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Integrating 3D Printing in Primary Mathematics Education: Enhancing Pupils' Conceptual Understanding of Geometry

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Abstract

The use of technology in schools is a strategic move to help students, especially in primary school better understand basic math concepts. In Malaysia, the rapid growth of educational technology has opened up new ways to deal with the problems of teaching and learning geometry, which is often seen as an abstract and hard subject. This article examines literature on technology integration, emphasizing the impact of three-dimensional (3D) printing on the improvement of geometry education. 3D printing helps students see abstract ideas like shape, measurement, volume, and spatial relationships. It also gives them real-world, hands-on learning opportunities. The study shows that 3D printing is a good way to make abstract ideas more concrete by using hands-on and fun methods. Additionally, this conceptual paper emphasizes the potential of integrating 3D printing with Problem-Based Learning (PBL) to enhance student engagement and improve proficiency in geometry. These results indicate that 3D printing serves as both an effective pedagogical instrument and a revolutionary technology for enhancing mathematics education.

Keywords: Spatial Ability Development, Geometry Learning, 3D Printing, Primary School, Mathematics

Introduction

The term geometry originates from the Greek word geo, meaning earth, and metria, referring to measurement, reflecting its early association with understanding and quantifying the physical world (Bahariah B.H.B. et al., 2017). Historically, geometry has been central to the advancement of mathematical thinking, particularly within ancient civilizations such as Egypt and Babylonia, where mathematical ideas were closely linked to practical needs (Hollings & Parkinson, 2024). Records such as the Rhind Papyrus, dated to approximately 2000 BCE, illustrate how early societies applied geometric reasoning to tasks involving land measurement and construction planning (Norliza, 2021). These early applications demonstrate that geometry functioned not only as a mathematical discipline but also as a practical and intellectual framework for problem-solving.

As mathematics education developed over time, geometry became an essential component of the school curriculum, widely acknowledged for its role in nurturing logical thinking,

analytical reasoning, and problem-solving abilities among learners (Hasanah & Agung, 2020). Introducing geometry at an early educational stage supports pupils in developing an understanding of shapes, spatial relationships, and structural concepts that underpin broader mathematical reasoning (Mochamad Surya et al., 2021). Importantly, geometry is closely connected to real-world contexts, suggesting that effective instruction should extend beyond abstract explanations and incorporate active, experience-based learning.

Nevertheless, many primary school pupils perceive geometry as difficult and highly abstract. Research has consistently shown that learners encounter challenges in visualizing three-dimensional objects, understanding spatial relationships and grasping abstract geometric ideas (Andriliani et al., 2022; Mantik et al., 2023; Mandala et al., 2025). Such learning difficulties highlight the necessity for pedagogical approaches that can better support pupils in constructing meaningful and coherent geometric understanding.

From a pedagogical standpoint, geometry instruction aligns strongly with constructivist learning theory, which posits that learners develop knowledge through active engagement with their surroundings. In mathematics education, strategies that involve concrete materials and experiential learning have been found to be particularly effective in facilitating conceptual understanding, especially when dealing with abstract content such as geometry (Ismail, 2020). The use of physical manipulatives enables pupils to explore geometric forms directly, supporting the development of spatial reasoning and mathematical logic through hands-on interaction.

Consistent with these theoretical foundations, the integration of technology in geometry learning has gained increasing attention in recent years. Geometry education is closely linked with disciplines such as science, technology and engineering, reflecting the growing emphasis on STEM-oriented learning (Syed Zainuddin & Abdullah, 2023). Previous studies indicate that digital tools, including dynamic geometry software, can enhance students' understanding by providing interactive and visual representations of geometric concepts (Gurmu et al., 2024). More recently, 3D printing has emerged as a promising instructional approach, offering pupils opportunities to engage with tangible three-dimensional models that promote experiential and exploratory learning.

Accordingly, this study aims to identify the factors contributing to the decline in students' achievement in geometry, to examine the importance of 3D printing technology in supporting the teaching and learning of geometric concepts and to explore effective approaches for integrating 3D printing technology into mathematics education, particularly within the context of geometry instruction.

Decline in The Geometry and Measurement Domain in TIMSS 2023

Malaysia's participation in the Trends in Mathematics and Science Studies (TIMSS) 2023 marked its seventh involvement at the Grade Eight (Form Two student at Malaysia) level since the country's first participation in 1999 (Kementerian Pendidikan Malaysia, 2024). The number of questions allocated to each mathematics content domain in the TIMSS 2023 Grade Eight assessment is presented in table below.

Percentage of Questions Allocated for Each Content Domain in the TIMSS 2023 Grade Eight Mathematics Assessment

Content Domain: Grade Eight	Percent (%)
Number	30%
Algebra	30%
Geometry and Measurement	20%
Data and Probability	20%

Note. Source: Trends in International Mathematics and Science Study – TIMSS 2023 Preliminary Report- Kementerian Pelajaran Malaysia

The Geometry and Measurement domain constitutes one of the four main domains assessed in TIMSS 2023. According to the Educational Policy Planning and Research Division (2024), this domain accounted for 20% of the overall assessment items. Although its percentage is comparatively lower than that of the Number and Algebra domains, Geometry and Measurement remain significant and should not be overlooked, as mastery in this domain is crucial to ensure students' overall competency in the international assessment.

Percentage Topic Areas for the Geometry and Measurement Content Domain

Topic Areas: Geometry and Measurement (20%)
1. Identifying and constructing types of angles and pairs of lines, as well as applying relationships between angles on lines and within geometric figures, including angle and line segment measurements; reading and plotting points on the Cartesian plane to solve problems. This also includes tasks involving the measurement of angles and line segments, as well as problem-solving with points on the Cartesian plane.
2. Recognizing two-dimensional shapes and applying their geometric properties (e.g., the sum of interior angles of triangles and quadrilaterals and the properties of isosceles triangles), including calculating perimeter and area, as well as applying the Pythagorean theorem.
3. Determining the results of geometric transformations (translations, reflections, and rotations) in the plane; recognizing and applying the properties of congruent triangles and similar quadrilaterals.
4. Identifying three-dimensional shapes and applying their geometric properties to calculate surface area and volume, as well as relating three-dimensional shapes to their two-dimensional representations.

Note. Source: Trends in International Mathematics and Science Study – TIMSS 2023- Kementerian Pelajaran Malaysia

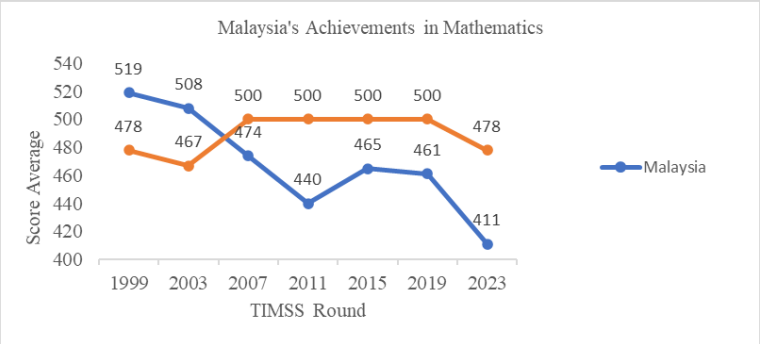
The average mathematics achievement scores of the 44 countries participating in TIMSS 2023 are presented in table below.

Average Mathematics Achievement Scores of TIMSS 2023 Participating Countries

Country	Average Score	Comparison with the Last Cycle of Participation
Singapore	605	-10
Chinese Taipei	602	-10
South Korea	596	-11
Japan	595	Unchanged
Hong Kong	575	-4
England	525	+10
Ireland	522	-2
Czech Republic	518	+14
Sweden	517	+15
Lithuania	514	-7
Austria	512	Newly Participating Country
Australia	509	-9
Turkey	509	+13
Hungary	506	-10
Finland	504	-5
Norway	501	-2
Italy	501	+3
Malta	499	+6
Romania	496	+17
Cyprus	494	-7
United Arab Emirates	489	+15
United States of America	488	-27
Israel	487	-32
France	479	-4
Azerbaijan	479	Newly Participating Country
Portugal	475	-25
Georgia	467	+5
Kazakhstan	454	-33
Qatar	451	+8
Bahrain	426	-55
Iran	423	-23
Uzbekistan	421	Newly Participating Country
Chile	416	-25
Oman	411	Unchanged
Malaysia	411	-50
Kuwait	399	-4
Saudi Arabia	397	+3
South Africa	397	+7
Jordan	388	-32
Palestine	382	-23
Brazil	378	Newly Participating Country
Morocco	378	-10
New Zealand	485	+4(did not meet the minimum standard for school participation rate)
Côte d'Ivoire	463	Newly Participating Country (Achievement could not be reliably estimated)

Note. Source: IEA's Trends in International Mathematics and Science Study – TIMSS 2023

Malaysia did worse on TIMSS 2023 than it did on the 2019 cycle, going from 461 points to 411 points. Malaysia is one of the five countries that saw the biggest drop in scores, with a loss of 50 points. The drop in Malaysia's TIMSS 2023 math scores shows that something is wrong and needs to be fixed right away, starting with primary school. Figure 1 shows how well Malaysia did in TIMSS Mathematics from 1999 to 2023.



Malaysia's Average Mathematics Achievement Scores

> *"Malaysia's highest achievement in mathematics was recorded in 1999, during its first participation in TIMSS, with a score of 519 points, surpassing the international average score of 487 points. Performance began to decline in the 2003 cycle with an average score of 508 points and further dropped in the 2007 cycle to 474 points, which was 26 points below the international average. Malaysia's performance continued to deteriorate in the 2011 cycle, falling below both the international average and the midpoint benchmark",* (Kementerian Pelajaran Malaysia, 2024).

Nevertheless, in the TIMSS 2015 cycle, Malaysia's performance showed an improvement of 25 points compared to the previous cycle. However, this upward trend was not sustained, as Malaysia's achievement declined again in the 2019 and 2023 cycles." (Kementerian Pendidikan Malaysia, 2024). Therefore, when comparing Malaysia's average performance against the international average scores in TIMSS Mathematics from 1999 to 2023, the data confirms that Malaysia's achievement has been inconsistent and remains below the international average benchmark.

Malaysia's achievement trends in TIMSS by mathematics content domain from 2007 to 2023

Years	Number	Algebra	Geometry and Measurement	Data and Probability
2007	**494**	**455**	**474**	**459**
2011	**451**	**430**	**432**	**429**
2015	**472**	**467**	**455**	**451**
2019	**458**	**456**	**466**	**457**
2023	**409**	**406**	**417**	**403**

Note. Source: Trends in International Mathematics and Science Study – TIMSS 2023-Kementerian Pelajaran MalaysiaFictitious data, for illustration purposes only

According to the Kementerian Pendidikan Malaysia (2024), Malaysia's achievement in all content domains of TIMSS 2023 decreased compared to TIMSS 2019. Therefore, this matter should be given serious attention to identify the main cause of the deterioration. Additionally,

proactive measures should be taken to reduce existing gaps. The emphasis on the aspects of understanding, measuring, and applying geometric shapes makes this topic important for primary school pupils to master.

These findings also show that mathematical achievement is very worrying among students in Malaysia, including from the aspect of geometry, based on the results of the international achievement of TIMSS and PISA (Hock Wuong & Rajoo, 2024). This statement is supported by an article which highlights that the weak level of mathematical mastery has placed Malaysia at a low ranking compared to developed Asian countries (Hasrin & Maat, 2022), with a decrease of 4 points compared to the average score in 2015. While in the study of Mohamad & Abd Karim (2023), the average decline in TIMSS and PISA achievement scores has had a significant impact on the Malaysian curriculum, especially for mathematics subjects.

The results also show that the average scores for geometry and measurement TIMSS 2007–2023 show that math achievement has not been consistent. The TIMSS 2023 average score was higher than the national average, but it was 57 points lower than the TIMSS 2019 average. Monan and J. Donald (2024) also found similar results when they looked at TIMSS statistics from 1999 to 2023. They found that Malaysian students' performance in geometry and cognitive skills had both gotten worse. Moreover, geometry education has been demonstrated to impact the overall mathematical performance of Malaysian students, as indicated by the country's TIMSS results (Syed Zainuddin & Abdullah, 2023). This downward trend is very worrying, and it needs to be dealt with right away to make sure that the quality of education in this country does not fall far behind that of other countries.

The Importance of 3D Printing in Geometry

Geometry is very important in many parts of everyday life, such as architecture, technology, the visual arts and science. Geometry is a fundamental topic in the primary school mathematics curriculum because it has many practical uses in real life (Shing Kit & Mahmud, 2023). However, primary school students have a lot of wrong ideas about geometry, especially when it comes to understanding three-dimensional shapes and other basic parts of the subject. This means that many students have trouble learning the subject (Nadzeri et al., 2022). So, using 3D printing to make simple geometric shapes that fit with the math lessons can help students learn geometry better by clearing up any misunderstandings they may have.

Meanwhile, 3D printing can also boost innovation by speeding up the design, testing and modification process without having to change any of the equipment that is already in use (Javaid et al., 2022). This benefit can also boost students' desire to learn more about printing, which can help them become more creative, better at solving problems and more involved in their learning through hands-on experiences (Khurma et al., 2023). So, combining 3D printing with geometry topics could make the curriculum better by making learning more fun and useful.

Additionally, a study by Kit Ng et al. (2022) also found that students' understanding of abstract geometric concepts can be improved by doing activities that involve physically moving objects using 3D printing or 3D pens. These activities, such as mentally rotating and changing three-dimensional objects, can help people become more creative, understand things better

and think critically. So, adding 3D printing to the mix makes learning more valuable by helping students understand geometric ideas in a natural and real-world way.

Nevertheless, as highlighted by Huleihil (2017), using 3D printing in education encourages higher-order thinking, new ideas and creativity. Furthermore, 3D printing facilitates the production of physical models of intricate geometric forms, thereby improving students' capacity to visualize and understand abstract mathematical principles (Muminovic et al., 2023). These kinds of hands-on activities are very important for helping students learn how to think critically and solve problems and they also make them more interested and motivated. In the end, these benefits can help students do better in math, especially in geometry.

According to Muminovic et al. (2023) assert that the incorporation of 3D printing in educational settings is essential for fostering students' interest in mathematics and improving their comprehension of spatial and graphical concepts through experiential learning. This method necessitates that students actively utilize geometric and spatial skills, thereby solidifying their understanding of geometry in real-world situations (Marianna & Ildiko, 2019). As a result, using this kind of technology makes it easier to rethink traditional geometric ideas, helps people understand geometry better in modern settings and makes learning more flexible and interactive.

Integration of 3D Printing In Primary Mathematics Education

Integration of 3D Printing with Geometry

3D printing is a technology that enables users to create three-dimensional objects based on digital models. In the context of teaching geometry, this technology lets students make and build geometric shapes in real life. significantly improve math learning outcomes, especially through Hu & Liu (2022), who say that using 3D printing in primary school math geometry shows that 3D printing technology can help students understand geometric concepts and get involved with 3D products. In the same way, Ng et al. (2020) found that a "Papert-inspired" way of teaching called "learning by making" helps students learn geometry by having them build real things in 3D printing environments.

However, Huleihil (2017) said that 3D printing needs higher-order thinking, new ideas and creativity to help people imagine things and let students see numbers, two-dimensional shapes and three-dimensional objects. The incorporation of 3D printing in geometry education facilitates students in constructing and directly visualizing geometric shapes (Ng et al., 2020). The use of 3D printing in geometry education not only helps students think, be creative, and come up with new ideas, but it also helps them see things in space better by actively building and exploring 2D and 3D geometry concepts.

Utilizing 3D printing technology in STEM project-based learning activities improves students' comprehension of engineering design processes (Lin et al., 2018). In college, using 3D printing in geometry classes has made it easier to look at abstract ideas like Platonic solids in a more concrete way (Torres, 2024). The incorporation of 3D printing enhances opportunities for innovation and creativity, facilitating experiential learning that allows students to visualize and manipulate geometric shapes, thereby deepening their understanding of abstract concepts (Hu & Liu, 2022). This integration not only enhances

educational experiences but also fosters innovation across various disciplines associated with geometry, particularly at the educational level.

According to Marianna & Ildiko (2019), using 3D-printed models in the classroom helps students learn geometry by giving them something real to work with. Additionally, students acquire practical skills through the design and creation of 3D models, necessitating the application of geometric and spatial knowledge (Marianna & Ildiko, 2019). The use of 3D printing in geometry not only helps with formal learning, but it also encourages informal exploration and creativity in math (Kit Ng et al., 2022a). Consequently, the incorporation of 3D printing into geometry education will enhance students' spatial visualization abilities and motivation by engaging them with tangible materials, while also promoting practical skills, informal exploration, and creativity within the realm of mathematics.

Nonetheless, informal learning challenges may emerge when geometric shapes, including squares, triangles, circles, and rectangles, are displayed in random or disorganized configurations, potentially resulting in confusion or misidentification among students (Flores-Bascuñana et al., 2020). This problem can make it harder to learn basic geometry concepts about shapes and space. Thus, the combination of 3D printing technology and geometry is very useful for filling in these gaps because it encourages students to look deeper and improves their long-term skills in comparing and contrasting geometric ideas.

Additionally, measuring and calculating the sizes of 3D-printed objects lets students work with real models, which helps them understand how measurement and math relationships work better (Dang et al., 2024). There are many educational benefits to 3D printing but there are also some problems, like the fact that both teachers and students need more time to learn how to use the technology (Hu & Liu, 2022). Because of this, teachers and students need more time to do activities that combine 3D printing machines with geometry. This will make the activities go more smoothly without taking away from the time set aside for other subjects.

Integration of 3D Printing with Problem-Based Learning [PBL]

Geometry is a fundamental component of the math curriculum for primary school students. It is used in many areas of daily life, such as architecture, technology, visual arts, and science (Shing Kit & Mahmud, 2023). Many primary school students, on the other hand, have trouble understanding important geometric ideas, especially when it comes to three-dimensional shapes. This can lead to misunderstandings that last for a long time (Nadzeri et al., 2022). In this context, 3D printing stands out as a great way to learn because it gives students real-life examples of geometric shapes that help them understand and have meaningful learning experiences.

The integration of 3D printing in classrooms not only improves comprehension but also encourages creativity, problem-solving and higher-order thinking skills (Huleihil, 2017; Javaid et al., 2022). 3D printing encourages experimentation and innovation by letting students design, test and change geometric models in a hands-on setting. It also encourages active engagement and motivation (Khurma et al., 2023). These experiences enhance spatial reasoning by engaging learners in the manipulation of three-dimensional objects, executing

mental rotations and visualizing transformations, which in turn enriches their conceptual comprehension (Kit Ng et al., 2022a; Muminovic et al., 2023).

Furthermore, 3D printing fits well with Problem-Based Learning (PBL), which is a teaching method that focuses on learning by solving real-world problems. This framework allows students to work on interactive projects that require them to use geometric and spatial reasoning in real-world situations. For example, students could make and build scale models of everyday things or structures that use a variety of geometric shapes in a way that makes sense. These activities reinforce geometric knowledge and promote collaboration, analytical thinking and creativity, while also giving students the chance to explore on their own.

By using 3D printing in conjunction with PBL, teachers can turn abstract geometric ideas into real-world experiences that make sense in context. This method makes students more motivated, helps them think critically and helps them solve problems, which leads to better learning and higher scores in math, especially in geometry. The hands-on nature of this integration also fits with constructivist learning theories because it lets students actively build knowledge by manipulating, experimenting and reflecting in a structured but flexible learning environment.

Discussion

Decline in The Geometry Domain in TIMSS 2023

TIMSS 2023 showed that Malaysia's math scores had dropped a lot, especially in the areas of Geometry and Measurement. The average score in this area went down from 466 in 2019 to 417 in 2023, which is lower than the international average (Kementerian Pendidikan Malaysia, 2024). This drop shows that traditional teaching methods don't work for today's students. So, there is an urgent need for strategic reforms that include new ways of teaching, like using 3D printing technology to teach geometry in primary school. Recent research indicates that spatial visualization tools and 3D modeling enhance students' geometric reasoning and alleviate conceptual decline (Medina Herrera et al., 2024). Additionally, practical 3D printing applications in mathematics education have been documented to improve students' engagement and comprehension of three-dimensional shapes (Kit Ng et al., 2022b).

The Importance of 3D Printing

3D printing is becoming more and more well-known as a useful tool in education because it helps students learn in new, interesting and useful ways. Design-based tasks using the technology boost creativity and problem-solving skills while also improving spatial visualization, which is an important skill for making abstract ideas more concrete (Zhu et al., 2024). Kit Ng et al. (2022a) point out that 3D printing is a practical way to make prototypes quickly and cheaply, which makes it a good choice for classroom design and innovation activities. It also makes learning environments where students can explore, design and judge their own work. This experiential and constructivist learning approach not only maintains motivation but also enhances academic performance, especially in mathematics. Empirical studies validate that the integration of 3D printing in mathematics enhances comprehension of geometric shapes and promotes spatial reasoning (Muminovic et al., 2023). Furthermore, additive manufacturing in engineering education has demonstrated an enhancement of students' creativity, critical thinking and spatial abilities (Munir et al., 2025).

Integration of 3D Printing with Geometry

Geometry in primary school is an important building block that helps students learn how to visualize, think critically, solve problems, use deductive reasonin, and use logic in math (Tursynkulova et al., 2023). The capacity to comprehend shapes, measurement and spatial relationships in early geometry signifies a crucial milestone in students' cognitive development. Studies show that students often have trouble understanding these ideas, mostly because geometry is so abstract (Andriliani et al., 2022). These problems can be lessened by using teaching methods that focus on visual and physical representations. So, using technology like 3D printing can be very helpful in helping students understand geometric ideas in a more concrete and easy-to-understand way.

By designing and changing three-dimensional models, students can learn about geometric shapes in a real way (Surynková, 2023). Students can use design software like Tinkercad, Fusion 360, or Blender to make geometric shapes that help them understand things like symmetry, perimeter, surface area, and volume better. This hands-on method not only sparks students' interest and creativity, but it also helps them understand how geometry is used in the real world (Flores-Bascuñana et al., 2020). Recent research underscores that the incorporation of 3D printing in geometry classes enhances problem-solving, collaboration, and higher-order thinking, allowing students to convert abstract concepts into concrete results (Dang et al., 2024). So, 3D printing makes teaching better by connecting digital design with real-world math learning.

Integration of 3D Printing with Project-Based Learning (PBL)

The integration of 3D printing and Project-Based Learning (PBL) is a teaching method that uses math in real-life situations and in creative ways. Nevertheless, the effective implementation of this approach requires careful planning, including adequate infrastructure, professional training for teachers, and consistent maintenance of equipment, to ensure that the technology is utilized to its full potential within the educational ecosystem (Kit Ng et al., 2022a). Recent studies further emphasise that embedding 3D printing into PBL frameworks enhances learner motivation, supports iterative design thinking, and fosters deeper conceptual understanding (Radiopoulou et al., 2025). Additionally, a web-based modelling environment for 3D printing demonstrates how students can dynamically manipulate and test designs, thereby reinforcing feedback loops in project work (Grizioti et al., 2024). Through activities such as planning, designing, and printing geometric models, students not only strengthen their understanding of spatial and structural concepts but also develop collaboration, analytical reasoning, and technological skills relevant to the 21st century.

Conclusion

The integration of 3D printing in the teaching of geometry at the primary school level offers a more holistic and effective learning approach. This technology not only enhances students' understanding of geometric concepts but also fosters the development of essential skills needed to meet the challenges of the 21st century. Overall, the incorporation of 3D printing in mathematics education, particularly in the topic of geometry, holds significant potential to strengthen the learning experience of primary school students. Beyond facilitating the concrete visualization of shapes and spatial relationships, 3D printing stimulates critical thinking, creativity, and problem-solving skills among learners. Through

approaches such as Problem-Based Learning (PBL), students can actively engage in constructing their own knowledge through meaningful and applied learning experiences.

In light of Malaysia's declining performance in mathematics as reflected in TIMSS 2023, innovative approaches such as the integration of 3D printing should be considered as effective strategies to address learning challenges in complex topics such as geometry and measurement. Achieving this vision requires strong support from multiple stakeholders, including teachers, schools, and the Ministry of Education, particularly in terms of providing adequate infrastructure, training in technology use, and the development of appropriate teaching materials. Therefore, expanding the use of this technology within the mathematics curriculum at the primary level is essential in nurturing a generation that is more creative, innovative, and competitive in the fields of STEM in the future.

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