

Teaching and Learning about Geometrical Shapes in Primary Education by Means of 3D Printing: A Case Study

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Abstract

This paper concerns the design, implementation, and evaluation of an educational intervention using 3D printing tools and 3D design software to teach geometric concepts to primary school students. As part of the research, an educational intervention involving digital design, 3D printing, and assembling a cube puzzle, based on Froebel's "Gifts," to support students' understanding of geometric shapes and solid shapes and their properties was designed. Forty (40) fourth-grade students attended two primary schools in the Prefecture of Achaia, Greece, participated in the study. A mixed-method approach was used as the research methodology. The research tools consisted of specially designed worksheets, cognitive content questionnaires before and after the intervention, a questionnaire to evaluate the process for the students, notes taken by the researcher/observer during the intervention, and a semi-structured interview with the teachers of each class. The results showed that the educational intervention using 3D printing contributed positively to the students' learning performance. The students stated that they found the educational activities particularly interesting, that they helped them to better understand the properties of geometric shapes, and that they would like to use the 3D printer also in other lessons. The classroom teachers expressed positive opinions about the use of 3D printing in the classroom.

Keywords: 3D printing, 3D designing, Froebel's "Gifts," primary education, geometry, geometric shapes and solid shapes

1. Introduction

Education has been significantly influenced by the integration of digital technologies since the 1980s. These technologies are seen to provide experiential learning opportunities for students, but also to improve teachers' expertise and development in cognitive subjects [1]. The integration of innovative teaching approaches in education that prioritize the development of 21st-century skills and respond to contemporary demands is also achieved using 3D modelling and printing. While nowadays 3D printing in education is becoming increasingly accessible at all levels of education and is used to teach geometric concepts, questions arise for both students and teachers [2].

The aim of the study was to utilize 3D printing in teaching geometric concepts to primary school students, specifically those in the fourth grade. Solid shapes, especially cubes and rectangular parallelepipeds, and their properties were the subject studied with the help of digital 3D design/modelling of solid shapes and their 3D printing. The research questions concern whether the use of 3D modelling and printing in teaching geometric solid shapes and their properties has a positive effect on student performance, and whether teachers have a positive attitude towards the integration of 3D printing into the learning process.

2. Literature review

2.1. The utilisation of 3D printing in education

Focusing on learning through construction [3], 3D printing technology has become a valuable tool for learning. It is widely used in various educational settings, including primary schools [4] secondary schools [5], and higher education institutions [6].

Indeed, 3D printing has been described as the new technology that will transform education [7]. This is because its creative and educational potential makes it an excellent platform for children, who, by designing and printing 3D objects, further develop their abstract and spatial thinking [8] and problem-solving skills, as it helps them visualize concepts such as volume.

Since 2000 researchers focused on 3D design to teach geometry and used technology to create and display 3D models of various shapes that were previously limited to linear drawings, supported the idea of experiential learning of using 3D printers in math assignments, call elementary school to create their own prisms and pyramids to learn the geometric properties and cross-sections of solids [8-16].

2.2. Challenges of 3D printing in education

Although 3D printers are gaining popularity internationally at all levels of education, their integration poses challenges. Bull, et al. [17] observed that in the school system, the current generation of teachers is unable to take advantage of the possibilities offered. On the other hand, teachers do not receive adequate guidance on how to use 3D printers. Furthermore, students, in some cases, become anxious and frustrated with their level of skill in operating the required software and the time and effort required to operate it [15]. Furthermore, when technical problems occur and the implementation of 3D printing does not work, they become frustrated [12]. Furthermore, it has been found that they have different learning rates in 3D printing projects due to these technical challenges.

Students and teachers could benefit from these challenges to build digital skills, change the way they view learning, and improve their teaching/learning in the future [5].

2.3. Teaching solid shapes in primary education

Geometry functions as a tool that facilitates the understanding and analysis of the natural world around us. It allows us to describe, examine, and interpret our environment. Therefore, geometry is incorporated into the mathematics curricula of both primary and secondary education [13,14]. Geometric knowledge and geometric thinking are acquired and cultivated through active interaction with shapes and their exploration [14]. According to Frobisher and Orton [18], when children learn experientially, they understand the connections between knowledge, concepts, and skills in various aspects of geometry. This means that teachers need to consider the child's environment and adapt their teaching approach to geometry, using a more experiential approach based on students' spatial ability [19].

In Greece, the new curriculum for Mathematics in Primary School is characterized by interdisciplinarity, focusing on student-centred teaching approaches, collaborative learning, and experiential knowledge acquisition through games and new technologies. In the lower grades (1st and 2nd grade), geometry is taught empirically and intuitively. Students learn the concepts of geometric shapes and solid bodies through puzzles and constructions and are gradually introduced to the concepts of perimeter and vertical and parallel lines. In the following grades (3rd and 4th grade), geometric shapes and solid bodies are taught through games such as tangrams. In the upper grades (5th and 6th grade), through problems and activities, students learn how to calculate the perimeter of various geometric shapes, the area, the volume of solid bodies, as well as the types of triangles in terms of angles and sides, the verticality, the heights of the triangle, the reduction and enlargement of shapes, and the construction of the circle. Digital activities and micro-experiments that develop their knowledge and skills are proposed to be used.

2.4. Friedrich Froebel's "Gifts" and Geometry

Froebel was convinced that children gain a deeper understanding of the world around them when they are given opportunities to interact with it through specific activities. He emphasized the crucial role of play in children's educational development and recommended that children be given well-chosen materials during play in order to stimulate their understanding of the world. He therefore developed special educational games for his kindergarten, known as "Gifts" ("Spielgaben") [20].

The 1st Gift consists of six balls made of different materials, while the 2nd consists of a variety of solid shapes (cube, cylinder, sphere). In contrast, the 3rd, 4th, 5th, and 6th Gifts, which are relevant to the present research, represent the idea of breaking down the cube into smaller units, such as small cubes, small rectangular parallelepipeds, and triangular prisms of various sizes.

Studies using Froebel's Gifts with preschool and primary school children provided evidence of geometric reasoning and strategies in solving construction problems [20] and utilizing Froebel's Gifts to design educational interventions and research tools with preschool children provided evidence of cultivating problem-solving strategies [21].

3. Aim of the study and research Questions

The purpose of this study was to utilize 3D printing in teaching geometric concepts to primary school students, specifically those in the fourth grade. Solid shapes, specifically cubes and rectangular parallelepipeds, and their properties were the subject of study with the help of digital 3D design/modelling of solid shapes and their 3D printing.

The research questions that the study attempts to answer are as follows:

- *Can the use of 3D printing in teaching geometric solid shapes and their properties enhance the performance of primary school students?*
- *Can Tinkercad 3D design software enhance students' understanding of geometric solid shapes and their properties?*
- *What are the views of primary school teachers on the integration of 3D printing into the learning process?*

4. Methodology

In this study, a mixed method was attempted, combining different research methods (quantitative and qualitative research). The 3D printing software used was Tinkercad (<https://www.tinkercad.com/>), and the 3D printer used was the Creality3D Ender-2 Pro.

The teaching and learning activities composing the intervention are based on Froebel's "Gifts," especially on *Gifts 3, 4, and 6*. Through "*Gift 3*" which consists of small cubes that make up a large cube, children begin to see the pieces as part of the whole cube and their relationship to the whole. Comparing "*Gift 3*" with "*Gift 4*" which consists only of rectangular parallelepipeds, it is emphasized that the rectangular parallelepiped and the small cubes are equivalent in terms of the number of edges, vertices, and faces, but they are different in terms of their length. As for "*Gift 6*" it consists of rectangular parallelepipeds and square prisms. Students called to design and print their cube puzzle and then built the cube of the other group describing the parts of the puzzle they used and their properties.

For the analysis of quantitative data, descriptive and inferential statistical analysis was utilised, while for the analysis of qualitative data, a thematic analysis was used. Shapiro Wilk test for normality used that showed non-normal data distributions. Therefore, non-parametric test Wilcoxon signed-rank test was used to detect statistically significant differences in the values of the factors and variables between groups and subgroups of the sample. Data was processed using the SPSS 27 package.

4.1. Research tools

The research tool for collecting data is:

Individual Pre-test/Post-test of cognitive content

Before and after the intervention, students were given individual pre-tests and post-tests. The pre-test consisted of eight exercises and the post-test of nine exercises. The first eight were common to both tests. They assessed the students' knowledge of the bases, edges, and vertices of the cube and rectangular parallelepiped, as well as the length, width, and height of these solid shapes. In the additional exercise in the post-test, students were asked to draw a piece of the cube puzzle they assembled during the intervention on millimetric paper and to find its dimensions.

Group Pre-test/Post-test of cognitive content

The group pre-test was titled "Time to make the cube puzzle" and the post-test "The other group's cube." The pre -test consisted of

7 instructions for constructing shapes/bodies and 25 questions that the group members were asked to answer while designing their cube puzzle in Tinkercad.

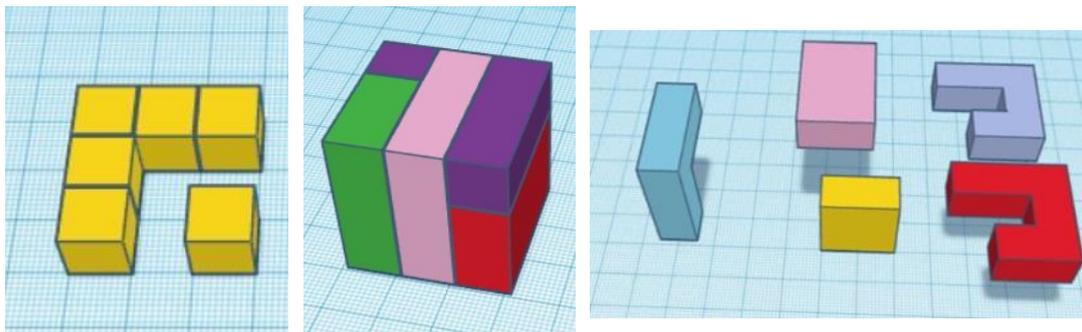


Fig.1: Examples of students' creations during according to group pre-test.

The group post-test consisted of 5 questions about the pieces of the cube puzzle that each group was asked to assemble. Both the pre-test and post-test were scored on a scale of 0-10.



Fig.2: Examples of students' creations during according to group post-test.

Worksheets

When working with the Tinkercad 3D printing software, students were given worksheets with pictured instructions and 12 activities: *Moving a solid object in the workspace, Changing the color of a solid object, Changing the dimensions and rotating a solid object, Forming a cube with specific dimensions (20 cm), Copying and pasting a solid shape, Moving a cube, Copying and pasting multiple solid shapes together, Rotating the workspace for a full view of the solid shape, Enlarging or reducing the size of a solid shape, Increasing the height of a solid shape by adding solid shapes to the top of the original shape, Grouping solids, Separating a cube into pieces*

Notes during participatory observation

During the activities, the researcher kept observation notes, recording the children's reactions, comments, cooperation, questions, successful completion of activities during the design of the cube puzzle, the time taken to complete the activities, and the children's willingness to participate.

Evaluation sheet

The evaluation sheet was consisted of eleven simple close-ended questions and was given to students along with the individual post-test and aimed to detect students' reactions while working on three-dimensional design/modelling and printing activities.

Teacher interviews

The interviews were semi-structured, consisted of thirteen open questions and designed to explore teachers' views on the use of 3D printers in the learning processes. The questions are based on the theoretical framework of the Technology Acceptance Model (TAM), (Moussawi et al., 2020) exploring the perceived usefulness, the perceived ease of use and the intention to use of digital tools.

Validity and Reliability

To ensure the content validity of the research tools, they all were thoroughly checked by two experts, one expert in ICT in education and one expert in teaching geometry. To test face validity the whole procedure was piloted with a group of 4 students. (Creswell, 2011). To ensure the reliability of the tests grading two teachers (the researcher and one more) graded the tests for each student and group of students and compare their results. In case of disagreement the mean value of the two grades was used.

4.2. The procedure

Fig.3 describes the three phases of the intervention with duration, the tools used, the activities for each one.

Phase A		Participatory observation
1 st session (45 min)	Introduction Individual pre-test	
2 nd session (60 min)	Discussion about 3D objects/ 3D printing Presentation of the 3D printing Watching 2D related Videos Groups creation	
3 rd session (45 min)	Groups of 2 students Working on the group pre-test with Tinkercad Groups creation for the next session	
Phase B		
1 st session (90 min)	Groups of 4 students Group pre-test 3D designing of the cube puzzle	
2 nd session (90 min)	3D printing of the parts of the cube puzzle Assembling the cube puzzle of another group Group post-test	
Phase c		
1 session (90 min)	Individual post-test Evaluation sheet Playing with the cube puzzles Teacher interview	

Fig.3: The phases of the intervention.

4.3. The sample

Forty students (26 girls and 14 boys) and three teachers (there women with ages 25, 43 and 52 years old and teaching experience of 2, 15 and 22 years) participated in the study.

5. Results and Discussion

The results of the study are presented by research tool: *Individual Pre-test/Post-test of cognitive content*
The median value of the pre-test was 5.99 (min: 1.66 and max: 9.80) and the median value of the post-test was 9.23 (min: 4.43 and max: 10.0). The difference is statistically significant ($Z=-5.20; p<.05$) showing that the intervention had positive effect on students' knowledge and performance.

Table 1: Number of students answered correctly per question/exercise.

exercise	<i>Number of students answered correctly</i>	
	<i>Pre-test</i>	<i>Post-test</i>
1 st exercise	26	34
2 nd exercise	12	34
3 rd exercise	14	38
4 th exercise	25	29
5 th exercise	19	32
6 th exercise	7	31
7 th exercise	24	33
8 th exercise	6	35

Common mistakes, especially at the pre-test, were concerning confusion between edges and vertices, between edges and bases, between length and width, between number of edges and vertices, the use of "same" bases instead of "equal" ones, the use of solid rectangle instead of cube, the use of 2 thin cubes instead of a parallelogram. Concerning the 9th exercise, 10 students completed the exercise correctly, 8 students correctly identified the dimensions of the shapes, but made mistakes in drawing the

parts of the cube puzzle, 3 students drew curved lines instead of straight lines and 15 students measured width and height wrong.

Group Pre-test/Post-test of cognitive content

There were no statistically significant differences in the grades between the group pre and post test ($Z=-1.05; p>.05$). The mode values for the test were equal to 10 at both pre and post tests.

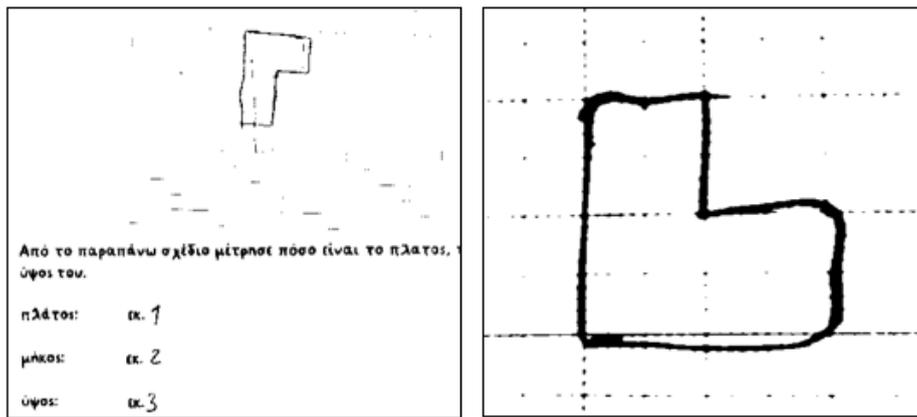


Fig.4: Examples of students answers at the 9th exercise.

Worksheets and participatory observation

The notes based on the participatory observation while students were working on the worksheet showed that students worked in groups, collaborating each other, discussing issues, agreeing and disagreeing, helping each other, asking the advice of the other

student, encouraging each other and rewarding each other's efforts when the outcome was successful. They seemed that they enjoyed the activities and they are working without showing signs of fatigue or boredom.



Fig.5: Students working based on the worksheets.

Evaluation sheet

Thirty-seven (37) students (92.5%) did not know what a 3D printer was and only 1 student (2.5%) had seen a 3D printer before the educational intervention. None of the students knew that it was possible to create 3D designs using computer applications, and none had ever used Tinkercad software before.

Thirty-two students (32.5%) responded that Tinkercad was "difficult" to use, 5 students (12.5%) that it was "neither difficult nor easy," and 22 students (55%) that it was "easy." Twenty-one students (52.5%) stated that they "really liked" working with it, 6 students (15%) that they "quite liked" it, but 10 students (5%) that they "didn't like it at all."

Twenty-one students (52.5%) said they "really liked" working during the intervention with the 3D printer, 6 students (15%) "liked it quite a bit," 10 students (25%) "liked it a little. Twenty-three (23) students (57.5%) said that it helped them to better understand solid bodies and their properties, and 17 students (42.5%) answered that it "maybe" helped them. Regarding the

activities that took place during the meetings, 20 students (50%) responded that they found them easy, 18 students (45%) found them "neither difficult nor easy," while 2 students (5%) found them "difficult." Also, 37 students (92.5%) answered that they enjoyed the activities "very much" and 3 students (7.5%) "a little."

When asked if they would like to use the 3D printer in other classes, all students responded positively. Finally, when asked how they felt when the instructor informed them about the activities that would be carried out for the design and printing of the cube puzzle, 28 students (70%) said they were excited, 8 students (20%) said they felt nothing, while 4 students (10%) said they felt anxious.

Teacher interviews

All three teachers mentioned in their interviews that a 3D printer would be useful, but they were hesitant about their own ability to use it properly and would like to receive training before using it. They also all believe that using a 3D printer would enhance

the effectiveness of their teaching and that it would be an enjoyable process for both their students and themselves. Now that their students are familiar with the Tinkercad environment, all teachers had a positive attitude towards using it in their teaching in the future.

They also believe that activities such as the one implemented in their classes enhance cooperation among students, students learn to think in more complex ways and are introduced to the world of technology, they realize that a problem can be solved in many ways, and they learn and understand cognitive subjects in a fun and playful way. On the other hand, they do not consider it easy to make use of such activities often as it is a time-consuming process, but also because they need training and technological as well as pedagogical support to use a 3D printer in their classroom. Summarising the above we can say that they expressed positive perceived usefulness, perceived ease of use and willingness to use 3D designing and 3D printing with their students.

6. Conclusion

The conclusions of the study are presented with research questions and then a summarizing comment based on the literature are given.

Can the use of 3D printing in teaching geometric solid shapes and their properties enhance the performance of primary school students?

The use of 3D printing can support and enhance the performance of primary school students about geometric solid shapes and their properties as statistically significant differences arose between the grades of individual pre and post-tests. The grades after the intervention were significantly higher.

The results based on the worksheets analysis and the observation confirm these conclusions.

Can Tinkercad 3D design software enhance students' understanding of geometric solid shapes and their properties?

Students working with Tinkercad 3D design software understood the concepts of "base," "edge," "vertices" by designing the cube puzzle. The results of the post individual and group post-test show that. Furthermore, the students themselves feel that they learnt more in this way.

What are the views of primary school teachers on the integration of 3D printing into the learning process?

All teachers mentioned in their interviews that a 3D printer would be useful, but they were hesitant about their own ability to use it properly and ask for training. They believe that using the 3D printer would enhance the effectiveness of their teaching and that it would be an enjoyable process for both the students and themselves. All teachers had a positive attitude towards using it in their teaching in the future. They also believe that activities such as the one implemented in their classes enhance cooperation among students, students learn to think in more complex ways and are introduced to the world of technology, they realize that a problem can be solved in many ways, and they learn and understand cognitive subjects in a fun and playful way. On the other hand, they do not consider it easy to make use of such activities as it is a time-consuming process and they need support.

Additionally, most students reported that when the researcher first announced the activities that would follow, they felt excited.

As the study concerns only two schools, 40 students and 3 teachers, the conclusions cannot be generalized but they can contribute to the research and pedagogical discussion of the utilization of emerging technologies in education and especially of the utilization of 3D designing and 3D printing.

Studies have reported that design projects involving physical prototyping, such as 3D printing, can form the basis for improving understanding of science and mathematics. Researchers argue that students benefit from learning opportunities that draw mathematical knowledge from direct experience and externalize mathematical concepts using representations [17,22,23]. 3D printing offers educators opportunities to revolutionize mathematics education by providing students with cognitive and social support for the creation of mathematical concepts, particularly three-dimensional visual-spatial sense [19]. Although there are still many challenges, such as hardware and software optimization, processing, formatting, printing, and maintenance issues, 3D printing is an effective tool for developing mathematical understanding. The maker movement has been promoted rigorously over the years, and mathematics is one of the key elements of STEM education [24].

Future studies with larger random samples with students of different ages and with longer interventions covering a larger part of the cognitive subject of geometry, especially in primary school, should offer data and results that might be important and useful to the educational community.

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