

3D Pens in Geometry Education: A Tool for Pre-Service Mathematics Teachers

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Abstract. In recent years, mathematics education has increasingly emphasized the importance of manipulative and visualization aids that allow different forms of representation of mathematical objects to be linked. One such aid is the 3D pen, which allows simple three-dimensional models to be created directly during lessons. In this article, we present a method of incorporating the 3D pen into the teaching of spatial geometry as part of the training of future mathematics teachers, specifically in the topic of planar cross-sections of solids, and we analyze its didactic potential.

Keywords: solid geometry, 3D pen, innovative didactic strategies

1 Introduction and related work

Spatial geometry has long been one of the topics that causes significant difficulties for mathematics students, as well as primary and secondary school students. Traditional teaching is often based exclusively on two-dimensional sketches in a plane, most often in cabinet projection, which can be a significant cognitive burden for some students. To overcome this issue, it is necessary to stimulate the mental representation and transformation of objects and their relations, also known as spatial reasoning [3]. As suggested by Fujita et al. in their study [1], it can be improved by using domain-specific knowledge to correctly reason about 2D representations of 3D geometrical shapes. Palatník and Abrahamson state in [15], that geometry education in 2D media is historically based on the representational cognitivist model, and the construction of 3D models lets the student use their natural capacities of multimodal perception, which may be linked to the core ideas of constructionism [2].

In our work, we focus on one of the most challenging areas, which is the planar section of polyhedra, which requires not only knowledge of formal construction procedures but also the ability to visualize and mentally manipulate three-dimensional objects. We employ learning-as-making approach in training of the pre-service teachers on the topic of cross-sections by utilization of 3D pens with other commonly available tools as laminator and paper. As noted in [11], the aid of 3D pens provided a better retention of 3D solids and their properties compared to dynamic geometry environments (e. g. Cabri3D, GeoGebra).

The implementation of the use of 3D pens in teaching mathematics is being explored mainly for groups of students with a specific age and country. In one of the first works, Ng and Sinclair describe how 3D drawings improved the learning of shapes, functions, and calculus in the elementary and middle school level [12]. The feasibility of using 3D pens in primary schools (for students aged 12–13) is also supported by our preliminary results in [17]. As suggested in [9], 3D pens also support diagrammatic and manipulative learning of the properties of 2D shapes. The use of a 3D pen to explore the properties of prisms and cross-sections of solids (by drawing their outlines) was shown to be effective by conducting diffractive analysis in [10] and by a design-based mixed-methods study in [13]. The affective states of secondary students while using 3D pens for spatial geometry tasks were studied by Rosenski and Palatnik [18], and they concluded that 3D sketching develops a positive bond with the problems. Using 3D sketched models may also improve the perceptual, sequential, and operational apprehension of a 2D figure [16]. Meangru provided an extensive study on how 3D printing and 3D pens affect teachers in-service in their teaching identities towards mathematics [7]. In addition, several analyzes and reviews exploring the use of 3D printing in mathematics education are available; see [4] and [5].

The use of 3D pens also improved the student’s spatial reasoning results in other areas such as dentistry education and architecture. More specifically, tracing of muscles of mastication using 3D pens secured better posttest results compared to traditional drawing of 2D diagrams [6]. The idea of combining 3D pen models with additional processing – hanging, heating, and inverting – was explored in the creation of gridshell models used by designers for prototyping [8].

2 Preparing Pre-Service Mathematics Teachers to Use 3D Pens in Geometry Instruction

Given the proven positive benefits of using 3D pens in mathematics teaching, we decided to include this tool in the training of future mathematics teachers. The aim was not only to familiarize students with the technical capabilities of the 3D pen, but above all to boost their confidence in using it through direct experience. It appears that learning to work with a new teaching aid is more effective if students have the opportunity to see it used in specific teaching situations and try it out for themselves. Such experience contributes to building confidence in the teaching potential of the tool and increases the likelihood that future teachers will be willing and able to use it in their teaching practice. It was particularly important for students to experience for themselves that the 3D pen can significantly aid understanding of the subject matter, especially in the field of spatial geometry.

The didactic intervention was implemented as part of a semester course, named *Geometry (3)*, focused on solid geometry in the mathematics teacher training program. The name of the course emphasizes that this is the third and final geometry-related course in the bachelor’s study program ‘Teaching Mathematics in Combination’. Twenty students preparing to become mathematics

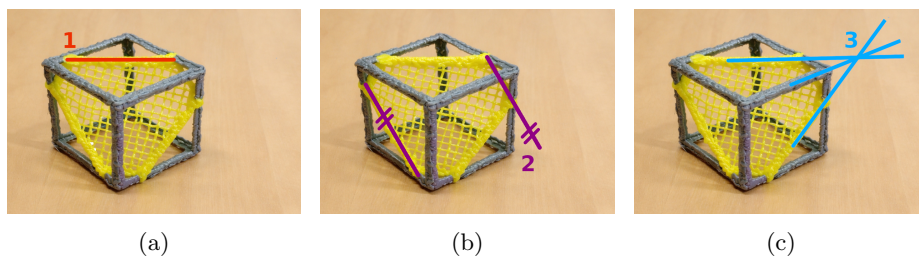


Fig. 1: Illustration of the three basic rules commonly used in secondary school instruction for constructing cross-sections of solids.

teachers in elementary or secondary schools participated in the course. Although the subject was not compulsory, all students in the given year enrolled in it. Most of them cited their own negative experience with solid geometry during their secondary school studies as their main motivation, perceiving it as problematic and difficult to understand.

2.1 Conventional Paper-and-Pencil-Based Approach for Cross-Sections of Solids

The teaching took the form of lectures and practical exercises. We decided to include work with a 3D pen in the thematic unit on cross-sections of solids. After theoretical preparation in the form of lectures, the students completed a 90-minute practical exercise during which they constructed cross-sections of solids using cabinet projection. Cubes, prisms, and pyramids with bases formed by regular polygons were chosen as model solids. In traditional secondary school geometry instruction, planar cross-sections of solids are typically constructed using a set of fundamental rules that guide students in determining the shape of the cross-section based on the spatial relationships between the cutting plane and the faces of the solid. When working with cubes, students are commonly taught to rely on the following three rules, which form the basis of the standard paper-based construction approach:

Rule 1. Same-face segment rule (Fig. 1a).

If two points of the cross-section lie on the same face of the cube, then the entire line segment between them also belongs to the cross-section.

Rule 2. Parallel-faces imply parallel edges (Fig. 1b).

Any two edges of the cross-section that lie in parallel faces of the cube are themselves parallel.

Rule 3. Concurrency of pairwise intersections (Fig. 1c).

If three planes are pairwise non-parallel and are arranged so that they share a common point, then each pair intersects in a line, and those three lines are concurrent – they all meet at that single point.

These rules enable students to systematically identify the vertices and edges of the cross-section and to complete its construction using planar drawings.

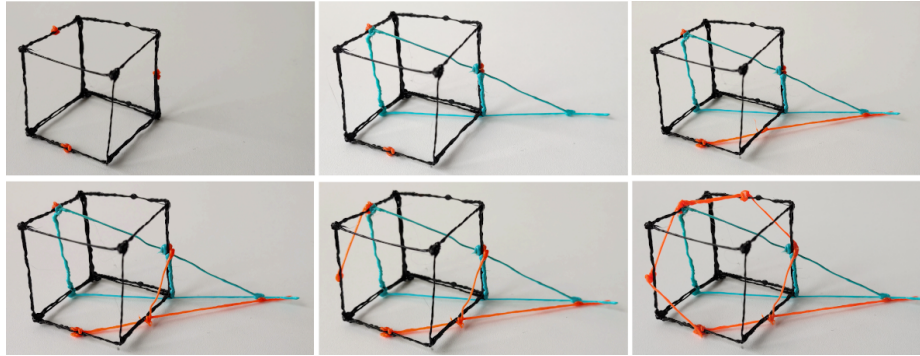


Fig. 2: Complete process of constructing a cross-section directly in three-dimensional space using a 3D pen. The three orange points on the cube define the section plane, and the entire cross-section is constructed step by step using an auxiliary plane (shown in blue), following the same principles as in the corresponding two-dimensional paper-based construction.

However, their successful application presupposes a well-developed ability to mentally interpret spatial relationships from two-dimensional representations. Moreover, the physical model (Fig. 1) enables tactile verification of geometric properties. For example, as seen in Fig. 1b, students can trace parallel edges simultaneously with both hands, reinforcing the perception of their identical direction in space.

Although the construction of cross-sections of solids is a topic that students are expected to have already covered at the secondary school level, significant differences between students were observed during our lesson. The majority of the students were able to identify and construct sections correctly. Difficulties were evident in the application of Rule 3 for the group of students who struggled with the task. When the three planes referenced by the rule were represented by two cube faces together with the cutting plane (Fig. 1c), the students were able to complete the construction successfully. In contrast, when the configuration involved only one cube face, the cutting plane, and an auxiliary plane that had to be constructed (Fig. 2, the third step), several students encountered difficulties. The construction of the auxiliary plane appears to require a higher level of spatial reasoning, making this configuration substantially more demanding.

2.2 Spatial Construction of Cross-Sections Using a 3D Pen

A week later, another 90-minute practical lesson followed, dedicated to working with a 3D pen. In the introductory part, this tool was presented to students, followed by a short instructional video demonstrating the basic principles of working with a 3D pen. The students were also briefly acquainted with the results of foreign research focused on the use of 3D pens in mathematics teaching, with particular attention paid to the work [14], which highlights the benefits of this tool in geometry teaching. This theoretical framework was followed by a

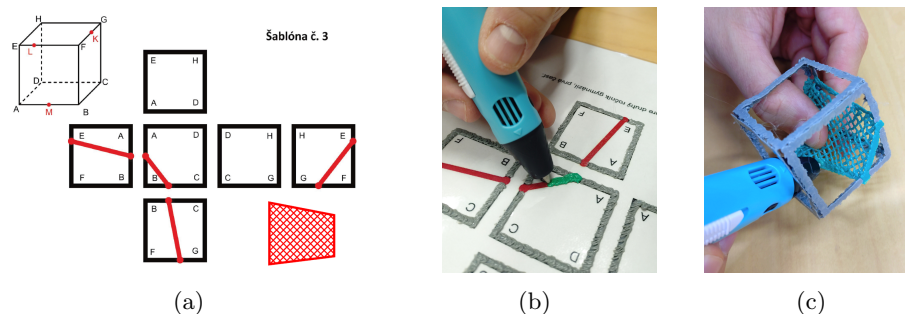


Fig. 3: Step-by-step construction of a spatial model using a 3D pen: template preparation (a), gradual construction of individual cube faces and the cross-sectional polygon (b), and final assembly of the model by joining the individual faces (c).

particular didactic example demonstrating the use of a 3D pen for constructing a cube cross-section directly in a three-dimensional space (Fig. 2). The example illustrated how observing the construction process in a spatial setting – together with the possibility of physically handling the model, rotating it, and viewing it from different perspectives – can support the connection between students' mental representations of the geometric situation and its two-dimensional projection on paper.

The remaining part of the lesson, approximately 60 minutes, was devoted to independent work by the students. Working in pairs, they constructed models of cross-sections of cube according to prepared templates, which were laminated in plastic foil to allow the completed parts to be easily peeled off after cooling. The main objective of this phase was for the students to learn how to work with a 3D pen, including inserting the filament, setting the appropriate printing speed, changing filaments of different colors, and safely cleaning the pen after finishing work. The prepared templates (see Fig. 3a) focused on creating different cross-sections of a cube, which allowed students to observe that the resulting cross-sections could be polygons with three, four, five, or six sides. First, the students created individual cube faces with the corresponding polygon as cross-section (see Fig. 3b), then joined the sides into a spatial model, and finally inserted the cross-section itself into it (see Fig. 3c). Working in pairs proved to be beneficial, especially when connecting the individual sides, as one student ensured the correct position of the sides and maintained right angles, while the other connected them using a 3D pen. Examples of models created by students are shown in Fig. 4.

3 Individual Student Work: Semester Project

After acquiring basic skills in working with a 3D pen, the students were assigned an individual semester project. The aim of the project was to construct a spatial

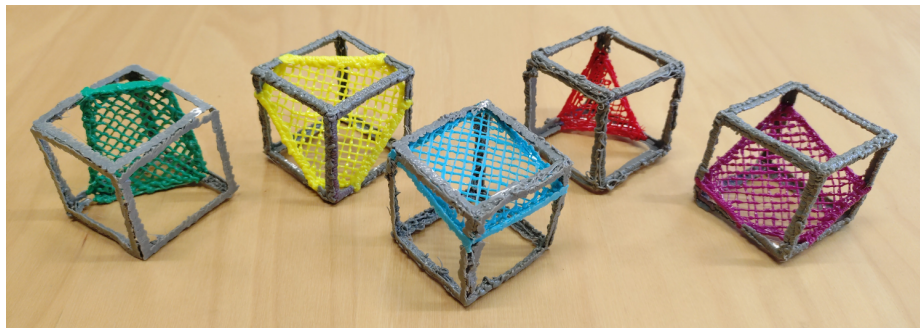


Fig. 4: Models of various cube cross-sections constructed by students in the initial training session with a 3D pen, illustrating a variety of possible cross-sections.

model of a solid, together with its planar cross-section, using a 3D pen. Both solid and cutting plane could be freely chosen by the students.

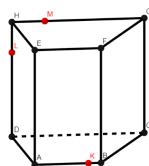
To support the successful completion of the project, the students were given the opportunity to borrow a 3D pen for home use. This opportunity provided them with sufficient time to improve their proficiency with the tool and to experiment with it according to their individual needs and working pace. Working outside the classroom environment allowed students to engage with the 3D pen in a less constrained setting, which many perceived as more comfortable than working exclusively under direct teacher supervision. At the same time, care was taken to ensure that participation in the project did not impose any financial burden on students. All necessary consumables, including filaments, were provided by the faculty at no cost. In addition, a laminating machine for sealing the templates in protective foil was freely available at the faculty and could be used by students as needed. These organizational measures were intended to remove potential external barriers and allow students to fully focus on the mathematical and didactic aspects of the project.

3.1 Geometric Construction of the Cross-Section

The project was designed as a multi-stage task with clearly defined steps. First, the students selected a reference solid to work with and identified three points on the solid that uniquely determined the section plane α (see Fig. 5). They then constructed the solid cross-section by the plane α using a cabinet projection. As part of this phase, students were required to provide a written description of the construction process and illustrate the individual construction steps. During this stage, they were allowed to use the 3D pen as a supporting tool and to sketch the entire situation directly in three-dimensional space, as demonstrated during the previous training lesson. The main objective of this part of the project was to develop the essential skills required for future teaching practice. In particular, the ability to correctly record construction procedures and consistently apply the principles of cabinet projection was improved. These results are valu-

Meno: L. K.

Úloha: Zostrojte rez daného štvorbokého hranola ABCDEFGH rovinou KLM, pričom $K \in AB$, $L \in DH$ a $M \in GH$.



**Postup
konštrukcie:**

1. $L \in DCGH$, $M \in DCGH \Rightarrow LM \in DCGH$
2. $ABEF \parallel DCGH \Rightarrow LM \parallel KN$
3. $X, X \in LM \cap CD$ ($LM \in DCGH$, $CD \in DCGH$)
4. $K \in ABCD$, $X \in ABCD \Rightarrow KX \in ABCD$
5. $O, O \in KX \cap AD$ ($KX \in ABCD$, $AD \in ABCD$)
6. $L \in AEHD$, $O \in AEHD \Rightarrow LO \in AEHD$
7. $Y, Y \in EH \cap LO$ ($EH \in AEHD$, $LO \in AEHD$)
8. $ABCD \parallel EFGH \Rightarrow KO \parallel MY$
9. $P, P \in MY \cap GF$ ($MY \in EFGH$, $P \in EFGH$)
10. $N \in BCGF$, $P \in BCGF \Rightarrow NP \in BCGF$
11. Rezom kocky je šesťuholník KLMNOP.

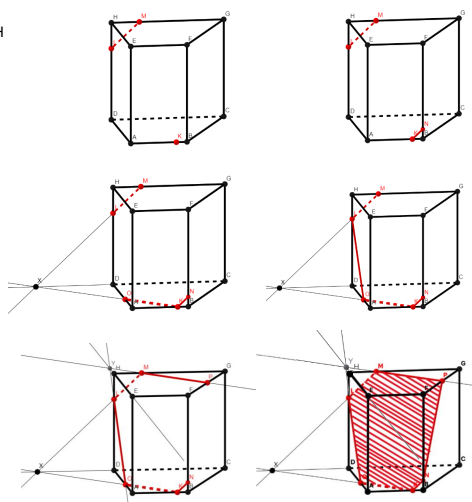


Fig. 5: Phase 1 of the semester project: selection of a reference solid and three points defining the section plane, classical construction of the cross-section using cabinet projection, and illustration of the individual construction steps.

able, since a significant proportion of students experienced difficulties with these competencies.

Allowing students to freely choose the solid for their project placed them in the role of task designers rather than mere solvers of predefined problems. This shift is particularly important in the preparation of future mathematics teachers as it provides them with valuable experience in formulating mathematical tasks and instructional situations. Instead of engaging only with passively received content from prescribed textbooks, students were encouraged to take an active and creative role in the design of learning activities. Such experiences may foster the development of professional autonomy and support future teachers in introducing their own innovative approaches to geometry instruction, adapting tasks to the needs of their students rather than relying exclusively on standard textbook exercises.

3.2 Template Design and Physical Modeling Using a 3D Pen

In the second part of the project, the students were required to design a template that would allow the construction of a physical model on a scale of 1:1 using a 3D pen. To achieve this, they had to determine the exact shape of the cross-sectional polygon using analytical geometry, including calculations of side lengths and angle measures (see Fig. 6). The purpose of this phase was to explicitly connect constructive geometry with analytical geometry, which the students had studied in the previous academic year. The project was intentionally de-

Úloha: Podstava hranolu ABCDEFGH je lichoběžník ABCD v rovině $z = 0$, vrcholy $A = (-1, 5/2, 0)$, $B = (4, 5/2, 0)$, $C = (8, 5/2, 0)$, $D = (2, 5/2, 0)$. Výška hranolu je 8 cm. Různová rovina je určena body $K = (7/2, 5/2, 0)$, $L = (0, 0, 9/2)$, $M = (3/2, 0, 6)$.

Řešení:
 Vypočítáme normálu roviny $n = (L-K) \times (M-K) = (-7/2, 5/2, 9/2) \times (-5/2, 5/2, 6) = (-5, 16, 5)$
 Rovnice roviny je potom $-5x + 16y + 5z = d = 0$,
 koeficienty d doplníme součinem jeho souřadnic, např. 45 : $-5x + 16y + 5z = 45/2$,
 upravíme: $-10x + 32y + 10z = 45$

Na určenou rovinu Q a P vypočítáme příslušné body DA, BF, FG a vzdálenosti roviny a vnitřní roviny.
 Pro hranu DA použijeme parametrickou rovnici $K(t) = (0, 0, 0) + t(0, 0, 8)$, dosadíme do rovnice roviny a vyřešíme:
 $10t = 45/2 \Rightarrow t = 9/4$
 Bod D na hraně DA: $K(9/4) = (0, 0, 18/4) = (0, 0, 9/2)$
 Bod E na hraně EF: $L(9/4) = (9/4, 5/2, 9/2)$
 Bod F na hraně FG: $M(9/4) = (9/4, 5/2, 15/2)$

Úloha 2:
 Vypočítáme délku úsečky KL : $|KL| = \sqrt{(-7/2)^2 + (5/2)^2 + (9/2)^2} = \sqrt{130}/2 \approx 5.91$ cm
 Vypočítáme délku úsečky LM : $|LM| = \sqrt{(0-3/2)^2 + (0-0)^2 + (9/2-6)^2} = \sqrt{45}/2 \approx 3.06$ cm
 Vypočítáme délku úsečky KL : $|KL| = \sqrt{(-7/2)^2 + (5/2)^2 + (9/2)^2} = \sqrt{130}/2 \approx 5.91$ cm
 Vypočítáme délku úsečky LM : $|LM| = \sqrt{(0-3/2)^2 + (0-0)^2 + (9/2-6)^2} = \sqrt{45}/2 \approx 3.06$ cm
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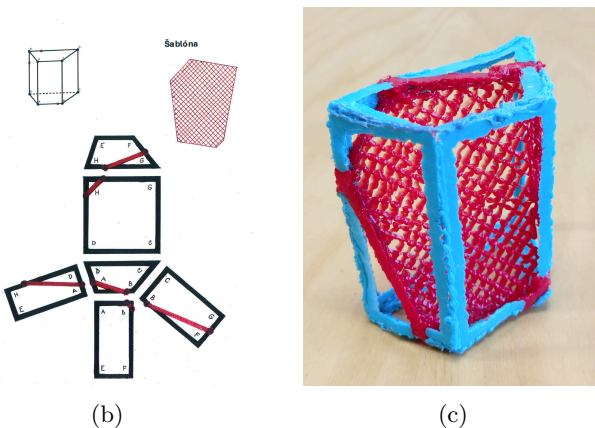


Fig. 6: Phase 2 of the semester project: determination of the cross-sectional polygon using analytical geometry (a) creation of template (b) used to construct an accurate spatial model with a 3D pen (c).

signed to integrate different geometric approaches into a coherent whole. The goal was to help students realize that these approaches represent different perspectives on the same mathematical situation. In this way, the students were able to experience a practical application of knowledge that they had previously encountered primarily in theoretical textbook problems.

The templates could be created using either any suitable software or manually. This flexibility was intentional, as the level of digital literacy among students varied and the use of digital tools was not intended to become a barrier to the successful completion of the project.

An additional objective of the project was to enable pre-service teachers to acquire the ability to construct physical models of a 3D sketch of the given assignment, a skill that can be effectively applied in their future pedagogical practice across a wide range of topics in solid geometry. The use of precisely scaled models is not limited to the topic of cross-sections of solids, but can also support instruction on volume and surface area calculations, metric relationships within solids, spatial diagonals, and the determination of angles between edges, faces, or planes. Such models can be particularly beneficial for pupils whom these pre-service teachers will teach in the future, especially those who experience difficulties with spatial visualization or abstract geometric reasoning. By working with models of exact dimensions, learners are better able to connect numerical calculations with tangible spatial representations, which supports deeper conceptual understanding and may reduce typical misconceptions in stereometry. In this way, the competencies developed by pre-service teachers through the project have the potential to positively influence the quality of geometry instruction and student learning outcomes in their future classrooms.



Fig. 7: Examples of selected student projects showing completed 3D models of solids and their cross-sections. In addition to cubes commonly used in instruction, students demonstrated creativity by choosing more complex solids.

4 Findings and Discussion

The student projects were evaluated based on observations made during their implementation, analysis of the submitted outputs, and reflective feedback provided by the participants. From the students' perspective, the project-based work with the 3D pen was consistently described as the most engaging and interesting part of the practical exercises within the course. This perception was reflected not only in verbal feedback, but also in the level of effort invested in the project outcomes.

Although students were free to choose the reference solid for their project, several of them voluntarily selected geometrically more complex objects, such as an octahedron or a hexagonal prism, rather than limiting themselves to simpler solids. We also observed that many students spent considerable time selecting suitable color combinations of fibers. These observations suggest a high level of intrinsic motivation and indicate that the students cared about the quality and visual appearance of their final models, which can be interpreted as evidence of genuine engagement with the task.

The open nature of the assignment also allowed the students' creativity to emerge. In several cases, students demonstrated originality in the selection of the section plane and in the design of non-trivial cross-sections, aiming to construct visually and mathematically interesting configurations (in one instance, a student even selected points determining the section plane α outside the reference solid, see Fig. 7, green cube behind). Such creative engagement is particularly valuable in the context of teacher education, as it reflects the ability to design meaningful mathematical tasks rather than merely reproducing standard textbook problems. The white cube with red cross-section (see Fig. 7, center) illustrates the self-verification function of the physical model. An incorrectly de-

terminated cross-sectional polygon results in a mismatch between the constructed section and the solid model (the section is too small to fit into the cube). The physical assembly process thus provides immediate feedback, allowing students to identify and correct computational or construction errors independently, without direct teacher intervention. A correct fit was achieved only when the proportions of the cross-section were accurately determined during the template design phase.

For all participating students, this project represented their first experience with constructing a physical spatial model and their first direct encounter with 3D printing technologies. None of the students had prior experience with 3D pens or 3D printing in general. This aspect of the project was evaluated very positively, as students reported that they gained a new practical skill that they perceived as relevant and transferable to their future professional practice.

Importantly, several students expressed their intention to use 3D pens in their future teaching careers, either directly in classroom instruction with students or as a tool for preparing custom teaching aids during lesson planning. This finding points to the potential of the project to influence not only the understanding of geometry by students, but also their beliefs about the use of innovative tools in mathematics education.

The students unanimously agreed that working with the 3D pen supported their understanding and solution of stereometric problems. Although this claim is based on subjective perceptions of students and was not examined through a dedicated experimental design, it is noteworthy that all students successfully solved the stereometry task included in the final exam. The solutions were correct in terms of geometric reasoning, with only minor inaccuracies observed in the written documentation of the construction procedures. This result provides an additional, though indirect, indication that the project may have contributed positively to students' competence in spatial geometry.

An additional outcome of the project was the creation of a shared collection of solved tasks focused on cross-sections of solids. Through their individual projects, the students collectively produced 20 distinct and fully documented examples, each accompanied by a spatial model and a clearly described construction procedure. This collection represents an immediately applicable resource for their future teaching practice, as it provides ready-made instructional material that can be used when introducing or revising the topic of cross-sections in secondary school geometry. In this sense, the project not only supported the learning of the students during the course but also contributed to the development of a practical repository of teaching materials that pre-service teachers can use in their professional work.

The 3D pens also have limitations that should be considered in educational use, especially if the models are intended for long-term classroom use. The models created in this way are relatively fragile, which may affect their long-term durability with frequent classroom use. An important advantage of 3D pens lies in their significantly lower cost compared to 3D printers and the absence of requirements for specialized software skills. Moreover, the majority of schools

are not equipped with 3D printers because of their cost, hence the use of 3D pens may be considered more appealing. From a technological perspective, it should also be noted that 3D pens represent a relatively recent and still evolving technology, and the quality of commercially available devices is not yet fully standardized. Lower-cost models may exhibit technical shortcomings, such as overheating power adapters; therefore, careful selection of equipment is essential to ensure safe and reliable operation in school environments. The accuracy and comfort of drawing are also influenced by the quality of the filament. For example, filaments with lower melting temperatures allow for more precise handling when creating lines in space, as they cool more quickly and are therefore less prone to deformation caused by gravity.

5 Conclusion and Future Work

We presented a design-based approach to integrating 3D pens into spatial geometry instruction for pre-service mathematics teachers, focusing on planar cross-sections of solids. Combining traditional paper methods with hands-on modeling allowed participants to directly explore geometric relationships and link two-dimensional representations with three-dimensional structures. Observations, student work, and feedback showed high engagement, creativity, and perceived learning benefits, indicating that 3D pen-supported activities have strong didactic potential in geometry education.

We plan to extend the approach used in this study to secondary school classrooms. We aim to examine the impact of 3D pens and spatial models on students' stereometric concept understanding and problem-solving skills. Unlike the present study, which focused on pre-service teachers, future research will include data collection and analysis of students' learning outcomes. We also aim to make the developed teaching materials freely available online. This platform will include templates for constructing solids and their cross-sections, as well as videos demonstrating how to use 3D pens in geometry lessons. The goal is to support mathematicians and facilitate the adoption of these activities in the classroom. This may encourage further research and hands-on geometry teaching.

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