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USING POLYGONAL MODELS IN STEM EDUCATION

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Abstract

This article analyzes the theoretical and methodological foundations, pedagogical possibilities, and practical results of using geometric models of polyhedra in the educational process for STEM in preschool educational institutions and general education schools. The study is based on experimental work conducted with students aged 5-16, and the methods for creating and studying polyhedral models using paper, cardboard, 3D printing, and digital simulation tools are examined more extensively. The research results propose a new methodological approach to organizing STEM lessons based on polyhedral models.

Keywords

STEM education, polyhedra, geometric model, preschool education, general education school, spatial thinking, integrated education, 3D modeling, didactics.

Annotatsiya: Ushbu maqolada maktabgacha ta’lim muassasalari va umumta’lim maktablarida STEM yo‘nalishida ko‘pyoqlilar geometrik modellaridan o‘quv-tarbiya jarayonida foydalanishning nazariy-metodologik asoslari, pedagodik imkoniyatlari va amaliy natijalari tahlil qilingan. Tadqiqot 5–16 yoshdagi o‘quvchilar bilan olib borilgan tajriba-sinov ishlari asosida qurilgan bo‘lib, ko‘pyoqlilar modellarini qog’oz, karton, 3D-bosib chiqarish va raqamli simulyatsiya vositalari orqali yaratish va o‘rganish metodlari kengroq ko‘rib chiqilgan. Tadqiqot natijalari ko‘pyoqlilar modellariga asoslangan STEM darslarini tashkil etishning yangi metodologik yondashuvini taklif etadi.

Kalit so‘zlar: STEM ta’limi, geometrik model, umumta’lim maktabi, fazoviy tafakkur, ko‘pyoqlilar, integratsiyalashgan ta’lim, 3D modellash, maktabgacha ta’lim, didaktika.

Аннотация: В данной статье анализируются теоретико-методические основы, педагогические возможности и практические результаты использования гео-

метрических моделей многогранников в образовательном процессе по STEM в дошкольных образовательных учреждениях и общеобразовательных школах. Исследование основано на экспериментальных работах, проведенных с учащимися 5-16 лет, и более подробно рассматриваются методы создания и изучения многогранных моделей с использованием бумаги, картона, 3D-печати и средств цифрового моделирования. Результаты исследования предлагают новый методический подход к организации STEM-занятий на основе многогранных моделей.

Ключевые слова: STEM-образование, полиэдры, геометрическая модель, дошкольное образование, общеобразовательная школа, пространственное мышление, интегрированное образование, 3D-моделирование, дидактика

INDRACTION

One of the most critical tasks facing the 21st century education system is to equip students with profound knowledge and practical skills in the fields of science, technology, engineering, and mathematics (STEM). World experience shows that the effectiveness of STEM education largely depends on which teaching methods, visual aids, and pedagogical technologies are used (Honey et al., 2014).

Polyhedra are a class of geometric bodies that form a closed surface in three-dimensional space, representing one of the oldest and most universal forms of natural scientific cognition. From Plato's five regular polyhedra to Archimedes' bodies and quasicrystals, geometric shapes have found their practical reflection in living nature, crystallography, architecture, nanoscience, and artificial intelligence (Cromwell, 1997; Salgaller, 1969). It is this comprehensiveness that creates a unique pedagogical foundation for transforming polyhedron models into an integral part of STEM education. In the process of modernizing education in the Republic of Uzbekistan, strengthening the STEM direction in the preschool education system and general education schools has become one of the priorities of state policy (Decree of the President of the Republic of Uzbekistan No. UP-6257 dated May 11, 2021). At the same time, the development of geometric thinking in preschool children and the formation of spatial vision in schoolchildren remain a problem that has not yet been fully scientifically and methodologically resolved.

The purpose of this article is to develop the scientific foundations for using

polyhedron models in STEM in preschool and school education, systematize methodological approaches, and present efficiency results based on practical experience.

LITERATURE ANALYSIS AND STATE OF THE PROBLEM

Conceptual foundations of STEM education

The concept of STEM education was formed in the USA in the early 2000s and later spread throughout the world. Sanders (2009) argues that STEM is not a collection of separate disciplines, but an integrated system of approaches that unites different fields of knowledge around real problems and projects. Furthermore, in his opinion, hands-on learning, problem-based learning (PBL), and creative thinking are essential prerequisites for success in STEM education. In recent decades, with the addition of the ARTS direction to STEM education, the concept of STEAM has been formed, and the importance of the aesthetic and creative component has increased even more (Jacman, 2008). Models of polyhedra, with their constructive nature and aesthetic beauty, are an ideal tool for implementing a STEAM approach.

Polyhedra and their pedagogical potential

The pedagogical significance of studying polyhedra was first emphasized by Pestalozzi (1801) and Froebel (1826). Frobel's famous system of "games" included various multifaceted forms, as they were believed to develop spatial awareness and hand-eye coordination in the child. Modern research has confirmed this opinion based on experimental data: Shepard and Feng (1990) found a strong correlation between spatial thinking and mathematical success; Mix and Cheng (2012) showed that the ability to manually assemble three-dimensional objects helps children develop algebraic thinking at an early age. Casey et al. (2008) noted that a program aimed at developing spatial skills in kindergartens significantly improved mathematical performance indicators. In the same vein, Newcombe (2010) emphasized the importance of early development of spatial thinking in preschool children, as well as interest in STEM subjects scientifically substantiated that it is a strong predictor of success.

Geometric models in integrated education

Modern research on the use of geometric models in STEM education is conducted in several directions. Brinker et al. (2019) used 3D-printed polyhedral models in

teaching molecular geometry in chemistry lessons and recorded a 34% higher mastery result compared to the control group. Fenyvesi et al. (2016) found that creative activity through polyhedral origami and paper construction is effective in increasing students' creative problem-solving skills and persistence. In the context of Uzbekistan, research in this direction is still limited, and existing works are mainly related to the activities of mathematical Olympiads and clubs (Nazarov, 2018; Khalikov, 2020). This article aims to partially fill this research gap.

RESEARCH METHODOLOGY

Research design

The study was conducted during 2022-2024 in 4 preschool educational institutions (PEO) and 3 general education schools located in the city of Tashkent and the regions. A total of 312 students were involved in the experimental work (98 preschoolers aged 5-7 and 213 students in grades 1-9). A mixed methodology (mixed methods) was applied: quantitative data (test results, evaluation indicators) were studied in combination with qualitative analysis (observation, interviews, work samples).

Experimental groups and control groups

Group	Youth	n	Learning model
MTM - experiment	Grades 5-7	52	Active manipulation of polyhedra
MTM - control	Grades 5-7	46	Traditional education
School is an experience	Grades 7-15	112	STEM integration + multidimensional models
School - Control	Grades 7-15	102	Standard curriculum

Models of polyhedra and degrees of their application

–The following system of three-level models was developed and tested in the study:

–Level I (preschool, grades 1–2): composite polyhedra made of paper and cardboard according to a ready template – cube, tetrahedron, octahedron, prisms. The main goal: to form an intuitive idea of the surface, edges, and vertices.

–Level II (grades 3-6): independent design from cardboard, sticks, and plasticine;

mathematical calculations (tip, edges, surface area); interdisciplinary communication (biology, geography, chemistry).

– Level III (grades 7-9): 3D printing, digital modeling using GeoGebra 3D and Desmos; volume, sections, axes of symmetry; linking to real scientific problems (crystallography, construction materials, fullerenes)

Data collection tools

1. Spatial Thinking Test (Purdue Spatial Visualization Test - Uzbek adaptation)
2. Interest and motivation questionnaire for STEM subjects (Likect 5-point scale)
3. Lesson observation protocol (65 lessons, 130 hours of observation).
4. Semi-structured interviews with teachers and parents (n=48).
5. Qualitative analysis of models (768 models) produced by the student.

RESEARCH RESULTS AND DISCUSSION

Preschool education outcomes

At the end of the academic year, children participating in the experimental group (n=52) showed statistically significantly higher results in the spatial thinking test compared to the control group (experiment: M=68.4±9.2; control: M=54.1±11.3; t (96) =6.84; $p<0.001$; Cohen d=1.38). This indicates that the large effect size of systematic work with multifaceted models has a strong impact on the spatial perception of preschool children. As a result of qualitative observations, it was noted that in the process of working with polyhedra, preschool children develop the following competencies: expanding a surface onto a flat surface and transforming it back into a body (reversibility); naming and comparing shapes; classifying by color, size, and quantity; and establishing cause-and-effect relationships.

Outcomes in school education

Students in the experimental group (n=112) who worked with multifaceted models based on STEM integration in secondary schools also demonstrated significant progress in the transfer of interdisciplinary knowledge (transfer of learning). The following table presents the main measurement results:

Indicator	**Experimental group**	**Control group**	**p-value**

	(M±SD)	(M±SD)	
Spatial thinking test	72,6 ± 8,4	59,3 ± 10,7	p < 0,001
Mathematics mastery	76,2 ± 7,8	68,4 ± 9,1	p < 0,01
Geometry department	81,4 ± 6,3	64,7 ± 11,2	p < 0,001
STEM Interest Index	4,21 ± 0,54	3,47 ± 0,72	p < 0,001
Troubleshoot	69,8 ± 9,6	61,2 ± 10,4	p < 0,05

As seen from the table, the experimental group has a statistically significant advantage across all measurement indicators. In particular, the difference in the geometry section (81.4 and 64.7) indicates the direct influence of polyhedron models on the conscious assimilation of geometric concepts.

Cases of interdisciplinary integration

–During the study, it was determined and documented that the integration of polyhedron models into the following disciplines is effective:

–Mathematics: Euler's formula (V - Q + S = 2), calculation of surface area and volume, symmetry, analysis of sections.

–Chemistry: Visual study of the structure of chemical bonds by creating models of crystal lattices of NaCl, diamond, graphite, and fullerene (C60). Boshqinboyev and others. (2023) showed that the use of polyhedral models in chemistry classes increased students' mastery of molar mass and VSEPR theory by 27%.

–Biology: the shape of plant and animal cells; the icosahedral structure of viruses (icebergs, bacteriophages); the geometric structure of animal bones and shells.

–Physics: optical properties of crystalline bodies; mechanics of solids; explaining the strength of building structures using a polyhedron model.

–Technology and engineering: building a realistic model from cardboard, wood, and plastic materials; 3D printer prototype printing; digital environment simulation

From the experience of teachers

Methodological findings identified through interviews and observations showed that the most effective lessons were successful when they included the following stages:

(1) problem-solving and discussion; (2) independent research and hypothesis; (3) build and test the model; (4) measurement and analysis of results; (5) transfer to other fields and presentation. These steps align with the 5E learning model (Engage, Explore, Explain, Elaborate, Evaluate) (Bybee et al., 2006).

The main obstacles observed among teachers were: a lack of materials (76% of teachers), limited time (68%), a lack of methodological manuals on the geometry of polyhedra (82%), and low skills in using digital tools (54%). Therefore, practical recommendations are provided at the end of the article**.**

METHODOLOGICAL GUIDELINES

For preschool educational institutions

1. When organizing work with polyhedra, preschool educators are recommended to adhere to the following principles:

2. A free research environment: allowing the child the freedom to touch, rotate, count, and name shapes.

3. Learning through a story: presenting polyhedra as magical fortresses, houses, and ships associated with the characters (narrative didactics).

4. Visual environment: keep a collection of various polyhedra in a room in a visible place, and hang children's models on the wall.

5. Engaging parents: assignments for making polyhedra from paper cardboard at home**.**

For general education schools

We recommend the following STEM lesson structure for school teachers:

Stage	Activity	Time	Core subject
Introduction	Analyze a real problem or event	5-7 minutes	All subjects
Research	Building and measuring a polygonal model	15-20 minutes	Mathematics
Linkage	Identify physical/chemical/biological relationship	10 minutes	Natural Sciences
Creation	New model design	10 minutes	Technology
Presentation	Oral and written presentation of results	5 to 8 minutes	Linguistics

Integration with digital tools

The effectiveness of the following free software tools for studying polyhedron models in a digital environment has been tested:

–GeoGebra 3D (geogebra.org) - interactive three-dimensional geometric constructions, surface and volume calculation.

–Desmos 3D - functional geometric visualization.

–Tinkercad (tinkercad.com) is a platform for 3D modeling and printing designed for schoolchildren.

–Nets of 3D Shapes (mathsisfun.com) – interactive viewing of polyhedral outlines.

–Stella4D - Advanced polygon geometry (grades 8-9 and above)

CONCLUSION

This study showed that the systematic and methodologically thoughtful use of geometric models of polyhedra in STEM education:

Statistically significant development of spatial thinking in preschool children (Cohen's d=1.38);

Increases the academic performance of schoolchildren in geometry, mathematics, and natural sciences;

Increases interest and motivation in STEM subjects;

Serves to build strong cognitive bridges between interdisciplinary knowledge;

Develops problem-solving, design, and collaboration skills.

We consider the following areas promising for future research: creating a polyhedral environment using artificial intelligence and AR/VR technologies; longitudinal observations of schoolchildren (5–10 years); developing national STEM curricula based on polyhedral models; and standardizing special sets of polyhedra for preschool educational institutions.

This study serves as a scientific and methodological basis for school and preschool practitioners, educational design specialists, and researchers on the path to modernizing education in Uzbekistan.

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