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ORIGINAL PAPER

Incorporating a 3D Printing Integrated STEM Module into a College Mathematics Content Course: Perceptions of Pre-service Elementary Teachers

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Abstract
This study explored pre-service teachers' perceptions of a 3D printing integrated science, technology, engineering, and mathematics (STEM) module within a college-level mathematics content course. Data from surveys and reflections collected from nineteen participants were analyzed. Results indicated that the pre-service teachers perceived improvement in their understanding in several areas: 3D printing technology, software utilization, the 3D crystal lattice structures, and the application of mathematical concepts in STEM contexts. The integration of 3D printing technology within the STEM module facilitated an experiential learning environment, enhancing the visualization and comprehension of geometric and measurement concepts. Furthermore, the exposure to the practical applications of mathematical concepts in fields such as chemistry, engineering, and technology enabled pre-service elementary teachers to situate their understanding within a more profound, interconnected, and pragmatic framework.

Keywords 3D printing · Mathematics · Integrated STEM · Pre-service elementary teachers · Geometry

Introduction

To bolster science, technology, engineering, and mathematics (STEM) literacy across all student demographics, STEM education has been the focus of heightened interest in recent years (Bybee, 2013). The consensus underscores the importance of early STEM education, ideally commencing at the elementary level or sooner, as pivotal for establishing a robust groundwork for students' subsequent STEM endeavors (Bybee, 2013). The current movement in STEM education advocates for an integrated approach that employs inquiry-based learning to immerse students in complex, real-world problem-solving (Margot & Kettler, 2019). This integrated approach allows students to identify and experience the connections between STEM concepts and skills learned in the school and their applications in real-world contexts (Buckner & Boyd, 2015; Bybee, 2013). As such, it is likely to promote motivation for learning, and improve student interests, achievement, and persistence (National Research Council, 2013). Nonetheless, reports have shown a deficiency in elementary educators' training in mathematics and science (National Academy of Engineering, National Research Council [NAE NRC], 2014), with even less exposure to engineering and technology. The shortfall in teacher education programs resulted in educators who "did not feel fully prepared to integrate STEM subjects" within their curriculum (Margot & Kettler, 2019, p.12).

In preparation for teaching mathematics and science, U.S. elementary pre-service teachers (PSETs) typically complete mathematics and science content and pedagogy courses within their teacher education programs (Garner et al., 2023; Liu, 2020). However, the mathematics content courses are often taught in traditional ways, focusing on concept mastery and the application of solutions to well-defined problems found in textbooks. The significance and application of mathematics within actual science, technology and engineering contexts are frequently underrepresented in these

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courses, consequently restricting PSETs' opportunities to comprehend the interconnectivity of various STEM disciplines (Liu, 2020). By incorporating STEM inquiries into college-level mathematics content courses, PSETs can cultivate a more profound understanding of the application of mathematical concepts in real-world scenarios and expand their perspectives on the role of mathematics in addressing STEM-related challenges.

The integration of technology into STEM inquiries has been pivotal in offering interactive and hands-on learning experiences. For example, the inclusion of 3D printing technology engages students in experiential activities. Utilizing 3D printing for design and problem-solving within STEM contexts not only deepens students' understanding of STEM concepts but also fosters their creativity and imagination (Brown & Burge, 2014; Lin et al., 2018, 2021). Moreover, 3D printing allows learners to investigate the interrelationships among various STEM subjects, potentially augmenting their interest in these fields (Novak & Wisdom, 2018). Existing research has employed 3D printing technology to assist pre-service teachers or K-12 students in visualizing and modeling their reasoning (e.g., Asempapa & Love, 2021; Huleihil, 2017) and to learn from productive failure (Dickson et al., 2021) within mathematics education. However, there is a scarcity of studies on the integration of 3D printing into STEM inquiries that specifically enhance the application of mathematical concepts, such as geometry and measurement, in the realm of teacher preparation. This study seeks to explore pre-service teachers' perceptions of a 3D printing integrated STEM module within a college-level mathematics content course.

Literature Review

The Integrated STEM Approach

STEM education has garnered significant attention in recent years due to the growing acknowledgement of STEM-related fields as vital to the future workforce. It plays a pivotal role in equipping students for success in these areas. Early engagement with STEM can inspire students' interest and drive to pursue careers in the STEM-related fields. Bybee (2013) also underscores that early development of STEM literacy is foundation for enabling students to apply STEM concepts to real-world challenges and to make knowledgeable decisions as conscientious members of society.

The integrated STEM approach, endorsed by the education research community, affords learners the opportunity to develop knowledge across multiple relevant disciplines and to comprehend the interconnections and practical applications of these concepts (Breiner et al., 2012; Gomez & Albrecht, 2013; Margot & Kettler, 2019; Shernoff et al., 2017). This approach aims to amalgamate elements of science, technology, engineering, and mathematics into cohesive instructional units that draw upon real-world connections (Moore et al., 2014). Employing project-based or inquiry-based learning strategies, the integrated approach engages students in authentic problem-solving activities, cultivates collaboration, critical thinking, and creativity, thereby resulting the learning experience more interconnected and relevant (Stohlmann et al., 2012).

Integrated STEM activities facilitate the development of cross-disciplinary knowledge and address the challenge K-12 students face in grasping the relevance and application of STEM concepts, as well as in synthesizing ideas across various fields (National Academy of Engineering & National Research Council [NAE & NRC], 2014; Shernoff et al., 2017). The research literature further advocates for the integration of technology into STEM curricula. For instance, employing technological tools such as 3D printers in STEM education equips students with tangible, experiential learning through the processes of design and creation. This hands-on approach can enhance their grasp of STEM concepts and cultivate creativity and imagination (Lin et al., 2021).

3D Printing in Mathematics Education

3D printing technology has become increasingly prevalent as an instructional resource, particularly within STEM education. This technology enables the fabrication of three-dimensional objects through an additive process, where material is applied in successive layers (Cheng et al., 2021; Scalfani & Vaid, 2014). The procedure initiates with the creation of a 3D digital model, often using computer-aided design (CAD) software. Once the model is optimized for printing, the file is transferred to a 3D printer, which methodically extrudes plastic filament to construct the object layer by layer (Brown, 2015; Novak & Wisdom, 2018).

Although 3D printing technology has been utilized in informal learning environments such as museums and libraries for over a decade, its integration into formal education curricula in K-12 and higher education sectors is a relatively recent phenomenon. The shift can be attributed to the decreased cost of 3D printers and the availability of open-source CAD programs (Elrod, 2017; Johnson et al., 2015). A recent scoping review by Ng et al. (2022) indicated a greater prevalence of research on the use of 3D printing within formal mathematics education compared to informal settings, suggesting a more substantial adoption of the technology in structured educational environments. However, studies have identified a lack of knowledge and experience with 3D printing and modeling among educators (e.g., Trust et al., 2021), and a low adoption rate of 3D printing, particularly in elementary schools (Branko et al., 2023). These findings highlight the imperative need for teacher education programs to enhance training in emerging 3D printing technologies. Additionally, research on the integration of 3D printing into pre-service teacher education remains limited (Novak & Wisdom, 2018).

Research has demonstrated that 3D printing technology can enhance STEM education by providing students with visualization and hands-on learning experiences (Cheng et al., 2020). The use of 3D printing for creation and problem-solving enables students to comprehend spatial relationships among objects, thereby fostering the development of spatial and visualization skills (Brown, 2015; Ng et al., 2022), skills that are essential in many STEM careers. In addition, interactive experiences with 3D printing technology have been shown to increase students' interests and motivation in STEM fields. Cheng et al. (2020) found that the degree of STEM integration in 3D printing activities directly influenced students' motivation in mathematics. Another study by Dickson et al. (2021) revealed that integrating 3D printing into middle school mathematics lessons encourage productive learning experiences and resilience in students through the exploration of "productive" failures.

3D printing can augment learning in mathematics by aiding in the visualization of three-dimensional objects. Students can create digital or physical models of geometric shapes such as spheres, cylinders, cones, and pyramids, thereby gaining a clearer understanding of these forms (Ng et al., 2022). A study on primary students using 3D pens demonstrated the potential of these tools in helping students solidify their geometric learning outcomes (Ng et al., 2020). The manipulation of digital 3D shapes via CAD software can help young learners grasp concepts related to dimensions, directions, positions, and orientations (Panorkou & Pratt, 2016). Additionally, the use of physical models allows students to visualize mathematical concepts and their interrelationships, potentially improving their understanding of the topics like the volume of 3D solids (Ng, 2017). Ng et al.'s (2022) scoping review indicated that 3D printing has been utilized to visualize mathematical concepts at all levels of education, enhancing the learning of geometric properties and cross-sections in elementary school (Ng & Ferrara, 2020), as well as functions and calculus in high school (Dilling & Witzke, 2020).

Furthermore, the design and creation of artifacts through 3D printing can offer students meaningful opportunities to apply mathematical concepts. For example, students can observe how a 3D digital model is positioned within the software's coordinate system, monitor the object's creation layer by layer on the printer's build plate, and consider the precise measurements and placements required (Dickson et al., 2021). They can also evaluate the scale of the object relative to printing time and calculate the costs and materials needed, considering the design's complexity and size (Ng, 2017). The use of various mathematical concepts during the artifact creation and problem-solving process with 3D printing technology helps deepen students' understanding of abstract mathematical concepts in practical contexts and increase the perceived relevance of mathematics in real-world applications.

Integrating 3D Printing in Teacher Education to Enhance STEM Education

The integration of 3D printing into teacher education has demonstrated promising potential to enhance STEM education. In their scoping review, Ng et al. (2022) identified six articles focused on equipping primary or secondary teachers with the skills to design 3D printing lessons. Asempapa and Love (2021) provided a day-long professional development session for in-service teachers, emphasizing the application of mathematical modeling concepts to design 3D printing solutions for integrative STEM lessons. Their participants reported increased knowledge in specific areas of mathematical modeling, and most teachers expressed a higher likelihood of incorporating mathematical modeling into their teaching. Moreover, Kaya et al. (2019) conducted a study that integrated 3D printing into an elementary science teaching methods course, emphasizing the engineering design process, and observed an increase in pre-service teachers' self-efficacy beliefs in teach engineering effectively. Novak and Wisdom (2018) implemented a project-based learning activity involving 3D printing for pre-service elementary teachers, which resulted significant improvement in their science teaching efficacy, interest in science, perceived competence in K-3 technological and engineering design science standards, as well as a significant reduction in their anxiety about teaching science. Cheng et al. (2024) investigated the beliefs of K-12 teachers and found that while teachers perceived 3D printing integration as beneficial for students, they needed to develop the ability to use 3D printers and to connect 3D printing with curricula. This study supports the need for integrating 3D printing in teacher education to develop teachers' knowledge and skills in 3D printing technology and the pedagogical knowledge to integrate it into their curricula. Overall, teacher education programs can benefit from incorporating 3D printing technology, thereby boosting educators' confidence in meeting STEM standards, and improving their attitudes toward STEM education. With the growing accessibility of 3D printing technology, further research is essential to determine effective applications across various STEM disciplines, supporting teacher education and future teaching practices.

Research Questions

This study explored pre-service teachers' perceptions of a 3D printing integrated STEM module within a college-level mathematics content course. The developed module engaged

PSETs in creating 3D objects by connecting and applying geometry and measurement concepts within STEM contexts and using 3D printing technology. The research questions that guided this study are:

1. How do pre-service teachers perceive their learning within a 3D printing integrated STEM module?
2. How do per-service teachers perceive the 3D printing integrated STEM module itself?

Research Method

This study was guided by the case study method, which employs real-life contexts as research settings and is well-suited to addresses descriptive and exploratory questions that typically begin with 'what' or 'how' (Yin, 2012).

Participants and Context

Twenty-five pre-service teachers enrolled in a mathematics content course at a northwestern university in the US were recruited in this study. However, data from only 19 participants were included in this paper, as they completed data collection process. All 19 participants were female, with an average age of 21.5-year-old. Of these participants, nine were sophomores, five were freshmen, four were juniors, and one was in her fifth year. The mathematics content course is a mandatory component of the teacher education program for all pre-service teachers. Students worked in groups of three or four in the STEM module.

3D Printing Integrated STEM Module

The STEM module, "3D Crystal Lattice Structure of Solids: Visualization and 3D Printing", was designed to help PSETs connect the geometry concepts with real-world applications in a practical and engaging way. Added to the PSETs' mathematics content course, this module provided a context for PSETs to understand how geometric concepts, such as regular polygons, platonic solids, and symmetry, is observed and applied in science and engineering. Connecting to the chemistry concepts, the module offered five interactive simulation applications for exploring various chemical structures, including primitive cubic structure, face-centered cubic structure, and ideal perovskite structure. These structures can be observed in everyday chemicals (e.g., sodium chloride/rock salt), as well as in cutting-edge research on solar energy (e.g., perovskite).

The STEM module comprised three 75-min class sessions. During these classes, PSETs were enabled to design and visualize crystal lattice structures using interactive simulation applications and 3D printing. In the first session, PSETs were introduced to key STEM concepts relevant to the topic, such as various chemical compounds and structures, and their connections to everyday uses. PSETs then utilized interactive simulation applications (see Fig. 1 for an example) to analyze these chemical structures. PSETs adjusted parameters such as atom size, interatomic distances, and the overall scale, and rotated the models to observe cubic patterns and symmetries. By manipulating these parameters, they designed various crystal lattice structures, which they later 3D printed.

In the subsequent sessions, PSETs learned about the operation of 3D printers and experimented with related platforms and software, including Thingiverse and Cura. Thingiverse, a web platform and repository, allows users to upload, share, and download free 3D printable designs. Due to a lack of time for PSETs to learn 3D modeling skills, they were directed to explore the 3D models already designed and shared on Thingiverse to acquire printable 3D designs. PSETs were also introduced to Cura, a software used in this study to prepare 3D models for printing by converting them into instructions for 3D printers. After exploring these two resources and identifying 3D designs for printing, PSETs practiced 3D printing by transferring source files from Thingiverse and their designed crystal lattice structures from the simulations into Cura to prepare them for 3D printing. Within Cura, they fine-tuned print settings and adjusted scaling to achieve optimal printing quality, considering the limitations of time and resources. Figure 1 presents an interactive simulation application interface from the module, detailing a solid structure following parameter adjustment, alongside examples of the 3D printed solids. The researchers developed worksheets for PSETs to guide the inquiry process. Additionally, STEM experts, including a faculty member and a doctoral research assistant in Computer Science, aided with the 3D printing process.

Data Sources and Data Analysis

Data on the PSET's perceived learning and their perceptions of the 3D printing integrated STEM module were gathered through surveys and student reflections. Pre- and post-module surveys assessed the PSETs' self-reported knowledge of 3D printing and software application, asking them to rate their understanding on a scale from 1 (*Not Knowledgeable at All*) to 5 (*Extremely Knowledgeable*). For instance, one survey item prompted, "Please rate your knowledge level in the following technology-related activities: 3D printing." Additionally, the post-module survey also had participants rated the statement, "The STEM module facilitated my understanding of how Mathematics, Science, Technology, and Engineering relate to real-world phenomena," using a five-point Likert scale ranging from *Strongly Disagree* to *Strongly Agree*.

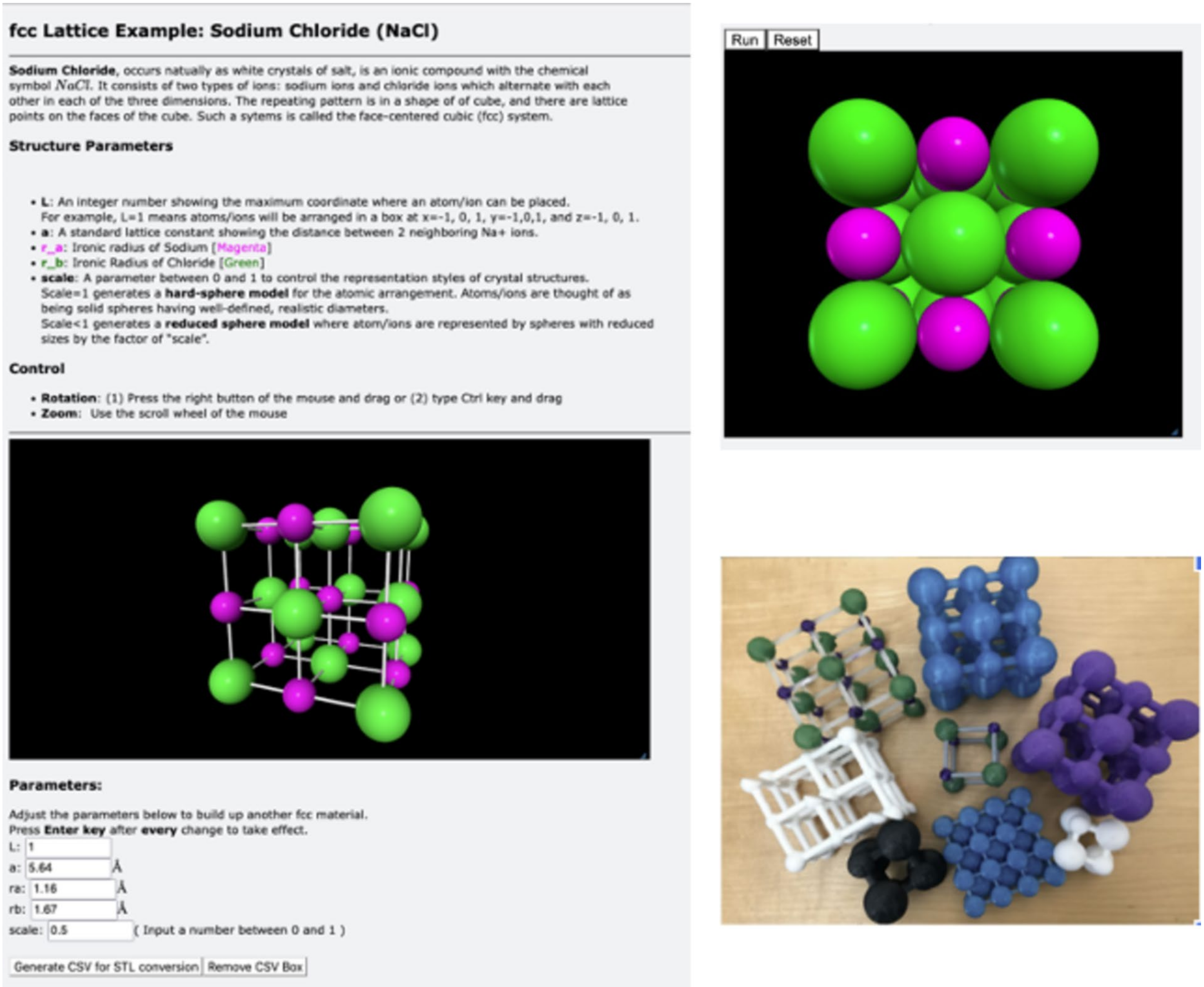

Fig. 1 Interface of the interactive simulation application (Left), a resulted solid structure following parameter adjustments (Upper Right), and examples of 3D-printed solids (Bottom Right)

Reflections were requested from the PSETs as part of their coursework, guided by specific questions to foster deep reflection on their learning experiences within the course. For example, reflection prompts included questions such as, "How well does the STEM module/3D crystal structure solids activity connect to the rest of the class materials? What did you learn and what gaps do you believe you still have in your understanding?" Each PSET was required to write a minimum of two paragraphs in response to the set of prompts. Both the survey questions and reflection questions were reviewed for validity by a group of experienced STEM faculty members.

The quantitative data from the pre- and post-surveys were analyzed using descriptive statistics to calculate means and standard deviations for each survey question. Wilcoxon signed-ranks tests were conducted to examine the differences in PSETs' perceived learning before and after completing the STEM module, as the data were not normally distributed. The reflection data were analyzed using thematic analysis, a qualitative approach that involves identifying patterns and themes within the data and developing a coding framework to systematically categorize the data into meaningful themes (Braun & Clarke, 2006). Following the suggestions of Braun and Clarke (2006), the researchers first familiarized themselves with the survey data by reading and re-reading it to gain a comprehensive understanding of the content. Then, the individual ideas within the reflection data were coded, and similar ideas were grouped together to create categories. Relevant categories were further grouped to create themes that represent important and patterned responses in the data set (Braun & Clarke, 2006). The use of survey and critical reflection data sources in this study allows for a comprehensive and triangulated analysis of the data, providing a robust understanding of PSETs' perceived learning and their perceptions of the 3D printing integrated STEM module.

Results

Perceived Learning in a 3D Printing Integrated STEM Module

The perceived learning of PSETs was assessed through survey questions as well as reflection. The pre- and post- survey questions were used to assessed participants' learning in 3D printing and software use. The pre- survey results indicated that participants rated their prior knowledge from "*Not Knowledgeable at All*" to "*Moderately Knowledgeable*" about 3D printing (M = 1.42, SD = 0.69) and from "*Not Knowledgeable at All*" to "*Very Knowledgeable*" about software use (M = 2.26, SD = 1.12). The post-survey results showed that, on average, participants rated themselves between "*Moderately Knowledgeable*" to "*Very Knowledgeable*" for both 3D printing (M = 3.84, SD = 0.96) and software use (M = 3.58, SD = 1.31). Figure 2 below presents the mean scores for knowledge about 3D printing and software use in the pre- and post- surveys. Wilcoxon signed-ranks tests revealed that after experiencing the 3D printing integrated STEM module, the participants reported significantly increased knowledge of 3D printing ($Z = -3.895$, $p < 0.001$) and significantly increased knowledge of using software ($Z = -3.354$, $p < 0.001$) compared to the pre-survey results.

The theme analysis of the reflection data identified that students perceived their learning gain in the following three areas: 1) knowledge and skills in 3D printing, 2) knowledge in 3D crystal lattice structures, and 3) mathematics in the context of STEM.

Knowledge and Skills in 3D Printing

The reflection data indicated that most participants ($n = 15$) acquired valuable knowledge and practical skills in 3D printing, encompassing both 3D printers and 3D printing software aspects. They reported learning to operate a 3D printer, with one participant sharing that "through this class, I have learned how to use a 3D printer, including how to turn it on, heat it up, and connect the computer software to the printer." Additionally, participants developed proficiency in using 3D printing software, gaining the ability to "control the size and placement of the solid and to split an object in half," as one participant noted. When preparing objects for 3D printing, participants manipulated the digital models using Cura. Within the software, they adjusted the orientation of 3D objects to examine properties such as coordinates and scaled the models to appropriate sizes to ensure feasible printing times (e.g., 3 hours versus 50 minutes). These reflections corroborate the survey findings that PSETs enhanced their knowledge and skills in 3D printing, including the adept use of 3D printers and software.

However, some participants expressed frustration due to technical issues with the 3D printers. One participant reflected on the challenges they encountered and stated that "one of the biggest challenges we came upon was that the printers do not always work the first time, it taught us to be patient, especially with technology." At the same time, these technical issues also sparked participants' curiosity and desire to learn more about 3D printing technology. For example, another participant expressed that,

> I also knew a lot about the 3D printing process but I feel there was more I could have learned about such as why it has to heat up so much before printing and what the probing of the corners means. There were times where the 3D printer would get stuck …but I had no idea how to fix it so maybe learning how to fix simple problems.

Given that the STEM module dedicated only one class session to introduce 3D printers and software, PSETs noted gaps in their learning through reflections. These insights can serve as valuable feedback for enhancing the curriculum design to bridge these gaps.

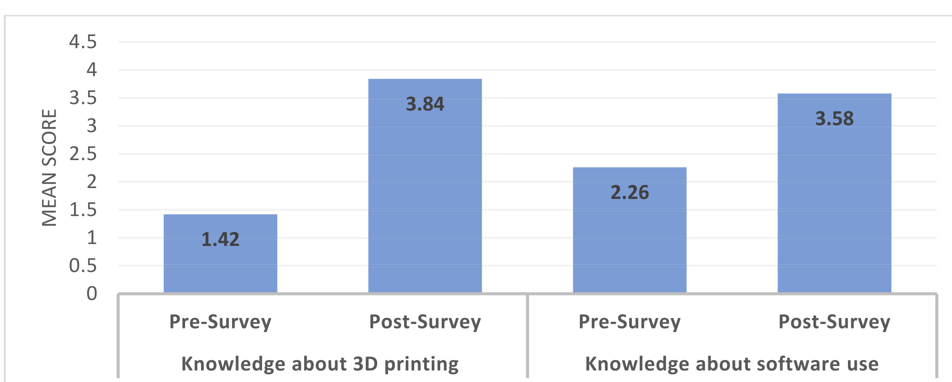

Fig. 2 Comparison of PSET mean scores for knowledge about 3D printing and software use before and after intervention

Knowledge in 3D Crystal Lattice Structures

The second theme in PSETs' perceived learning pertains to their understanding of the 3D crystal lattice structures. Through the STEM module, PSETs were introduced to common crystal lattice structures, such as those found in table salt and batteries. They engaged with interactive simulations to examine various crystal lattice structures, manipulating parameters like atom size and distance to observe changes in the crystals' appearance. One participant noted,

> In class, we started by learning about the different solids and what they look like. This helped us understand what the FCC [face-centered cube] solids would look like as well as how to classify them. It also gave us a sense of what the 3-D shapes would look like on a 2-D sheet of paper or on the computer screen.

Another participant observed, "By altering different values away from their original state, it changed the look of the crystal structure solids which, in turn, changed the volume and surface area. However, the symmetry always stayed the same."

Furthermore, PSETs recognized that different crystal structures exhibit various forms of symmetry, including rotational symmetry and reflectional symmetry, and that patterns change based on the atomic composition of the molecule. One participant highlighted that "the website [interactive simulations] where you could look at all the solids was very interesting and showed how similar solids can be but with one little switch, it can completely change everything." While many participants found the interactive simulations for visualizing crystal structures interesting and informative, some wished to delve deeper into understanding the full range of structures and their distinct characteristics to better convey this knowledge in their future teaching roles.

Mathematics in the Context of STEM

The third theme in PSETs' perceived learning revolves around the application of mathematics within the STEM context. The STEM module provided opportunities for PSETs to apply mathematical concepts to real-world situations. In their reflection, PSETs detailed their use of mathematical concepts learned in the course, such as measurements, regular polygons, rotational and reflectional symmetry, surface area, volume, and scaling, in the design and 3D printing of crystal lattice structures. For example, one participant described how 3D printing reinforced the concept of volume, stating that "you would look at volume as a whole shape or figure the 3D print was made from the bottom up and you can see every side included when you calculate volume." Another participant shared her experiences with applying measurement concepts in the module,

> In class, we learned about volume and different attributes of geometry such as length, width, height, area, and circumference. These were all displayed when we got to adjust the height, volume, and length of the 3D structures to create our own unique shapes.

Additionally, participants observed practical applications of the mathematical concepts of rotational and reflectional symmetry in 3D printing crystal lattice solids. One participant highlighted the need to print a 3D crystal lattice solid in halves due to balance issues in 3D printing, noting that this was an excellent demonstration of applying symmetry concepts: "when printing the solids, they would have to be printed in half. So having two symmetrically even pieces then glued together would give us a full shape."

Some participants reflected on how the STEM module allowed them to appreciate the use of mathematical concepts in real-world contexts. One participant thoughtfully noted, "the activity of 3D printing, in itself, facilitates thought processes related to mathematics, specifically geometry. The process itself relies heavily on the properties of geometry to create a stable figure." Another participant mentioned, "I experienced a great example of how we use geometry in the real world. The 3D structure online activity really helped me visualize the idea of 3D printing and put the class curriculum into perspective."

Through the STEM module, which linked course content with practical applications, participants gained a more profound understanding of how mathematics is employed in STEM fields. This contextualized approach to mathematics learning and application is poised to benefit their future teaching endeavors.

Perceptions of the 3D Printing Integrated STEM Module

Positive Perceptions of the STEM Module by PSETs

A post-survey question asked PSETs to rate on a five-point Likert scale, ranging from *Strongly Disagree* to *Strongly Agree,* whether the STEM module helped them connect mathematics, science, technology, and engineering content to real-world phenomena. All except one PSET rated this statement as *Somewhat Agree* or *Strongly Agree,* with an average rating of 4.2 out of 5. Reflections from PSETs also revealed a generally positive perception of the STEM module, noting it was engaging and providing hands-on activities that applied their learning. Participants described the STEM module using adjectives such as "interesting," "very fun," "informative," "effective," and "important." One participant reported, "I loved learning about 3D printing… I found the module to be very effective in keeping myself engaged throughout this course…" Another participant reflected that "I really enjoyed the STEM learning, as I have never used a 3D printer before, and was thankful that I got the opportunity."

Several participants noted that they were initially intimidated by the subject of the STEM module when they first introduced to it. However, after engaging with the module, they reported more open and positive attitudes. One reflected that "at first, I was a little intimidated by the 3D printers because I am not that great with technology, but once we started, I realized how easy it was to get the hang of it, and I also had some fun along the way." Similarly, another participant shared, "I thought this was a very fun activity that we did, and I learned a lot. I am proud to say I now know how to 3D print, and it was a lot easier to learn than I first perceived when told about the assignment." Overall, the positive feedback from PSETs underscores the engaging and effective nature of the STEM module, with some participants overcoming their initial reservations and developing a more favorable attitude towards the subject through hands-on learning experiences.

Hands-on Experiences Reinforcing Mathematical Concepts in the STEM Module

Several PSETs reflected on how the hands-on experiences offered in the STEM module reinforced or enhanced their understanding of the mathematical concepts learned in the course and prepared them for future teaching. One participant appreciated how the hands-on activity helped solidify her learning, especially through visualizing concepts during the 3D printing process, stating, "I am a very visual learner, so being able to work with different materials and then make those connections to the lesson we learned in the lecture format really helped me tremendously."

Participants also recognized the importance of incorporating hands-on STEM activities that involve mathematics in future teaching. One participant remarked,

> ...our class is centered around teaching, so experimenting with a hands-on project was great for our class, as future teachers, to explore exciting new ways we can teach our students. STEM activities involve math, so teachers should create STEM projects that can help their students learn or reinforce the math they are teaching in a tangible and interesting way.

During the process of preparing 3D objects for printing, participants were able to apply various mathematical concepts like scaling (a similarity concept) and symmetry in the real-life context. For instance, one participant related the concept of volume to her observation of the additive layers of 3D shapes produced by the printer. Another participant described adjusting the dimensions of a 3D model to different scales in Cura, effectively creating similar objects of various sizes. Additionally, a participant demonstrated the application of symmetry by detailing the process of printing a 3D crystal solid in two halves and then joining them together.

Moreover, participants recognized the interconnectedness of mathematics in various STEM disciplines. One individual emphasized the STEM module's role in showing the practical importance of mathematics and geometry in fields such as engineering. They pointed out that even at the elementary school level, understanding geometry is fundamental to STEM activities involving building or creation, where decisions about shapes and surfaces are essential.

Discussion

Perceived Learning in a 3D Printing Integrated STEM Module

This case study explored PSETs' perceived learning within a 3D printing integrated STEM module, revealing enhanced knowledge and skills in areas such as 3D printing, software use, knowledge of 3D crystal lattice structures, and the application of mathematics within STEM context. Pre- and post-survey results indicated a significant increase in participants' knowledge of 3D printing and software use following exposure to the STEM module. PSETs reported increased proficiency, gaining valuable operational skills for 3D printers and software applications. This outcome is promising, demonstrating that PSETs can acquire foundational 3D printing and software knowledge from a brief integrated STEM module, corroborating findings from Ng et al. (2022), which suggest that 3D printing bolsters students' digital competencies, including modeling and spatial skills.

Nonetheless, technical issues during the 3D printing activities presented obstacles, echoing difficulties reported in prior studies (e.g., Bower et al., 2020; Cheng et al., 2020; Dickson et al., 2021; Song, 2018). Although learning from mistakes is a crucial component of Moore et al. (2014) framework for quality K-12 STEM education, and productive failure can be beneficial (Dickson et al., 2021), such technical issues may still cause frustration and demotivation. To mitigate this, future implementations should promote a growth mindset in dealing with technical challenges and provide comprehensive troubleshooting guidance to better prepare PSETs for potential difficulties. This is increasingly important as 3D printing technology gains prominence across disciplines, and troubleshooting abilities become essential for teachers integrating this technology in their classrooms.

Analysis of PSETs' reflections revealed that participants not only gained knowledge of 3D crystal lattice structures but also effectively applied mathematical concepts within the STEM applications during the module. Participants adeptly utilized mathematical concepts in the design and 3D printing of their crystal structures. Digitally manipulating 3D objects with 3D printing preparation software enhanced participants' visualization of symmetry, patterns, and the function of scaling. This finding aligns with prior literature, demonstrating that the use of 3D computer-aided design can enhance the development of spatial skills and mathematical concepts like geometry shape and space (Ng & Chan, 2019), and dimensions, such as directions, positions, and orientations (Panorkou & Pratt, 2016). It also supports the findings of Ng et al. (2022) that 3D printing helps students overcome difficulties about 3D geometry such as mental rotation and mental transformation of 3D figures, making abstract thinking more concreate (e.g., Huleihil, 2017; Ng et al., 2020).

The STEM module effectively allowed participants to apply mathematical concepts and recognize the relevance of mathematics within STEM fields. This underscores the interdisciplinary nature of STEM education and aligns with the objectives of the integrated STEM approach. This approach focuses on interconnecting learning across multiple STEM disciplines for application in real-world contexts, thereby enhancing the quality of K-12 STEM education (Moore et al., 2014). This study showcases the potential of a 3D printing integrated STEM module to enhance pre-service teachers' comprehension of 3D printing and software use, preparing them to incorporate this technology into their future educational settings.

Perceptions of the 3D Printing Integrated STEM Module

The positive perceptions of the STEM module among many PSETs suggest that it successfully engaged the participants through hands-on learning experiences. This finding is in line with previous research indicating that active, experiential learning can enhance student engagement, motivation, and learning outcomes in STEM education (e.g., Long, et al., 2020). The participants' positive feedback regarding the visualization of 3D printed models reinforces the notion that visual aids are effective in supporting the learning process, particularly for visual learners (Mayer, 2001). In addition, the hands-on experiences with 3D printing not only reinforced mathematical concepts and enhanced understanding, but also equipped participants for future teaching by offering concrete and engaging examples of how 3D printing can serve as a context for applying mathematical concepts. Participants acknowledged the value of integrating 3D printing into their future teaching to make mathematical concepts more accessible and relevant to their students. This study helps address Cheng et al.'s (2024) call for developing educators' pedagogical knowledge of integrating 3D printing into their curricula.

Within the STEM module, PSETs were provide with a conducive environment to explore and apply their mathematical knowledge and skills by creating 3D crystal lattice structures through 3D printing technology. They also received support in developing their 3D priting skills. This finding is consistent with Trust et al.'s (2021) suggestions that both current and future teachers benefit from engaging with 3D printing and modeling technology in a supportive setting, where they have access to expert guidance to understand the technology and troubleshoot effectively.

Both the survey and reflection data revealed that the majority of PSETs agreed that the STEM module effectively facilitated the connection of mathematics, science, technology, and engineering concepts to real-world phenomena. This finding aligns with the integrated STEM educational approach prompted by the research community, which advocates for connecting STEM disciplines and solving real-world problems through hands-on and project-based learning (Bybee, 2013; Wang et al., 2020). Comments from participants suggest that the module provided opportunities to apply mathematical concepts in the context of 3D printing, corroborating the positive effects documented in previous research on 3D printing within mathematics education (Ng, 2017; Ng et al., 2022). This also corresponds with findings that teachers who participated in extensive professional development involving integrated STEM activities developed a more profound understanding of the interrelationships among STEM fields (Ching et al., 2020). The participants' favorable feedback on the module's capacity to connect STEM content with real-world applications and mathematical concepts highlights the effectiveness of an integrated STEM education. Future studies could further investigate the impact of integrating 3D printing technology into additional STEM subjects to enhance PSETs' learning outcomes in those subjects. Additionally, due to time limitations, this study only allowed PSETs to use pre-designed 3D models and did not provide the opportunity to design their own 3D objects from scratch. Future studies are encouraged to provide opportunities for pre-service teachers to create 3D models themselves as a context for applying and understanding geometry concepts in a mathematics content course.

Limitations

Since this study involved pre-service teachers from only one university, the findings may not be representative of pre-service teachers at large. The influence of the 3D printing integrated STEM module needs to be further examined in other contexts or PSETs of various backgrounds and characteristics. Additionally, the study's reliance on self-reported learning perceptions may introduce bias or reporting inaccuracies. Future research with larger and more diverse samples, along with the use of objective learning outcome measures such as performance assessments, could provide a stronger validation of the findings and enable broader generalization of the results.

Conclusion

This case study provides an in-depth examination of PSETs' perceived learning and perceptions of the 3D printing integrated STEM module. The results of this study support the inclusion of such modules in college mathematics content courses for PSETs. Integrating 3D printing technology into the STEM module facilitated hands-on learning and the visualization of geometric and measurement concepts, thereby making them more comprehensible or PSETs. Despite the novelty of 3D printing technology for most participants, they were able to grasp the technology and troubleshoot issues effectively. The application of mathematical concepts in chemistry, engineering, and technology enabled PSETs to place their understanding within a broader, more interconnected, and practical context. These insights can inform the development and implementation of integrated STEM components within teacher education programs, aiming to prepare PSETs more effectively to incorporate STEM inquiries into their future teaching practices.

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Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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