedagogically sound activities. By structuring course objectives around clearly defined intersections of TPACK domains, we aim to build preservice teachers' self-efficacy and readiness to implement 3DMP technologies in ways that enhance mathematics learning. Ultimately, the use of TPACK in course and questionnaire design enabled us to precisely target and evaluate preservice teachers' perceived self-efficacy relating to how they will integrate emerging technologies, such as 3D modelling and printing, into their future teaching practices.

Self-efficacy

Self-efficacy refers to an individual's belief in their ability to perform specific actions required to achieve particular goals [11]. According to Bandura, self-efficacy influences motivation, persistence, and performance. Individuals with high self-efficacy approach challenges enthusiastically and persist despite obstacles, whereas those with low self-efficacy tend to evade or abandon complex tasks. In educational technology, self-efficacy refers to teachers' confidence in their ability to effectively integrate technological instruments into their teaching. Recent research reinforces that preservice teachers' technology integration self-efficacy significantly affects their likelihood of incorporating technology meaningfully into instruction [16, 17].

In the context of integrating emerging technologies such as 3D modelling and printing into mathematics education, technology integration self-efficacy becomes especially critical. Teachers' perceptions of their technological competence influence their willingness to experiment with new digital tools, adapt pedagogical strategies, and persist through implementation challenges [17]. Recognising this reality, a core aim of our preservice teacher education course was to explicitly build participants' confidence across all domains of the Technological Pedagogical Content Knowledge framework. By considering self-efficacy alongside TPACK competencies, our course aimed to ensure that participants not only acquired the necessary technical skills but also felt empowered to apply these skills confidently and effectively within mathematics teaching contexts.

Methods

Research Questions

This study investigated preservice teachers' self-perceptions regarding their knowledge to integrate 3D modelling and printing into mathematics education through two specific research questions:

1. **How do preservice mathematics teachers perceive their self-efficacy across the different dimensions of TPACK when integrating 3D modelling and printing?**
2. **What reasons do preservice teachers provide for their perceived levels of confidence across each TPACK domain?**

These questions address the critical issue identified in existing literature regarding the need to build preservice teachers' confidence alongside technological, pedagogical, and content knowledge, thereby ensuring balanced and meaningful integration of emerging educational technologies such as 3DMP [14, 16, 17].

Context and Participants

This research focused on an elective 3DMP course for preservice mathematics teachers at a public university in Austria during the winter semester of 2024–2025. The present study analysed data from one group of 22 preservice teachers who voluntarily completed a pre-course questionnaire. Participants were advanced bachelor's degree students with varying levels of teacher experience and proficiency with technological tools.

Data Collection

Data were collected using an online questionnaire designed explicitly around the TPACK framework. The questionnaire consisted of 15 questions. Seven questions required participants to rate their self-confidence across each TPACK subdomain (Technological Knowledge, Pedagogical Knowledge, Content Knowledge, and their intersections) using a 5-point Likert scale. Additionally, eight open-ended questions prompted participants to elaborate on the reasons behind their confidence ratings, with one final, open-ended question for general reflections. This combination of quantitative and qualitative questions was intended to capture both the level of preservice teachers' self-perceived efficacy and the underlying factors influencing these perceptions.

Data Analysis

Data analysis consisted of descriptive statistics for the numerical Likert-scale responses, summarising the preservice teachers' confidence levels across the TPACK domains. Thematic analysis [18] was employed to analyse responses to the open-ended follow-up questions, which asked participants to explain the reasons behind the confidence rating they had chosen. In this sense, the qualitative strand was designed to complement the quantitative data, providing explanatory insights into the numerical scores.

The analysis followed Braun and Clarke's six-phase process. First, responses were read multiple times for familiarisation. Second, initial codes were generated to capture specific reasons provided by participants (e.g., prior experience, lack of technical knowledge, availability of resources). Third, codes were collated into broader categories that reflected patterned responses across participants. For instance, several codes relating to technical difficulties and lack of prior exposure were grouped into a broader category of “technological barriers.” Fourth, categories were reviewed and refined to ensure coherence and distinction. Finally, categories were organised into overarching themes that illustrated the main factors influencing self-efficacy perceptions.

The coding was deductive, as it was guided by the structure of the Likert-scale questions (TPACK domains), but allowed for inductive refinement as new explanations emerged. This approach ensured that the qualitative analysis directly illuminated the quantitative ratings, thereby enabling informed recommendations for refining the course design and addressing specific participant needs.

Results

This section presents an integrated analysis of the TPACK self-assessment data collected from participants, combining quantitative results from Likert-scale items with qualitative insights drawn from open-ended responses, to answer both research questions. The analysis addresses participants’ perceived competencies across the seven TPACK subdomains—Technological Knowledge (TK), Content Knowledge (CK), Pedagogical Knowledge (PK), Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPACK)—with a particular focus on their ability to integrate technology into mathematics teaching.

Descriptive statistics for each of the seven TPACK subdomains are presented in Table 1. Participants responded to one Likert-scale item per subdomain, with responses ranging from 1 (Not at all confident) to 5 (Extremely confident). The results indicate notable differences in self-perceived competence across the TPACK dimensions (see Figure 1).

Table 1. Mean and standard deviation of the Likert-scale answers

Subdomain	Mean	SD
TK	2.41	1.30
CK	3.18	1.30
PK	3.68	1.25
PCK	3.59	1.30
TCK	2.23	1.31
TPK	2.64	1.33
TPACK	3.45	1.30

Participants reported the highest confidence in Pedagogical Knowledge (PK) (M = 3.68, SD = 1.25) and Pedagogical Content Knowledge (PCK) (M = 3.59, SD = 1.30), suggesting a strong sense of efficacy in both general instructional strategies and the specific teaching of mathematics. This quantitative pattern was mirrored in the open-ended responses, where participants frequently referenced their educational backgrounds and preparation for hands-on teaching. As one participant explained, *“As a chemistry student, I had a lot of courses about hands-on activities, especially for the lab,”* while another remarked, *“Teaching mathematical concepts shouldn’t be a problem, but because I am not working yet, I do not have the practical experience to be too confident.”* Such comments indicate that, although some respondents are still gaining practical classroom experience, they feel well-equipped by their studies to approach pedagogical challenges.

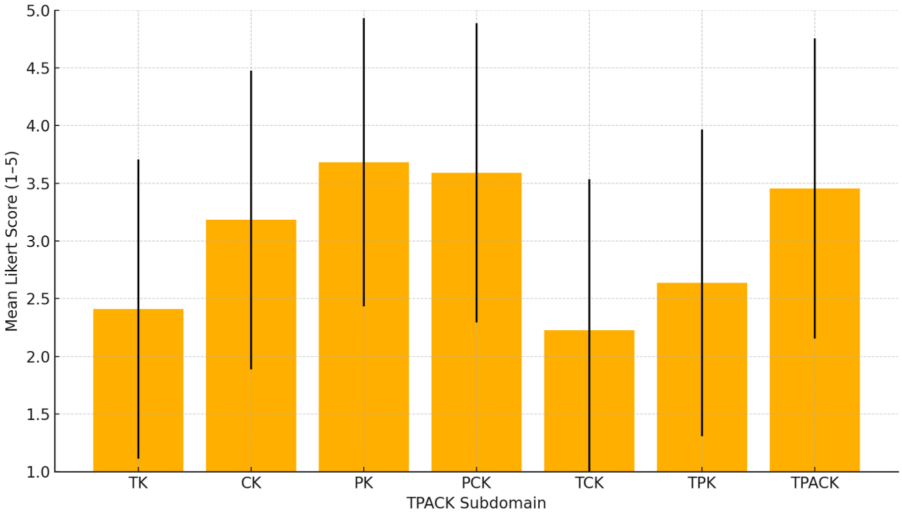

Figure 1. Mean and standard deviation of Likert Scores per TPACK subdomain

Confidence in Content Knowledge (CK) was also relatively high (M = 3.18, SD = 1.30), reflecting a general feeling of preparedness in mathematics. Participants often described themselves as confident in mathematical concepts, even if there were isolated areas—such as financial mathematics or the use of advanced digital tools—where their experience was more limited. For instance, one participant noted, *"I think I understand math concepts pretty good but I previously haven't thought about how to use 3D printing and modeling in my lessons, because 3D printers are not very common in school."* Overall, these qualitative insights reinforce the survey data, painting a picture of participants as educators with solid foundations in both mathematics and pedagogy.

In contrast, confidence related to technology was markedly lower. Technological Knowledge (TK) (M = 2.41, SD = 1.30) and Technological Content Knowledge (TCK) (M = 2.23, SD = 1.31) had the lowest means among all subdomains. This suggests that participants perceive themselves as less proficient in using technology in general and, more specifically, in integrating technological tools into mathematics instruction. The open-ended responses provide context for these lower scores, revealing a landscape characterised by limited exposure and uncertainty. Many participants acknowledged minimal hands-on experience with educational technology, particularly tools relevant to mathematics. As one explained, *"Not really confident, because I have never done that before."* Another participant wrote, *"I've just used GeoGebra for personal use and understanding things while solving exercises. But I never used Tinkercad or other things which you need for 3D printing."* Even those who expressed curiosity about new tools emphasised their unfamiliarity, noting, for example, *"Tinkercad didn't seem hard to learn… I would need a little more time to get more acquainted with the tool, and I haven't used GeoGebra for 3D printing yet."*

Technological Pedagogical Knowledge (TPK) was also comparatively low (M = 2.64, SD = 1.33), indicating limited confidence in employing technology to support general pedagogical practices. Here, participants described using technology only occasionally or tentatively, often for basic tasks. One shared, *"I've used GeoGebra to model a volume of revolution and this helped students to understand the concept better. But I don't teach in a school yet, so I for sure need more training."* Another reflected, *"The usage of digital blackboards is still new to me."* Collectively, these qualitative perspectives reinforce the quantitative findings, highlighting technology integration as a primary area of need and opportunity for growth within the group.

Interestingly, the mean score for Technological Pedagogical Content Knowledge (TPACK) was somewhat higher (M = 3.45, SD = 1.30), approaching the levels observed for PCK and CK. This result may reflect a recognition of the potential for effective integration of technology in mathematics education, even if participants rate their technological skills more modestly. In the open-ended responses, some participants mentioned prior coursework or limited experiences that gave them a sense of what integrated teaching could entail. For example, one participant shared, *"I have had some courses about that, so I guess that I am rather confident about that,"* suggesting that even brief exposure to TPACK concepts can enhance perceived capability. Others acknowledged the gap between theory and practice, expressing both optimism and a need for further development: *"I still need practical experience to learn and improve. Example: I let students learn via digital experiments (which were not possible in a real setting)."* While some admitted uncertainty—*"I don't have much experience, therefore I don't really know…"*—the overall tone suggested that participants viewed technology integration as achievable and valuable, provided they were given the right opportunities and support. This blend of aspiration and realism likely contributed to the relatively elevated TPACK scores.

Taken together, these results suggest that while participants feel well prepared in pedagogy and mathematics content, there is a clear need for targeted professional development in the use and integration of technology, particularly in the context of mathematics teaching. The relatively higher TPACK score may indicate optimism or perceived potential for growth with appropriate support and training.

Discussion and Conclusions

The results of this study offer a nuanced view of preservice mathematics teachers' readiness to integrate 3D modelling and printing into their future classrooms. As highlighted in previous research, the adoption of emerging educational technologies, such as 3DMP, depends not only on the availability of resources and institutional support but also critically on teachers' knowledge, confidence, and beliefs about their capabilities [11, 12, 14].

The present findings reveal a marked contrast between participants' high confidence in content and pedagogy and their much lower confidence in technology-related domains. Quantitatively, preservice teachers reported the greatest sense of efficacy in Pedagogical Knowledge (PK) and Pedagogical Content Knowledge (PCK), reflecting strong foundations in general teaching strategies and mathematics-specific instructional skills. These results resonate with the participants' narratives, which frequently referenced coursework and practice in hands-on, student-centred learning: *"As a chemistry student, I had a lot of courses about hands-on activities, especially for the lab."* Their confidence in Content Knowledge (CK) was also robust, with participants describing themselves as comfortable with core mathematical concepts.

However, a different picture emerged regarding technology. Scores for Technological Knowledge (TK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK) were notably lower. Preservice teachers' responses showed that this gap was shaped by participants' limited experience with digital tools relevant to mathematics education. Many reported that their use of technology was restricted mainly to personal study or simple applications—*"I've just used GeoGebra for personal use… But I never used Tinkercad or other things which you need for 3D printing."*—while others noted that classroom use of such technologies remained largely aspirational. These responses align with existing literature, which highlights that preservice teachers often feel unprepared or lack the self-efficacy to adopt emerging technologies, even when they recognise their pedagogical value [2, 5].

Despite these challenges, the study also surfaced signs of optimism and potential growth. Notably, the mean for Technological Pedagogical Content Knowledge (TPACK) was higher than expected given the individual technology-related scores. Participants attributed this to exposure during their coursework and a growing awareness of technology's capacity to enhance mathematics learning. Some described initial experiences in integrating technology with pedagogy and content, for example, through digital experiments or software demonstrations, even as they acknowledged that *"I still need practical experience to learn and improve."* This suggests that while confidence may lag behind knowledge, preservice teachers are open to growth and are motivated to develop their abilities. Participants also made connections between 3DMP and specific mathematical content. For example, several mentioned the potential to represent geometric objects such as Platonic solids, explore cross-sections of three-dimensional solids, or model algebraic surfaces. Such examples illustrate how 3DMP can be directly tied to mathematics learning, particularly in fostering spatial reasoning and supporting students in visualising abstract concepts.

Taken together, these results emphasise the need for teacher education programs to address the full range of TPACK domains, rather than focusing narrowly on technological skills or content knowledge in isolation. The TPACK framework, as adopted in this course, offers a valuable roadmap: adequate preparation requires that preservice teachers not only acquire discrete knowledge but also develop the confidence and integrative capacity to apply technology in pedagogically and mathematically meaningful ways. Building self-efficacy must be as central as building competence; as [11] and recent research [17] have shown, confidence is critical to teachers' willingness to persist with and adopt innovations in the classroom.

The qualitative insights from this study reinforce the importance of starting from the perceptions and experiences of preservice teachers. Their reflections reveal both the barriers they face and the forms of support that would help them progress—such as more hands-on practice with 3DMP tools, concrete examples of integration in mathematics, and structured opportunities to experiment in low-stakes environments. By designing professional development that is attuned to these needs and foregrounds the integration of all TPACK dimensions, teacher education programs can better prepare future educators to harness the full pedagogical potential of emerging technologies.

It is also important to note that technology was not only the object of investigation but also the medium through which findings were generated. The study design required participants to reflect on their engagement with specific digital tools for 3D modelling (e.g., Tinkercad, GeoGebra 3D), and this experience directly shaped their self-reported confidence levels. In this sense, technology actively assisted in eliciting the qualitative insights and quantitative ratings that form the basis of our conclusions.

Like all empirical work, this study has limitations. The relatively small sample size (N = 22) restricts the generalisability of the findings beyond the specific context of this program. The results should therefore be interpreted as exploratory and illustrative rather than conclusive. However, the combination of quantitative ratings and qualitative explanations provides rich insights into preservice teachers' perceptions, which can inform future research and course design. Larger-scale studies, potentially conducted across different institutions and cultural contexts, would be valuable for testing the robustness of these findings and for further examining the interplay between technological self-efficacy, TPACK development, and the adoption of 3DMP in mathematics education.

In conclusion, supporting preservice mathematics teachers in developing both their skills and confidence in integrating these tools is necessary for the diffusion of innovations like 3DMP in mathematics education. Teacher educators should prioritise not only the delivery of knowledge but also the cultivation of self-efficacy across all domains of TPACK, thus empowering new teachers to become confident, creative, and reflective technology integrators.

References

[1] Lin, K.-Y., Hsiao, H.-S., Chang, Y.-S., Chien, Y.-H., & Wu, Y.-T. (2018). The effectiveness of using 3D printing technology in STEM project-based learning activities. EURASIA Journal of Mathematics, Science and Technology Education, 14(12).

[2] Tejera, M., Galiç, S., & Lavicza, Z. (2025). 3D modelling and printing in teacher education: A systematic literature review. Journal for STEM Education Research.

[3] Bull, G., & Groves, J. (2009). The democratisation of production. Learning & Leading with Technology, 37(3), 36–37.

[4] Novak, E., & Wisdom, S. (2018). Effects of 3D printing project-based learning on Preservice elementary teachers' science attitudes, science content knowledge, and anxiety about teaching science. Journal of Science Education and Technology, 27(5), 412–432.

[5] Anđić, B., Lavicza, Z., Ulbrich, E., Cvjetićanin, S., Petrović, F., & Maričić, M. (2024). Contribution of 3D modelling and printing to learning in primary schools: A case study with visually impaired students from an inclusive Biology classroom. Journal of Biological Education, 58(4), 795–811.

[6] Tejera, M., Bedewy, S. E., Galván, G., & Lavicza, Z. (2022). 3D printing and GeoGebra as artefacts in the process of studying mathematics through architectural modelling. Proceedings of the 13th ERME Topic Conference MEDA3, 244–251.

[7] Ford, S., & Minshall, T. (2019). Invited review article: Where and how 3D printing is used in teaching and education. Additive Manufacturing, 25, 131–150.

[8] Trust, T., & Maloy, R. W. (2017). Why 3D print? The 21 st -century skills students develop while engaging in 3D printing projects. Computers in the Schools, 34(4), 253–266.

[9] Surynková, P. (2023). 3D printing for mathematics education. In Electronic Proceedings of the 28th Asian Technology Conference in Mathematics (Invited Paper).

[10] Anđić, B., Šorgo, A., Helm, C., Weinhandl, R., & Lang, V. (2023). Exploring factors affecting elementary School teachers' adoption of 3D printers in teaching. TechTrends, 67(6), 990–1006.

[11] Bandura, A. (1997). Self-efficacy: The exercise of control. W. H. Freeman.

[12] Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.

[13] Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A framework for teacher knowledge. Teachers College Record: The Voice of Scholarship in Education, 108(6), 1017–1054.

[14] Koehler, M. J., Mishra, P., & Cain, W. (2013). What is Technological Pedagogical Content Knowledge (TPACK)? Journal of Education, 193(3), 13–19.

[15] Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15(2), 4–14.

[16] Tondeur, J., Van Braak, J., Siddiq, F., & Scherer, R. (2016). Time for a new approach to prepare future teachers for educational technology use: Its meaning and measurement. Computers & Education, 94, 134–150.

[17] Valtonen, T., Leppänen, U., Hyypiä, M., Kokko, A., Manninen, J., Vartiainen, H., Sointu, E., & Hirsto, L. (2021). Learning environments preferred by university students: A shift toward informal and flexible learning environments. Learning Environments Research, 24(3), 371–388.

[18] Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101.