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Using 3D Modeling to Develop Schoolchildren's Research Skills in the Process of Studying Natural Science Disciplines

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Abstract

3D modeling and prototyping are important areas of digital education and have undoubted didactic potential for the development of engineering thinking, that is highly sought after in today's economy. The authors suggest using 3D modeling technology to develop the research skills of schoolchildren when studying natural sciences and implementing interdisciplinary projects aimed at forming the foundations of a holistic scientific picture of the world through understanding the relationship and interdependence of the natural sciences. The purpose of the study is to theoretically substantiate and develop approaches to the development of schoolchildren's research skills when studying natural science disciplines based on 3D modeling.

The work uses the following classification of research skills: operational, communication, organizational, and information. For them, the authors have identified the corresponding indicators: conducting observations and research during modeling; putting forward a hypothesis; planning research activities; and analysis of information sources. The curriculum and lesson planning for the "Technology" course are presented, which allows students to develop research skills during the implementation of applied educational tasks. A system of tasks and sample models has been developed to support all stages of students' research activities during the implementation of educational interdisciplinary projects following the proposed lesson planning of the module.

In conclusion, the didactic potential of computer 3D modeling and prototyping for the development of research skills of schoolchildren is formulated: putting forward a hypothesis of a

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natural science nature and testing it experimentally; mastering the methodology of independent planning and conducting an experiment in compliance with safety regulations, etc.

Keywords: Industry 4.0, additive technologies, research skills of schoolchildren, interdisciplinary project, didactic potential, prototyping, reference model.

1. Introduction

K. Schwab, founder and president of the World Economic Forum, noted in 2016 that the world is on the verge of the fourth industrial revolution. In his opinion, the new technologies of Industry 4.0 should allow us to combine the physical, information, and biological worlds in the near future (Schwab, 2016).

According to the conclusions of A.A. Krushanov, the main directions of Industry 4.0 are the following advanced technologies: the Internet of Things, Additive Manufacturing, Artificial Intelligence, etc. (Krushanov, 2022). The requirements for engineering professions related to industrial production are gradually changing, and the job functions of specialists who will work in "smart" factories or conduct scientific research are being rethought (Bauer et al., 2022).

E. Bidaibekov, V. Grinshkun note that a comprehensive assessment of the digital maturity of the education system and the search for optimal didactic strategies are necessary (Bidaibekov, Grinshkun, 2021). The formation of new skills is possible by revising the content of education. The authors believe it is possible to develop digital skills through specialized disciplines such as computer science and technology. Or include training in digital competencies in all disciplines of the educational program as an end-to-end content line. Changing principles and approaches to education leads to the inevitable search for new approaches and techniques for organizing the educational process.

An example of such innovations could be the introduction of additive technologies into the general education system. For example, in 2017, the UK announced its plans to become a global leader in the additive manufacturing sector by 2025. The UK National Additive Manufacturing Strategy 2018–2025 has been adopted (Additive Manufacturing…, 2018). The strategy describes the main activities aimed at achieving the goal. The UK is already one of the largest countries in Europe for additive manufacturing (after Germany). In particular, due to the fact that a significant number of 3D printer manufacturers are concentrated in Europe (such as Ultimaker and Admatec) and online services that provide remote 3D printing services are developed (for example, Shapeways).

Education officials in Singapore are so convinced of the potential of new digital technologies that they plan to introduce the use of a 3D printer into the educational process of every primary school in the country within the next 5 years.

In Russia, the "Strategy for the Development of the Information Society in the Russian Federation for 2017–2030" was adopted, aimed at creating an information space taking into account the needs of citizens and society (Ukaz Prezidenta…, 2017). Thus, many developed countries of the world have entered into competition for primacy in the field of dissemination of additive technologies in education. N.L. Karavaev, E.V. Soboleva substantiate that the education system faces a responsible task – to give future specialists of the digital economy (engineers, technologists, designers, planners, etc.) sufficiently deep fundamental knowledge, to form research skills and practical skills in the latest technologies (Soboleva, Karavaev, 2020). The solution to this problem cannot be achieved without the use of digital tools in the educational process as part of the modern information and educational environment.

International pedagogical research PISA for 15 years has shown that the level of science literacy among Russian schoolchildren is not high enough (PISA Model…, 2020). The formation of natural science literacy does not come down to the integration of subject knowledge, skills, and abilities in physics, chemistry, and biology. To solve this educational problem, it is necessary to use special technologies and tools that can develop in students a special attitude towards understanding meta-subject tasks and a fundamentally different approach to their implementation.

It should be noted that at present it is important to acquaint students with such information technology tools that will be in demand in their future life in the digital economy. Among such promising technologies are 3D modeling and prototyping, which are gradually penetrating various spheres of human activity: from engineering and architecture to medicine and design (Gordeev, Ananikov, 2020). To date, several Russian (Mudrakova, Latushkina, 2020) and foreign studies (Huang et al., 2019) have already been carried out aimed at developing methods of teaching 3D modeling.

In particular, methods for developing engineering competencies using 3D technologies are being tested (Isaev, Plotnikov, 2019). Particular studies on the use of 3D tools in biology, chemistry (Petrov, 2023), and the training of future teachers (Masharova et al., 2020) are presented.

However, within the Russian educational system, there is a lack of scientifically based methodological approaches for incorporating 3D modeling technology into the study of natural science disciplines. This hinders the development of research skills among schoolchildren. Mainly single studies are conducted to describe the stages of introducing 3D printing technology into the educational process (Faritov, 2019).

So, despite the obvious developmental potential of 3D modeling technology and the growth of its popularity abroad, it has still not taken its rightful place in domestic methodological systems for teaching school subjects.

The presented study will allow pedagogical science to justify at a theoretical level the need to develop approaches to the development of schoolchildren's research skills when studying natural sciences based on 3D modeling. At the practical level, the authors present an appropriate approach (description of the structure and content of the module, a system of tasks and sample models).

2. Relevance

2.1. Literature review

2.1. Analysis of Russian scientific and pedagogical literature

A. V. Leontovich identifies the following functions of students' research activities at different levels of education (Leontovich, 2018). For example, in a basic school, this is the development in students of the ability to independently set a goal and achieve it in educational activities in the course of applying elements of research activities within the framework of curriculum subjects; in high school – the development of research competence and pre-professional skills as the basis for general and additional education. The author poses the problem of the relationship between the educational and research activities of schoolchildren.

The most logical from the point of view of natural science disciplines is the classification of skills proposed by V.I. Andreev. The scientist identifies four groups of skills: operational, information, communication, and organizational (Andreev, 1983). This classification generally corresponds to the main functions of pedagogical activity and most fully defines the range of research skills.

Additive technologies, as defined by E.A. Mamaeva, and T.N. Suvorova, are of great importance for improving the quality of training, as they allow the interdisciplinary nature of modeling activities to be realized. The student not only receives ready-made theoretical knowledge, but also finds himself in the state of a "researcher." In this state, he comes as close as possible to the real process of cognition. At the same time, preparing a clear conceptual framework and terminology is extremely important in order to remain ourselves and develop (Mamaeva, Suvorova, 2020). There are several factors contributing to this issue, such as the absence of necessary laboratory equipment, potential risks associated with certain scientific experiments, and the high costs of materials required for laboratory research (Petuchova et al., 2021).

As noted by I.D. Stolbova, L.V. Kochurova, and K.G. Nosov, traditional 2D image systems (projection) have become secondary both in information content and in technological terms. The basic concept of graphic education should initially and entirely be based on a digital 3D (volumetric) model that combines information about the product at all stages of its life cycle (Stolbova i dr., 2020). Research conducted by M.D. Dammer et al demonstrated that curricula, programs, and textbooks in education exhibit significant deficiencies. Specifically, they highlighted a tendency to undervalue the critical role of incorporating interdisciplinary connections in the teaching of natural sciences to schoolchildren (Dammer et al., 2018).

Some modern concepts of natural science education propose starting education in primary school with an integrative course. The need for integration in teaching is emphasized by many didactic scientists. For example, M.M. Abdurazakov, O.Yu. Lyaginova, and O.N. Tsvetkova indicate that the existing potential of interscientific relations and interdisciplinary connections will help modern school disciplines overcome emerging difficulties and successfully develop in the new conditions of digitalization (Abdurazakov i dr., 2021). However, it is necessary to have an appropriate methodological justification, pedagogical research reflected in the methodology and content of subject teaching at the level of sample programs

There are numerous challenges present in science education within Russian schools. For instance, a study conducted by N.V. Kochergina and A.A. Mashinyan highlights that, among the subjects in the natural science curriculum, the experimental component of the certification process is currently only included in the State Examinations for Physics and Chemistry. This underscores the importance of incorporating practical, hands-on learning experiences in all areas of science education to ensure a comprehensive understanding and assessment of students' knowledge and skills (Kochergina, Mashinyan, 2019). During the final certification in 11th grade, it has been noted that the experimental component is lacking in all disciplines. However, there is a growing discussion within the pedagogical community regarding the implementation of practical components using real equipment during the Unified State Exam in chemistry, physics, and biology. Research conducted by FIPI is actively exploring this possibility. Overall, the findings from studies on the quality of science education in schools indicate that the current methods employed to enhance students' natural science literacy are not sufficiently effective. It is imperative that we continue to evaluate and improve upon these methods to ensure that students are adequately prepared for future academic and professional endeavors.

The use of digital technologies such as 3D printing to support education is not new. The fields of architecture and engineering were the first to use rapid prototyping technologies for educational purposes (Gordeev, Ananikov, 2020).

A.T. Faritov notes that projects using 3D prototyping should involve students developing their unique models that have certain practical or aesthetic benefits (Faritov, 2019). The article presents a generalization of the author's experience in introducing 3D printing into extracurricular activities in a gymnasium in the city of Ulyanovsk. Based on a generalization of experimental data, A.T. Faritov concludes that only with the right methodological approach can the introduction of 3D modeling into the scientific research activities of schoolchildren be beneficial. Proper planning of such activities according to the age of students can bring creativity to learning and prepare them for the challenges of the future industry. However, the author does not propose such an approach either in this or in subsequent works (Faritov, 2019).

A more meaningful, in terms of scientific validity, option for using 3D modeling tools for teaching schoolchildren is presented in the work of E.A. Mikhlyakova, and T.N. Suvorova (Suvorova, Mikhlyakova, 2020). The authors describe the directions of pedagogical support for the creative creative activity of students within the framework of a personalized learning model based on 3D technologies. However, the potential of advanced technologies for the formation of scientific research skills of schoolchildren is not indicated here.

E.E. Petrov presents the results of studying foreign experience in teaching biology based on 3D models (Petrov, 2023). The author analyzes specialized software products and tools that make it possible to implement the study of individual sections of biology using three-dimensional geometric modeling tools. According to his conclusions, 3D learning technology is one of the new educational technologies implemented using information and telecommunication technologies in the process of virtual information interaction between a student and an educational resource.

O.A. Mudrakova and S.A. Latushkina prove that working with three-dimensional modeling improves students' perception of the material (Mudrakova, Latushkina, 2020). This software is much more fun to work with than regular 2D graphics programs (for example, Paint). Having generalized the experience, the authors construct a methodology, and consequently, lessons that were taught in 9th grade computer science lessons.

O.N. Vasilyeva and N.V. Konovalova describe a more holistic methodological work in engineering classes. This approach is designed to benefit not only gifted students with exceptional academic performance, but also those who may not excel in traditional subjects. By implementing this holistic approach, educators can cater to a wider range of students and provide a more inclusive learning environment in engineering education (Vasilieva, Konovalova, 2018). The authors prove that such classes provide an opportunity to develop the abilities and skills of technical thinking in modern schoolchildren (Engineering classes as a tool for professional navigation). The difference between the projects is the involvement of technical students in the educational process as mentors when schoolchildren perform research and design work. However, neither the curriculum nor lesson planning is presented, allowing other teachers to develop students' research skills during the implementation of applied educational tasks.

T.V. Masharova et al. scientifically substantiate the need to improve the training model, taking into account the capabilities of 3D technologies as a response to the challenges of Industry

4.0, ensuring competitiveness, supporting professional self-realization of the student, and developing in-demand innovative thinking (Masharova et al., 2020). The authors present methodological and organizational support for all stages of innovative activity using 3D technologies: analysis of the target market and target consumer (consumer portrait model); performing an analysis of competitors/analogs on the market; justification of the value of the proposed technical solution for the consumer (clarification of the practical problems that the invention will solve); assessment of novelty and social significance. However, the presented research focuses on training university students. And it does not take into consideration the specifics of schooling.

So, in most modern works, the authors identify various advantages of integrating additive technologies in teaching under the challenges of Industry 4.0:

- how to facilitate learning, increase the involvement and motivation of students (Faritov, 2019);
- how to inspire schoolchildren to be creative and improve their attitude towards STEM subjects (Vasilieva, Konovalova, 2018);
- how to help young people in professional self-determination (Suvorova, Mikhlyakova, 2020);
- how to increase the interest and involvement of the mentors themselves (Petuchova et al., 2021).

Comprehensive research is being carried out to improve the training of engineering and teaching staff at leading Russian universities.

At the same time, the resources of the information and educational environment are not sufficiently covered in the scientific literature, and in practice, the resources of the information and educational environment are not used in the formation of research skills in schoolchildren. However, in our country, unfortunately, there are often cases when a school 3D printer is used as a "display sample", demonstrating the fact of the presence of such a progressive object in an educational organization without any use it.

At the same time, a teacher's design of the educational process in a digital environment requires new approaches not only to planning new educational results but also to the selection of educational content, methods, and forms of organizing the educational process based on advanced (additive) technologies.

This determines the need to develop an approach that provides an opportunity to improve the methodology for organizing the research activities of schoolchildren, thereby promoting the development of their research skills by including in the content components related to 3D computer modeling technology.

2.2. Analysis of foreign studies

J. Savolainen and M. Collan conclude that the development of advanced technologies of Industry 4.0 will largely influence the evolution of the structure of production and educational processes (Savolainen, Collan, 2020). In the course of digital transformation, there is a need for a systematic review of existing business models, changes to business processes, and a transition to a qualitatively new government policy, including educational policy. This will require further improvement of the means and methods of applying digital innovations in the training of highly qualified specialists.

I. Gibson et al. note that additive manufacturing provides digital flexibility and efficiency in production operations (Gibson et al., 2021). 3D printing goes beyond industrial prototyping and the manufacturing process. This technology has become more accessible to small companies and even individuals. J. Marić, M. Opazo-Basáez, B. Vlačić, M. Dabic suggest that 3D modeling technologies and related application tools are the basis for Industry 5.0 (Marić et al., 2023).

E. Bauer, N. Heitzmann, and F. Fischer present a summary of information on promising directions for the development of scientific research in the field of application of modeling for educational purposes, development, and upbringing (Bauer et al., 2022). The authors identify vectors for further development, for example, the use of simulation technologies, which involve the use of virtual simulators. Modeling as a research activity encourages students to be active, which increases the intensity of their thinking processes.

T.-Ch. Huang, M.-Y. Chen, Ch.-Y. Lin's experimental data show that the use of 3D (three-dimensional) models of real objects is an important means of transmitting information, which can significantly increase the effectiveness of learning (Huang et al., 2019). The authors note the universal nature of the modeling method for activating cognition in a three-dimensional graphics environment. According to the authors' conclusions, manipulation with 3D models works best for the development of thought processes.

3D printing technologies can be used in a huge number of areas, and their potential is being developed by companies, enthusiasts, and educational institutions around the world. 3D printing has many benefits, and the technology allows inventors and developers to easily prototype objects that were previously only represented by 2D images and diagrams.

Ch.-Y. Huang and J. Wang describe an approach in which they propose to develop in children from elementary schools the concepts and skills associated with 3D design (modeling) and 3D printing from a practical point of view (Huang, Wang, 2022). As a result of their work on the concept of teaching 3D modeling, the most significant goals of this course in the training, education and development of schoolchildren were formulated:

1) development of spatial imagination and logical thinking;
2) development of creative activity and independence of schoolchildren when learning 3D modeling;
3) developing ideas about teamwork, methods of planning activities, and communication;
4) formation of ideas about working in the information environment;
5) formation and consolidation of initial knowledge and ideas about objects of the surrounding world, their structure, and purpose.

Cheng et al., conclude that the participation of schoolchildren in 3D modeling contributes to the activation of cognition, increased interest, and increased motivation (Cheng et al., 2020). Based on a review of a significant number of academic papers, the authors conclude that 3D printing technology has revolutionized the way STEM (science, technology, engineering, and mathematics) education and research is conducted. This revolutionary technology, they conclude, is project-based learning and free inventive creativity that promotes:

- development of mathematical thinking for two and three-dimensional dimensions when assembling from a flat form into a volume;
- design of functional objects and simple mechanisms in engineering creativity;
- realization of creative possibilities in color schemes;
- development of critical thinking, including solving real problems, and facilitating scientific learning.

The implementation of such educational practices presented by L. Cheng et al. (Cheng et al., 2020). The research is carried out at the expense of special funding (grant).

B. Anđić et al develop the ideas, noting that 3D modeling contributes to (Anđić et al., 2022):

- formation and development of students' creative and technical abilities;
- organizing the educational process based on sociocultural, spiritual, and moral values;
- creating and providing the necessary conditions for personal development, health promotion, professional self-determination, and creative development;
- formation of a common culture.

The peculiarity of their methodological approach is that B. Anđić et al. make the case for the importance of preparing teachers themselves to incorporate 3D into science teaching (Anđić et al., 2022). According to their conclusions, teachers of physics, biology, and chemistry need additional special technical training to fully realize the didactic potential of 3D. For example, how to connect and use 3D printers.

H. Pearson and A. Dube note that education based on 3D modeling teaches children more than theoretical knowledge in physics, biology, or mathematics (Pearson, Dube, 2022). An emphasis on hands-on learning with real-life applications, devices, and prototypes helps develop research skills (critical thinking, creativity, curiosity, decision making, leadership, entrepreneurship, accepting failure, and the like). Regardless of their future career, these skill sets go a long way in preparing kids to innovate.

And yet, despite the powerful didactic potential of 3D modeling for the development of scientific research skills of schoolchildren, as B. Anđić et al., few teachers are using this new environment and technology directly in the classroom. Hence, only a select few students benefit from modeling and prototyping (Anđić et al., 2022).

Educational 3D modeling is becoming widespread in the practice of thematic summer camps.

One example of such a camp is Try Engineering Summer Camp (USA). This is a two-week summer camp with joint education for children in grades VIII-XI. Camp changes take place at leading colleges and universities in the United States. During this shift, children study engineering disciplines and learn about advanced technologies. It is at this camp that they learn about the four main fields of engineering: electrical, mechanical, civil, and aeronautical. Sometimes, the first project is a 3D printer, which needs to be designed and printed to be used in the creation of subsequent projects (IEEE TryEngineering..., 2023).

Despite the undoubted developmental potential of 3D technologies, we must note that not all schools in the world have received financial support and the opportunity to purchase new equipment for use in the educational process.

Thus, 3D technology is rapidly changing the field of education. An appropriate information and educational environment is proving to be a promising resource, especially for education in the fields of science, technology, engineering, arts, and mathematics. This is convincingly shown by the analysis of the literature.

So, although some countries around the world have already developed approaches to the implementation of 3D modeling and prototyping into the educational process as part of classroom and extracurricular activities, as well as in the field of additional education. This experience requires more detailed study, comprehension, and systematization in order to further adapt to the conditions of the Russian school and develop, on its basis, original proprietary methods that are most effective for developing students' digital competencies.

2.2. Goals and objectives of the study

The purpose of the study is to theoretically substantiate and develop approaches to the development of schoolchildren's research skills when studying natural science disciplines based on 3D modeling.

To achieve this goal, the following tasks were identified:

1) to specify the concept of research skills, to determine the features of their formation, and to identify the features of the study of natural science disciplines at the level of secondary general education;

2) determine the didactic potential of 3D modeling and prototyping technology for the development of schoolchildren's research skills;

3) develop a system of tasks and sample models to support all stages of students' research activities during the implementation of educational interdisciplinary projects;

4) experimentally test the effectiveness of developing students' research skills through the introduction of 3D modeling technology into the educational process for the study of natural science disciplines.

3. Materials and methods

3.1. Theoretical and empirical methods

To solve the problems, the following research methods were used:

Theoretical analysis and synthesis of the literature to clarify the essence of research activities, define the concept of "research skills" and indicators of their formation. The work uses the following classification of skills: operational, communication, organizational, and information. These skills, corresponding to V.I. Andreev's classification (Andreev, 1983), were selected from several others according to the following criteria: compliance with the direction of research activity; taking into account the age characteristics of schoolchildren. For example, no less worthy classifications proposed by A.V. Leontovich (Leontovich, 2018) and P.Yu. Romanov (Romanov, 2003) are aimed mainly at students.

Indicators of the development of schoolchildren's research skills: conducting observations and research during modeling; putting forward a hypothesis; planning research activities; and analysis of information sources.

Analysis of the didactic possibilities of using 3D modeling and prototyping to develop schoolchildren's research skills.

The experimental base for the study was the Vyatka Technical Lyceum. This is a third-level public educational institution in Kirov. Training is conducted according to programs for grades 10–11 with in-depth study of subjects in individual profiles.

Methods of empirical research: the study of innovative experience, observation, conversation, questioning, and pedagogical experiment with schoolchildren is used at the stage of introducing 3D modeling technology into the educational process in the study of natural science disciplines. To determine the level of development of research skills among schoolchildren, we used:

- pedagogical observations carried out in lessons;
- text questionnaires that allow identifying and assessing the level of development of students' research skills.

An experimental research project was conducted from October 2019 to March 2022 in the 10th grade "A" class at Vyatka Technical Lyceum in the city of Kirov.

A total of 104 students participated in the study: 54 schoolchildren of the 10th grade, and 50 schoolchildren of the specialized network class. Control and experimental groups were formed from them. Each has 52 people.

All 104 schoolchildren were divided into experimental and control groups as follows:

1. Participants were asked to complete a research project. Its principles and assessment criteria (diagnostic tasks for operational, organizational and practical skills) are described in detail in paragraph 4.3.1. 4 hours are allotted to complete the project (including time to explain the task).
2. The maximum a student could score was 34. Level "Beginner" (from 0 to 10 points), "Basic" (from 11 to 28 points), "High" (from 29 to 34 points).
3. The subjects are distributed into groups in such a way as to ensure that each group has the same average values for research skills and the same distribution of each characteristic.

The assessment was carried out 2 times: before the introduction of 3D modeling tools into the educational process in the Technology course module for studying natural science disciplines and after.

To fulfill the requirement of representativeness, the size of the population studied is equal to the number of all students in the 10th grade of the lyceum.

Based on the results of the evaluation of the 3D project, the level of the student's research skills was determined. The levels were determined as follows: initial (reproductive), basic (partially exploratory), high (research). Their interpretation and assessment procedure are presented in paragraph 4.3.1.

When compiling assignments and determining levels by the criteria for the development of schoolchildren's research skills, the principles of constructing assignments for the All-Russian Olympiads for schoolchildren in "Technology", Direction: "Engineering, technology, and technical creativity" were taken into account.

Statistical processing of the obtained experimental data was performed using Pearson's $\chi 2$ (chi-square) criterion.

3.2. The base of research

The main goal of the experiment was to test the effectiveness of developing students' research skills through the introduction of 3D modeling technology into the educational process for the study of natural science disciplines.

There are several external variables that may greatly influence the validity and reliability of the experiment. These include the material and technical resources available, the motivation and mood of the students, parental consent, the experience and qualifications of the teacher, as well as the duration and timing of the classes. It is important to consider these factors when designing and conducting experiments to ensure accurate and meaningful results.

To take into account the external variables of the lyceum during the experiment, the following measures were implemented to counteract their influence on the experiment:

- the consent from all schoolchildren, their parents, and legal representatives prior to participation. Let us note that all lyceum students are highly motivated to achieve success, both in their educational activities and in their future professions. As a result, they actively participated in the development of projects both in class and in preparation for olympiads, competitions, and festivals;
- lesson planning of the "Prototyping" module was completed. The duration of classes and scheduled times did not change;
- strict control of conditions and fixation was carried out for the entire 3D modeling process. For example, special recommendations were drawn up (presented in paragraph 4.3.1).

Modeling and prototyping classes were held according to the schedule – 2 lessons per week (40 minutes each).

- classes were held in the same lyceum classrooms. The modeling tools and evaluation criteria for interdisciplinary projects have not changed.

In modeling courses, students become familiar with the basics of 3D modeling, learn to work in 3D programs, create models, and print them on a 3D printer. These modern skills will be useful to them in the future when studying at technical universities, as well as when participating in various competitions, including professional skills competitions.

All equipped classrooms, a library, and a canteen are available for disabled children and children with disabilities. The lyceum has a medical office, and a relaxation and psychological relief room as part of the "Accessible Environment" project.

The study was conducted in three stages from 2014 to 2022.

The pedagogical experiment involved 54 10th grade lyceum students and 50 students from the network profile class "Vyatka Technical Lyceum" in the city of Kirov. The average age of students was 17 years. In the experimental group of 52 people: 52 % were young people, 48 % were girls. Due to the age of the subjects, special attention was paid to compliance with the ethical standards of the study.

The modeling and prototyping teacher informed both schoolchildren and their parents about the stages of work and possible competitions and festivals for participation. For example, he answered all questions that arose and solved organizational difficulties. All information security rules and sanitary and hygienic requirements were observed. For example, the sketch was made according to the standard of the Unified System of Design Documentation on a paper sheet.

3.3. Stages of research

In the first stage of the study (2014–2017), an analysis of scientific, pedagogical, and educational literature on the research topic was carried out. The methodological and theoretical foundations of the research are determined, and existing approaches to organizing interdisciplinary projects in educational institutions are studied.

The role and prospects for using 3D modeling for the development of research skills are identified, the relevance of the research is substantiated, and the goal and objectives are formulated. Separate components of the developed system of tasks have been introduced into the learning process.

The historical background for the development of the research approach to teaching, approaches to the concept and classification of research skills, and their role in the process of studying natural sciences were considered.

Based on the results of this work, the authors clarify that students' research skills should be understood as their ability to consciously perform mental and practical actions that correspond to the logic of scientific research.

Based on the analysis of approaches to the classification of research skills, an approach was chosen according to which research skills are divided into the following classes: operational, organizational, information, and communication.

The completed theoretical analysis of the literature allows us to objectively conclude that it is through research skills that thinking develops most effectively. These skills contribute to the formation of a student's independent personality, ready to generate new ideas, make unconventional decisions, and capable of not only mastering the experience of older generations but also enriching and developing it with their achievements.

In the second stage (2017–2020), a confirmatory experiment was conducted, which made it possible to identify the relevance of developing a model of approaches to the use of 3D modeling for the development of research skills. Systematization, selection, and configuration of software and hardware were carried out.

A review of options for using 3D modeling and prototyping for educational purposes was carried out.

The authors also developed a system of tasks and sample models for the implementation of interdisciplinary projects, compiled a set of materials, and developed recommendations for teachers of physics, chemistry, and biology on the implementation of joint activities based on additive technologies.

Next, an experimental study was carried out, including:

1) acquaintance of 10th grade students with 3D modeling technology as part of the study of the subject "Technology";

2) implementation of interdisciplinary projects to develop students' research skills.

In the third stage (2020–2022), the results of the experiment were analyzed, systematized, and processed, conclusions were formulated and clarified, and the materials of the presented research were compiled.

4. Results

4.1. Theoretical foundations of using 3D modeling to develop schoolchildren's research skills in the process of studying natural science disciplines

Digital educational technologies have an undoubted didactic potential for the development of research skills because they make it possible to transform traditional learning into research-based learning, which is based on the productive activity of the students themselves.

In addition, the relevance of their use increases in the absence of laboratory instruments, in cases of risks arising as a result of certain scientific experiments, and in conditions of high cost of materials required for laboratory research.

But, despite this, we can note that, unfortunately, the means of informatization of education are not sufficiently used to develop research skills, and the theoretical aspects of this process are also not sufficiently covered in scientific research.

So, the study of natural science disciplines contributes to the development of a fundamentally new worldview of schoolchildren. In the course of manipulating objects (real, informational), students learn to propose original ways to solve problems, direct creative forces to implement innovative proposals, to satisfy cognitive interests and needs.

An analysis of domestic and foreign research also shows that one of the most important educational results obtained by schoolchildren in the process of natural science education is natural science literacy. It is an integrative learning result aimed at restoring the natural integrity of the cognitive process based on the interaction of the academic subjects: chemistry, biology, and physics at the level of general problems and concepts, their systems as the basis of the scientific picture of nature.

The content of natural science disciplines provides a foundation for fostering skills in creative activities such as educational and design research. Through educational research, students can enhance their general knowledge and develop a comprehensive scientific worldview with a humanistic and environmental focus. Understanding the impact of natural sciences on various aspects of society, including the environment, economy, technology, and ethics, is crucial for students to integrate into modern society and contribute to solving scientific challenges. By applying their knowledge in both typical and unconventional situations, students can cultivate a motivation for continuous self-improvement and lifelong learning.

The very content of the subject area "Natural Sciences" provides ample opportunities and prospects for organizing educational and research activities for high school students in the field of natural sciences.

The concept of natural science literacy, as well as the task of developing this type of functional literacy, are consistent with the requirements for educational results defined in the current federal standard for basic general education.

The comparison shows that the competencies that make up science literacy and the requirements of the standard are quite consistent with each other. But the current standard often uses different terms to define the relevant skills. Most importantly, these skills are "scattered" across groups of meta-subject and subject results, without forming a single block in the standard that shows the general goals and planned results of studying all natural science subjects.

One of the significant components of science literacy is research skills. Research skills are formed in the process of studying natural science disciplines.

The main way to develop research skills in class activities is to use a problem-based approach to learning. The systematic creation of problem situations stimulates the cognitive search activity of students.

The result is the independent solution of non-standard problems, comparative analysis, and generalizing conclusions to which the student comes. At the same time, the prospect of solving a problem on their own inspires students, mobilizes their volitional efforts, and makes the cognitive process attractive and personally significant.

Non-standard research situations activate students' activities and form such creative personality qualities as independence, systematic thinking, independence of judgment, flexibility, and criticality. Involving students in research situations has the greatest effect in classes where students with unstable attention and low interest in the subject predominate. Research activities bring variety to educational work, develop students' attention and thinking, and motivate them to provide mutual assistance; contribute to the development of students' ideological positions.

The formation and development of research skills can also occur in the process of students' project activities, since when carrying out projects it is necessary, one way or another, to use all types of research skills: operational, organizational, practical, and communicative.

One of the means of developing research skills can be the means of informatization of education, namely the use of the potential of 3D modeling and prototyping technology.

3D modeling is the process of creating a three-dimensional model of an object. The task of 3D modeling is to develop a visual three-dimensional image of the desired object. With the help of three-dimensional graphics, you can create an exact copy of a specific object and develop a new, previously non-existent object.

The process of creating a three-dimensional model includes the following stages: modeling, texturing, setting up lighting and observation points, and visualization (rendering).

The utilization of cutting-edge 3D modeling and prototyping technologies, along with the incorporation of modern materials in the production of equipment prototypes, has garnered significant attention in recent times. The interest in exploring these technologies and materials stems from the potential to generate 3D models using various graphic software programs, conduct thorough full-scale tests on them, and integrate them into educational settings.

By employing rapid prototyping technologies, intricate models can be created with ease, ensuring a safe manufacturing process. Parameters such as print quality, material composition, and surface finish are established when configuring tasks on advanced devices like 3D printers. The resulting prototype can then be scrutinized to assess its adherence to specified operational and technical requirements, as well as its structural integrity.

Thus, 3D modeling and prototyping is one of the important areas of digital education and has undoubted didactic potential in the development of engineering thinking, which is in demand in the modern economy.

Several countries around the world have already accumulated experience in introducing 3D modeling and prototyping into the educational process as part of class, extracurricular activities, and in the field of additional education.

The educational subject "Technology" is considered in the standard as motivating for the study of others and necessary for the formation of technological thinking. The content of basic general education in this subject includes previously unstudied areas, such as: agro- and biotechnologies: nanotechnologies; robotics and automatic control systems; technologies of electrical engineering, electronics and power engineering; construction; 3D modeling; and prototyping.

Consequently, the subject "Technology" ensures the use of a wide variety of interdisciplinary connections for their practical implementation into progressive ideas, products, and services that meet the needs of individuals, society and the state.

Analysis and generalization of this experience formed the basis for the development of a system of tasks and sample models for the use of 3D modeling and the development of research skills in the study of natural science disciplines.

4.2. A system of tasks and sample models for studying the "Prototyping" module of the "Technology" subject and implementing educational interdisciplinary projects

The subject "Technology" makes it possible to implement end-to-end lines in economic, environmental, legal, and entrepreneurial education, allows students to master the skills of converting materials, energy, and information, and ensures the success of professional socialization. As part of the Technology subject, students have the opportunity to design their product.

1. Taking into account the current situation with the lack of textbooks and teaching aids that include the study of modeling and prototyping at a level that allows schoolchildren to take part in competitions and olympiads, it seems appropriate to change the approach to introducing 3D modeling into the educational process. Possible thematic planning is presented in Table 1.

One of the means to improve the quality of science education is the use of interdisciplinary projects.

Such integrated learning promotes the development of a scientific style of thinking, makes it possible to widely use the natural science method of cognition, develops in students general concepts of geography, biology, physics, mathematics, chemistry, natural science, supra-subject knowledge, abilities, and skills (or meta-subject, through the inevitable development in these lessons key educational competencies).

Table 1. Thematic planning of the "Technology" course module

Name of section and topic	Number of hours
1. Introduction to Modeling	
Software interface. Working with objects	2
Boolean operations	2
Arrays: one-dimensional and multidimensional	2
Basics of polygonal modeling	2
Modeling to exact dimensions	2
Splines	2
Extrusion modifier	2
Rotation modifier	2
Simple lofting	2
Composite lofting	2
Modeling a composite object	2
2. 3D printing	
Printing software	1
Post-processing	1
The history of additive technologies	2
FDM printing technology	2
3D printer device	2
Consumables	2
Preparing the model for printing	2

Schoolchildren master educational material by solving one or another problem or problem situation. Of great importance is the use of tasks that involve the study of one issue or knowledge of one object using two and/or more educational disciplines.

Developing a task system involves a series of stages that must be carefully considered in order to create an effective and engaging educational experience.

First and foremost, it is essential to define the goals and objectives of the system, taking into account both formal and substantive aspects. For the proposed system of assignments for grades 10-11, the primary goal is to enhance research skills among students.

Next, the selection of the foundations of integration and the system-forming core is crucial. It is recommended to base the system-forming core on the main structural elements of the scientific knowledge system, including facts, concepts, phenomena, properties, quantities, theories, and laws.

Creating a course structure that aligns with societal requirements, the Basic Plan, and the age and level of students is the next step. The integrative didactic model consists of interconnected blocks that shape the educational process, encompassing principles, methods, forms, means, content, control, types of control, form of control, and means of control.

The integrated educational model incorporates elements from various pedagogical technologies, such as game technology, project technology, and traditional teaching methods. This combination enriches the learning process, making it more comprehensive, engaging, and effective, while ensuring the coherence and continuity of educational content across subjects.

Assessing the degree of integration of the course content, including intra-subject, inter-subject, and extra-subject integration at varying levels, is essential. This assessment is conducted according to the analysis scheme of the integrated program.

Finally, organizing the learning process involves utilizing a range of complex and individualized forms of training. The procedural aspect of the integrated course is supported by a diverse array of integrated lessons, learning tasks, teaching methods, and assessment strategies to evaluate students' educational progress effectively. This technology uses independent, problem-based, practical, research, creative work, as well as lectures that summarize lessons.

Let us give examples of a system of assignments and interdisciplinary projects.

Task No. 1. Selection, assessment of the capabilities of a specific software product and available equipment to create a given object;

Task No. 2. Training a group of students in the basic techniques of 3D modeling in a selected software product in accordance with hygienic, design-ergonomic, technical and technological, didactic requirements, requirements for documentation, requirements of a system-activity approach in teaching the development and operation of the model and a description of the methodology for its application in the educational process;

Task No. 3. Create a sketch, a 3D model of a robot, and prepare the model for printing on a 3D printer or printing. Prepare for the presentation of the project by students.

All finished projects were sent in advance by e-mail for evaluation, and in the absence of equipment, the project was sent separately to the lyceum for printing the created product. For each project, the teacher prepared sample models in advance.

Example of interdisciplinary project 1 (to develop research skills using 3D printing). The task is to make a boat that should float and not sink.

Note that tasks formulated using the capabilities of 3D modeling and prototyping allow the formation of meta-subject skills. For example, in the above example of designing a model of a boat, you can start studying or repeating a topic from physics "Archimedes' Law". To complicate the task, you can add the ability to transport cargo of a certain weight.

This assignment demonstrates a problem-based approach to learning. As a result of the announcement of this assignment, students have several research questions that they will solve during the lesson. In the process of pair work, they will formulate problems and put forward hypotheses about what the boat should be like so that it does not sink. After creating a model of an object in a computer-aided design system and then printing it out, the next step is experimentation.

As a result of experiments on the resulting object, conclusions will be drawn about the correctness of the hypotheses and the possible elimination of the shortcomings of the model. Which will require students to critically think and form new hypotheses. Repeated experiments with an object created independently will lead not only to an understanding of engineering concepts but also to the formation of research skills.

Example of an interdisciplinary project 2: Creating a working whistle.

Skills: determine what simple forms need to be used to create a 3D model in the program; select the necessary shapes and create a 3D model; compare the created model with the sample; eliminate defects and make necessary corrections; add new parts to your 3D model; evaluate the result and your model.

Another example of an interdisciplinary project could be the task of creating a catapult. Unlike the previous exercise, when creating a catapult, the entire object can no longer be printed, and in addition to thinking through the shape of the object, students must also take into account how to attach separately printed parts.

We especially note that the object requires a detailed study of the dependence of the projectile's flight range on the structure of the catapult. Students in this task usually put forward hypotheses related to changes in the length of the lever, the angle of departure, the initial speed, body weight, or the methods of attaching the axle. After printing the catapults, it is advisable to hold competitions for flight range or the ability to remove an obstacle (destroying a wall). In the future, you can invite students to design some other throwing weapon. Examples of catapults created by students during testing of this technique are presented in Figure 1.

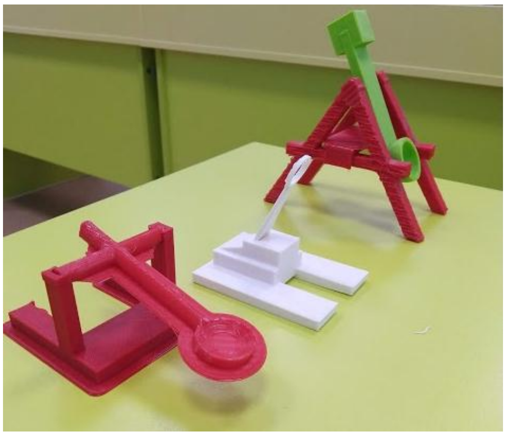

Fig. 1. Printed catapults

4.3. Experimental assessment

4.3.1. The ascertaining stage of the experiment

As noted above, the assessment of research skills included an assessment of the results of schoolchildren's research activities. Completed educational simulation projects.

All tasks and assessment criteria were developed by the authors based on examples of tasks from past All-Russian and international Olympiads directly related to technical 3D modeling and printing.

An example of a general task formulation: based on the proposed sample, develop a technical drawing of the product, create a model of the product, prepare a project for printing, and make drawings of the product.

For example, the product "Swing-balancer". Requirements for the overall dimensions of the product were determined. Other sizes and requirements:

- the swing model is functional (movable), and consists of at least 3 types of parts (base, beam, chairs – must be reflected on the sample model), other detailing is at the discretion of the student;
- the model is assembled from parts into a whole product using any connections designed by the student; the fastening of the chairs to the beam is strong (the chairs are separate parts, not a single unit with the beam); the connection between the beam and the base is movable;
- cross-sectional size of the beam;
- chairs must have free-form backs, the size of the back is not smaller than the seat;
- the base should be decorated on the sides with a simple decorative overlay (for example, as on the sample model);
- the design of the chairs and the design of the base should be developed independently, taking into account the requirements described above, not necessarily using tubes;
- when modeling, you should set the gaps between the parts for a free fit, taking into account the given dimensions.

Unspecified dimensions and design elements were performed at the student's discretion.

It was permissible to use structural elements that reduce the weight of the product while maintaining the basic shape and functionality.

Methodological recommendations for schoolchildren:

1. Printed models can be quite fragile, so for the product parts you should consider a shape that ensures sufficient structural strength;
2. When completing an assignment, you should be advised to constantly check the table of assessment criteria.
3. When developing a model, you should consider the printing error (when designing holes, grooves, and protrusions); you should not make the elements too small.
4. Send one part for printing while you work on the next one, save time.
5. Consider how to place the model in the slicer program, taking into account its shape and the loads on the resulting parts, as well as the effectiveness of supports and adhesion layers, so that the print is completed within the allotted time.
6. The optimal time for developing a model is half of the total time allotted for practice, do not forget about the final drawings of the product. Take your time, but remember that good timing is encouraged.

The evaluation criteria using the "Whistle" sample model as an example are presented in Table 2.

Table 2. Criteria, indicators and tasks for assessing the level of development of schoolchildren's research skills

Criterion	Indicator	Diagnostic tasks
Operational skills	Proposing a hypothesis	Read the text and answer the questions. There were 3 questions asked. For example, "What is the necessary component of a whistle?" The maximum possible number of points for completing a task at this stage is 3.
Organizational skills	Research planning	You need to make observations of the change in sound in different whistle designs. Present

Criterion	Indicator	Diagnostic tasks
		the result (in writing) in the form of a research plan. The maximum possible number of points for completing a task at this stage is 3.
Practical skills	Conducting observations and experimental studies	You have been assigned to make a whistle. Suggest a design. Do a sketch, describe the working principle and create the product. The maximum possible number of points for completing the task at this stage is 23. Detailed breakdown by points: Knowledge of the basic interface, work in a graphic editor and/or system (degree of independence in making a model) – 1 point. Accuracy of object modeling (compliance with the developed sketch) – 1 point. Complexity of implementation (configuration, technical solutions, number and complexity of tools used, presence of additional elements) – 15 points. Assessment of the quality of manufacturing of all parts – 6 points.
Information skills	Analysis of literary sources	Read the text and answer the questions. There were 5 questions offered. The maximum possible number of points for completing a task at this stage is 5.

The maximum a student could score was 34 points.

Thus, the level was diagnosed as "Initial" (from 0 to 10 points), "Basic" (from 11 to 28 points), "High" (from 29 to 34 points).

These research skills are universal, enabling schoolchildren to design their research activities in the context of the chosen problem. They are correlated with the stages of project activity. Next, the levels were determined directly. They are presented in Table 3.

Table 3. Levels of development of research skills of high school students

Required skills	Basic (reproductive)	Basic (partial search)	High (research)
Ability to define a goal, objectives, research problem	Able to set a goal, objectives, research problem under the guidance of a teacher	Able to partially independently set a goal, objectives, research problem	Able to independently formulate a goal, objectives, research problem
Ability to determine the structure of one's research (introduction, chapters, conclusion, appendix, list of sources and literature)	Able to determine the structure and draw up a simple plan of his research under the guidance of a teacher	Able to partially independently determine the structure and draw up a complex plan of his research	Able to independently determine the structure and complex plan of his research
Ability to select and present the necessary information following the structure of the study	Able to select and interpret the necessary information under the guidance of a teacher following the structure of the study	Able to partially independently select and present the necessary information following the structure of the study	Able to independently select and present the necessary information following the structure of the study
Ability to formulate research results, justify them and	Able to formulate research results, justify them and	Able to partially independently formulate research	Able to independently formulate research results, justify them

Required skills	Basic (reproductive)	Basic (partial search)	High (research)
present them	present them under the guidance of a teacher	results, justify them and present them	and present them

The results of the ascertaining stage of the study indicate that it is necessary to continue developing research skills in schoolchildren. This problem was solved at the formative stage of the study.

4.3.2. Forming stage of the experiment

In the experimental group, training was carried out using a system of tasks and sample models for the implementation of educational interdisciplinary projects. Students learned 3D modeling and prototyping through exercises with objects used in science disciplines.

The tasks included not only the reproduction of models but also conducting experiments and observations on them.

The training program corresponded to the lesson planning presented above.

When developing research skills, a certain set of conditions was created to help schoolchildren consciously engage in research activities. As part of the experimental search work, the following pedagogical conditions were created:

- conducting research lessons;
- the use of exercises and tasks of a research type (express research, conducting experiments, experiments with independently created models);
- involving schoolchildren in the implementation of research projects.

In the control group, students created 3D models while learning various modeling techniques.

While learning 3D modeling, students could take part in festivals and olympiads in the relevant field.

For example, the regional stages of the All-Russian Olympiad for schoolchildren in 3D technologies and the festival of scientific and technical creativity “3D-Chips” were held at the Children's Technology Park Quantorium in Kirov. The competition participants were 122 students in grades 1-11 from educational institutions in Kirov, Kirovo-Chepetsk, Omutninsk, Sovetsk, Belaya Kholunitsa, Lebyazhye and Murygino.

The Olympiad was held in interdisciplinary areas, using knowledge of 3D technologies: 3D drawing 3D-Art / 3D modeling and prototyping.

When completing the competition task, schoolchildren created and implemented their projects, showing imagination and engineering abilities, and presented their projects to the jury.

For example, schoolchildren from the experimental group created an arrow-shaped aircraft for animal space flights. It contained a building containing instruments, a laboratory, rest cabins, a control cabin, a capsule for spacewalks, and even a training area. On board the spaceship there were inhabitants - a cat and a turtle. To realize everything according to a creative idea, it is necessary to carefully and efficiently carry out all the elements and make connections.

As experts noted: the project is distinguished by a well-structured composition, a high level of sketches and drawings at the stage of developing the idea, and a high-quality connection of parts with each other.

4.3. 3. Control stage of the experiment

At the fixing stage of the experiment, the results of research activities – models for interdisciplinary projects – were also assessed. Let's formulate a hypothesis:

H0: the level of students' research skills through the introduction of 3D modeling technology into the educational process for studying natural science disciplines has remained unchanged.

H1: The level of research skills of schoolchildren has increased.

The assessment data before and after the experiment are presented in Table 4.

Table 4. Results of the development of schoolchildren's research skills

Level of formation	The number of tested (people)			
	Experimental group (52 pupils)		Control group (52 pupils)	
	Before	After	Before	After
Primary (reproductive)	26 (50.00 %)	18 (34.62 %)	26 (50.00 %)	22 (42.31 %)
Basic (partial search)	20 (38.46 %)	21 (40.38 %)	19 (36.54 %)	22 (42.31 %)
High (research)	6 (11.54 %)	13 (25.00 %)	7 (13.46 %)	8 (15.38 %)

We calculate the value of the criterion statistics before ($\chi 2obs.1$) and after ($\chi 2obs.2$) the experiment (significance level $\alpha = 0,05$. Comparing the empirical results and the table value ($\chi 2crit=5.99$), we obtain $\chi 2obs.1 < \chi 2crit$ ($0.103 < 5.99$), and $\chi 2obs.\ 2 > \chi 2crit$ ($6.184 > 5.99$). Therefore, H0 is rejected and hypothesis H1 is accepted. In other words, the effectiveness of developing students' research skills through the introduction of 3D modeling technology into the educational process for the study of natural science disciplines was experimentally tested.

Let us carry out a quantitative analysis of the experimental results. After the introduction of 3D modeling technology into the educational process for studying natural science disciplines, 25 % of students in the experimental group had a level of research skills defined as "High (research)" that turned out to be significant: (13 participants out of 52). While initially, this percentage was 11.54 % (6 students out of 52). The number of schoolchildren with the "Primary (reproductive)" level decreased from 50 % to 34.62 %.

The dynamics at the "Basic (partially search)" level is the least significant – 1.92%. This is due, in our opinion, to the fact that the majority (in percentage terms) of respondents moved to a high level.

In the control group, changes in the "High (research)" level are not so significant (from 13.46 % to 15.38 %).

After the completion of the experiment, 42.31% of schoolchildren in the control group had a "Basic" level of research skills (22 respondents out of 52). Initially, this percentage was 36.54 % (19 out of 52 respondents). The indicator for the level of formation "Primary" changed from 50 % to 42.31 %. So, the dynamics by levels in the control group are also present, but they are less significant.

5. Limitations

Let us now turn our focus to the potential limitations of the study:

The sample of students was not probabilistic, since the experimental and control groups were formed in such a way that the presence of the same research skills in each group was guaranteed. All participants are schoolchildren who have a high level of motivation to achieve success in educational and research activities.

When developing a system of tasks and sample models, many years of experience in 3D modeling and prototyping at the Vyatka Technical Lyceum were taken into account. It should be noted that the Vyatka Technical Lyceum has the material base, which was supplied within the framework of the national project "Education", and qualified teachers.

Work on the "Technology" course was carried out by the same teacher (E.A. Mamaeva) throughout the entire period of the study. Significantly better results in the experimental group are due to the potential of the developed lesson plan (system of tasks and sample models) aimed at developing the research skills of schoolchildren through the introduction of additive technologies into the educational process.

Participants in the experiment noted that the main difficulty when working with a 3D pen is creating a high-quality surface of products. It is especially difficult to obtain models that are hollow inside without the use of auxiliary elements. In addition, the works had to maintain a balance of composition, which also turned out to be a difficult task for the participants; some works were overloaded with elements.

Another point that received particular attention was the creation of moving elements. The students had to think very carefully about how to attach the parts.

While working on the project, schoolchildren not only acquired new skills but also learned to work harmoniously in a team.

Participants in the experiment noted the following possibilities for using 3D modeling in the educational process to prepare for life in the society of Industry 4.0:

– gaining experience in 3D modeling and printing;

– support for learning (interdisciplinary) under the challenges of the digital society and 21st century skills;

– creation of educational models that reflect real practical applied problems of an interdisciplinary nature;

– creation of assistive technologies (for teaching children with disabilities);

– support for information and educational activities in terms of preparation for in-demand professions in society.

6. Discussion

Significant positive changes in the level of development of research skills of students in the experimental group make it possible to recognize the hypothesis as confirmed and the research problems as solved.

This can be interpreted as the pedagogical effect of introducing a model of approaches to using 3D modeling to develop research skills in science learning.

The presented study refines the ideas of E. A. Mikhlyakova, and T. N. Suvorova regarding the implementation of 3D modeling for teaching schoolchildren (Suvorova, Mikhlyakova, 2020). In particular for:

– demonstration of a three-dimensional object;

– modeling an object based on a starting model specially prepared by the teacher,

– constructing a new object from an interactive collection of models;

– solving experimental problems using interacting objects;

– research into patterns during the influence of one object on another or the environment on an object;

– knowledge testing.

The findings are scientifically and methodologically complementary to the work of O.N. Vasilyeva, N.V. Konovalova (Vasilieva, Konovalova, 2018), and T.V. Masharova et al. since they rely on specific lesson planning and corresponding systems of assignments, and principles for constructing interdisciplinary projects (Masharova et al., 2020).

The authors tried to take into account and adapt the results of Ch.-Y. Huang, J. Wang about the experience of developing children's ideas and skills related to 3D design (modeling) and 3D printing (Huang, Wang, 2022).

When scientifically substantiating the didactic potential of 3D modeling to enhance cognition, increase interest and increase motivation, project-based learning, and free inventive creativity, the authors relied on the materials of L. Cheng et al. (Cheng et al., 2020).

Thus, the conclusions obtained during the discussion allow mentors to create additional conditions when preparing school graduates to achieve those global educational and scientific prospects that K. Schwab outlined in his description of the advanced technologies of Industry 4.0 (Schwab, 2016).

7. Conclusion

The presented study concretizes the concept of research skills by identifying its essence and content in the research of domestic scientists. It is noted that the factors for the development of research skills are the requirements of the current federal standard for the educational results of natural science disciplines (possession of the skills of conducting observations of individual objects, processes, and phenomena, their changes as a result of natural and anthropogenic influences, possession of the skills of analysis and interpretation of various information) and meta-subject results of mastering the main educational program (creation, application, and transformation of signs and symbols, models and diagrams for solving problems; definition of concepts, creation of generalizations, establishment of analogies, classification, establishment of cause-and-effect relationships, construction of logical reasoning, inferences and concluding).

The authors identified the didactic potential of computer 3D modeling and prototyping for the development of schoolchildren's research skills:

- putting forward a hypothesis of a natural scientific nature and testing it experimentally;

- mastering the methodology of independent planning and conducting an experiment in compliance with safety regulations;
- generalization of scientific information;
- assessment and analysis of the obtained modeling results during experimental work, checking them for reliability.

Despite the obvious developmental potential of 3D technologies, it should be noted some difficulties that arise when introducing 3D modeling into the educational process:

– not all schools in the world have financial support and the opportunity to purchase new equipment for use in the educational process;

– the problem of training teachers to use additive technology. In particular, to solve this problem, a series of trainings are being conducted on teaching teachers how to set up printers and use specialized software, as well as their methodological preparation for conducting classes using 3D modeling technologies;

– organizing access for participants in the didactic process to equipment for working with it.

The Technology course has been improved to teach schoolchildren how to create 3D models. The curriculum and lesson planning of the “Prototyping” module are presented, which allows students to develop research skills during the implementation of applied educational tasks.

Within the realm of 3D modeling, students will develop fundamental skills in creating 3D models, rapid prototyping of equipment and its components, and hands-on experience with cutting-edge technology. A comprehensive system of tasks and model examples has been established to guide students through all phases of their research endeavors as they engage in educational interdisciplinary projects aligned with the prescribed model. The application of individual tasks is illustrated with examples demonstrating the achievement of the benefits specified by the model. The effectiveness of developing students' research skills through the introduction of 3D modeling technology into the educational process for the study of natural science disciplines was experimentally tested.

Practical provisions can form the basis for the development of didactic teaching aids: collections of assignments, and methodological instructions.

Further research may be aimed at disseminating the proposed approaches to the development of students’ research skills at other levels of education (primary school, higher education) and additional education (Quantoriums, Growth Points, technical creativity centers, etc.).

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