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Peculiarities of Engineering Thinking Formation Using 3D Technology

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Abstract

The problem of the research is due to the need to create a special engineering style of thinking within the digital educational space, which implies readiness for research, creativity, responsibility, and supported by modern high-tech tools in order to provide resources for solving the problems of Industry 4.0.

The purpose of the study is to theoretically substantiate and experimentally verify the effectiveness of using 3D technologies for the formation of engineering thinking as an important competence of a high-demand specialist in the digital society.

The research methodology is a theoretical and methodological analysis and generalization of fundamental scientific works in the field of digitalization of education, training of engineering and technical personnel, three-dimensional modeling, application of software for the development of thinking. The pedagogical experiment uses the example of assessing the formation of personality qualities and skills that form the basis of engineering thinking. The sign criterion G is used as a method of statistical processing and verification of the reliability of the obtained results.

Research results. The authors clarify the concept "engineering thinking" in the context of training specialists for Industry 4.0 and substantiate the potential of 3D technologies for the formation of engineering thinking. They formulate the principles and supporting directions of the mentor of students' research activities in 3D modeling. The authors present a system of work on an interdisciplinary project underlining skills significant for the formation of engineering thinking.

The authors come to the conclusion that the use of 3D-technologies in training creates additional conditions for the development of qualities and skills that ensure the integrity of engineering thinking formation as a universal competence of a high-demand professional of the future.

Keywords: engineer of the future, 3D-model, principles of support, project, didactic potential, professional self-determination.

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1. Introduction

1.1. Relevance of the problem

The research is urgent due to the following factors:

1. An important condition for ensuring the country's technological and economic independence in the context of digitalization and integration of production processes is the training of high-quality engineering personnel (Varshavskaya, Kotyrlo, 2019).

2. Training a creative, responsible specialist with research skills and experience in intellectual activity supported by modern high-tech tools is an urgent area of modernization of science and education (Isaev, Plotnikov, 2019). The purpose of digitalization of education in the context of the development of Industry 4.0 is to effectively and flexibly apply the latest technologies to the transition to a person-oriented, continuous and non-linear educational process (Ilomäki, Lakkala, 2018). The digital era requires not only new skills from graduates of schools and universities, but also a different approach to organizing the education process in terms of training engineering personnel. In these conditions, Russian and foreign researchers (Tocháček et al., 2016; Terzidou et al., 2018; Szymanski, 2018; Soboleva, 2019; Karakozov, Ryzhova, 2019) point out that the didactic process in the era of automation and globalization should solve problems of socio-economic development of the country in the context of the formation of Industry 4.0.

3. According to R.A. Perelet (Perelet, 2019), foundation of the digital economy is a synthesis of previously existing material production and digital technologies, supporting the widespread use of artificial intelligence models and the development of the Internet of things. According to R. E. Paterson (Paterson, 2017), "smart products" will be the norm in a world where intelligent computerized devices (robots), the systems consisting of them, get opportunities for interaction in the preparation and deployment of automated production processes.

The new industrial, or technological (digital) revolution, has special demands to the highly qualified specialists of the future. Other scientists, for example V. Concepción (Concepción et al., 2018), reasonably conclude that in the educational space a priority is the task of preparing an independent personality through the formation of high-order thinking, including engineering. Engineering thinking in the new conditions of Industry 4.0 is perceived and interpreted as "a specific form of active reflection of the morphological and functional relationships of the subject structures of practice, aimed to meet the technical needs for knowledge, methods, techniques in order to create technical means and organize technologies" (Usoltsev, Shamalo, 2015).

The digital transformation of the manufacturing sector is already underway (Ranger, Mantzavinou, 2018). However, while implementing technological innovations, there can be problems due to insufficient training in terms of the formation of engineering thinking, which is based on the ability to analyze the composition, structure and principle of operation of technical objects in new conditions (Rozhik, 2017). There is a practical need to change the principles of organizing a digital educational environment for the development of engineering thinking among professionals of the future. The indicated need implies the integration of new technical means into real projects, their promotion in science and industry (Soboleva i dr., 2020a).

In connection with these factors, studying the potential of 3D modeling tools and technologies in terms of training engineers of the future is relevant (Suvorova, Mikhlyakova, 2020). Support for engineering education is one of the strategic priorities of the development of Russia. Therefore, engineering classes, physics and robotics laboratories, 3D modeling and prototyping workshops are created and developed. A digital school teacher gets additional opportunities for developing engineering thinking skills by combining educational and extracurricular work, supporting students in the construction of 3D devices not only for an educational project, but also for professional self-determination, participation in competitions.

Thus, there is an objective need to study peculiarities of the formation within the digital educational space of a special engineering style of thinking, which implies a willingness to research, creativity, responsibility, and supported by modern high-tech tools in order to provide resources for solving the problems of Industry 4.0.

1.2. Aims and objectives of the study

The aim of the study is due to the need to attract students to project activities in 3D-modeling for the formation of engineering thinking as a universal skill of a high-demand professional of the future.

Research Objectives:

– to clarify the concept "engineering thinking" in the context of training specialists for Industry 4.0;

– to substantiate the potential of 3D-technologies for the formation of engineering thinking as a necessary skill of high-demand professionals of the future;

– to formulate principles, directions of support of the mentor of students' research activities in 3D-modeling.

– to introduce a system of work on an interdisciplinary project, highlighting significant skills for the formation of engineering thinking.

– to experimentally confirm that the inclusion of students in practice-oriented activities for the design of three-dimensional models, the development of "smart" solutions for Industry 4.0 can improve the quality of training of a future specialist in terms of the formation of skills that form the basis of engineering thinking.

2. Relevance

2.1. Literature review

2.1.1. Analysis of Russian scientific and pedagogical literature

The formation of Industry 4.0 defines the introduction of new business models, according to which the "factories of the future" will work – enterprises capable of providing a fundamentally new level of productivity and competitiveness. Such a powerful push will be possible thanks to digital technologies that can process huge amounts of data and comprehensively manage production processes, from design and manufacturing to logistics and technical support for the product (Karakozov, Ryzhova, 2019). Requirements for technical professions related to industrial production are changing now, they are rethinking the tasks of specialists who have to work at smart plants or conduct scientific research (Varshavskaya, Kotyrlo, 2019). Therefore, the Russian school has a crucial task – to give future engineers, technologists, designers sufficiently deep knowledge and practical skills in the field of latest technologies so that they enter the digital world fully equipped (Isaev, Plotnikov, 2019).

Russian scientists E.V. Soboleva, N.I. Isupova in their studies (Soboleva i dr., 2020) treat the "engineer of the future" as a specialist who has a high culture, well aware of modern engineering and technology, economics and organization of production, knows how to use engineering methods for solving problems of Industry 4.0.

Studies of A.P. Usoltsev, T.N. Shamalo (Usoltsev, Shamalo, 2015) demonstrate that innovation activity has a complex structure: it is an integral result of many branched processes and should be considered in the unity of all their aspects. The core of this activity is specific engineering thinking, supporting all stages of the development and implementation of discoveries, ensuring their quality and productive practical application (Kudryavtsev, Yakimanskaya, 1964). Such thinking is formed over a rather long period in a favorable environment stimulating thought processes. It allows to assert that preparing young people for innovative activity and developing their corresponding thinking requires the use of innovative pedagogical technologies, techniques and tools (Suvorova, Mikhlyakova, 2020).

Engineering thinking is generally understood as thinking that supports the qualitative result of technical activity (Rozhik, 2017); a specific form of active reflection of the morphological and functional relationships of the subject structures of practice, aimed to meet the technical needs for knowledge, methods, techniques, in order to create technical means and organize technologies (Soboleva i dr., 2020a); the ability to make decisions that go beyond existing algorithms and technologies (Suvorova, Mikhlyakova, 2020); the skill to question the effectiveness of traditional methods, accept contradictions and rethink them creatively, show creativity and a culture of research (Isaev, Plotnikov, 2019).

In various approaches to studying the formation of a student's engineering thinking, which consider its development using special conditions (Isaev, Plotnikov, 2019) or modern teaching technologies (Soboleva i dr., 2020a), there is no strategy for organizing special activities (Ignatova, Filimontseva, 2019). The main task of modern education of the engineer of the future for Russia is not just the transfer of experience and knowledge, but the preparation of a competent specialist capable of self-development and self-realization, able to solve non-standard tasks, predict the outcome of future activities and focus on universal values (Martyakova, Gorchakova, 2019).

Summarizing all the approaches, we conclude that the concept of "engineering thinking" is related to the thought process leading to the solution of interdisciplinary engineering problems, creative ideas, innovations, and design projects.

According to I. Damyanov, N. Tsankov (Damyanov, Tsankov, 2018), the modeling activity allows students to get important skills to strengthen theoretical knowledge and awareness of their future professional career. However, mastering these tools requires significant thought efforts, imagination, engineering thinking, and the ability to self-creation. The mentor is required to organize targeted pedagogical support, involving the planning of innovative educational activities.

I.D. Stolbova, E.P. Aleksandrova, L.V. Kochurova, K.G. Nosov examine the profile aspects of graphic education (Stolbova i dr., 2019). The authors believe that in order to bridge the gap between the level of graduates' training and the real requirements of society and industry, it is necessary to introduce innovative educational technologies aimed to build the ability to work in a team, competencies in the field of digital technologies, willingness to carry out design based on spatial modeling. An important result of the work for the study is the justification of the need for the practice of implementing projects in 3D format for the development of engineering thinking. According to M.L. Soboleva, M.A. Fedotenko (Soboleva, Fedotenko, 2019), the main innovative technologies in education are the following: mobile platforms and services; training programs based on artificial intelligence and big data analysis; digital resources to influence feedback intensity; innovative forms of activating cognitive activity of students.

M. Chugunov, I.N. Polunina represent an interdisciplinary approach that integrates 3D modeling methods and tools in the educational process (Chugunov, Polunina, 2018). The problem is solved in two interconnected environments: full-scale and virtual. Work in 3D spaces is necessary for designing cyberphysical devices, implementing innovations in science and technology. They describe a scientific design approach based on the use of an integrated modeling environment. The design process is implemented as the creation of different types of models: full-scale and virtual. The authors substantiate that such an approach to design is very effective for strengthening intersubject communications, forming the foundations of creative research.

O.A. Mudrakova, S.A. Latushkina apply the didactic capabilities of 3D modeling in practice in order to develop spatial thinking (Mudrakova, Latushkina, 2020). Scientists analyze the features of classes, review the experience of using 3D-modeling in training.

An analysis of the requirements of Russian employers allows to reasonably conclude that a specialist with experience in three-dimensional modeling, capable of making discoveries and putting them into practice, can find a job as a designer, artist, visualizer, designer in the game and film industry (Varshavskaya, Kotyrlo, 2019). For example, when designing structures of mechanisms and buildings, a high-demand professional needs experience in the development of three-dimensional models according to drawings and technical specifications in computer modeling environments. When modeling the game world, a highly qualified specialist will need the speed of creating the model, applying the correct topology to make the 3D model and the original concept similar.

Thus, an analysis of Russian literature suggests that 3D modeling technologies really contribute to the formation of an educational space that supports the development of engineering thinking in the course of creative work on the construction of three-dimensional objects. As a result, domestic researchers recognize the need to improve the training model, taking into account the capabilities of 3D technologies to meet the challenges of the future, ensure competitiveness, support professional self-realization of a student, and develop demanded engineering thinking.

2.1.2. Analysis of foreign researches

D. Tocháček, J. Lapeš, V. Fuglík (Tocháček et al., 2016) note that the need for innovation in science and technology determines the need for engineering personnel capable of integrating knowledge from various industries. The educational environment has all the possibilities in order to fully respond to the challenges of the future. One option is training using 3D technology (Terzidou et al., 2018). Foreign researchers M. Rodríguez-Martín, P. Rodríguez-Gonzálvez, A. Sánchez-Patrocinio, J.R. Sánchez (Rodríguez-Martín et al., 2019) point out that modeling activities are a useful tool for creating universal competencies for the professions of the future, including engineering thinking.

A.I. Benzer, B. Yildiz prove that computer 3D modeling, as one of the innovative digital technologies, is able to provide great opportunities for the formation of demanded skills of students (Benzer, Yildiz, 2019). The authors study the influence of technology on the imagination, preparation for professional self-realization.

T.-Ch. Huang, Ch.-Y. Lin consider various aspects from 3D modeling to 3D printing (Huang, Lin, 2017). They demonstrate that work in a three-dimensional environment develops the skills of observation, design and information processing. However, individual differences and psycho-physiological characteristics can affect learning outcomes, understanding the principles of three-dimensional modeling. In the framework of 3D-modeling, students must learn to look at things from different angles, be able to build abstract cognitive spaces. T.-Ch. Huang, M.-Y. Chen, Ch.-Y. Lin note that as 3D technologies evolve, 3D printers are also being introduced into education as a means of cognition and learning (Huang et al., 2019). In addition, students get the opportunity to observe and physically respond to the model, improving the quality of design and understanding. A. Sánchez, C. Gonzalez-Gaya, P. Zulueta, Z. Sampaio discuss the use of prototypes to solve the problems of three-dimensional modeling and 3D printing as support for the development of mathematical understanding, creativity and technological literacy (Sánchez et al., 2019). T. Molano points out that one of the manifestations of the prevailing technological megatrends is 3D printing, along with robotics and new types of energy (Molano, 2020). A. Szymanski identifies the possibilities of 3D printing for the formation of an innovative type of thinking (3D thinking), as well as the advantages of using 3D printing resources in the educational process (Szymanski, 2018). Moreover, according to L. Wei, K. Lu, X. Zhang, another factor determining the relevance of the study of 3D technology and the practice of 3D modeling is the increasing competition in the labor market and in the global economic space (Wei et al., 2019).

K. Hutchison, L. Paatsch, A. Cloonan justify that the technology of creating three-dimensional images blur the boundaries of the real and virtual world. However, their practical application is largely limited to industrial prototyping, inclusion of computer-aided design/automated production for the manufacture of virtual models (Hutchison et al., 2020). The authors emphasize that mastering the methods of three-dimensional modeling becomes an important universal competency, and innovations supported by the use of 3D technologies can lead to breakthroughs in science and industry. In particular, modern 3D image transfer technologies support the development of the film and video industries. For example, glasses with multi-colored or polarizing filters create the illusion of volume. Soon real three-dimensional displays will be widespread both in science (for visualizing various kinds of 3D objects) and in the entertainment industry (Lin et al., 2020). The design of 3D displays embodies the principle of generating 3D images using a rapidly rotating flat screen (due to the inertia of human vision, a two-dimensional picture unfolds in three-dimensional); principle of creating a display according to the 2D principle (volume is built from discrete elements of variable brightness).

As B. Tepavčević notes, technologies that support 3D modeling must be implemented in all spheres of life (Tepavčević, 2017). 3D graphics technologies are a potential future development of the economy. For example, 3D printing can minimize the need for construction and technical documentation and lead directly to the printing of full-size experimental models preceding the construction of building structures (Novak, Wisdom, 2018). In addition, 3D designers will be able to use special methods and technologies in their work: visualization, animation, 3D design and rendering, which will turn ideas into digital objects. When converting 3D images into physical objects, specialists will turn directly to 3D modeling and design technologies.

Thus, if there is a certain disagreement in revealing the phenomenon of "engineering thinking", most researchers recognize the didactic potential of 3D technologies for the development of engineering thinking. The implementation of this involves the creation of conditions for the identification, motivation, support and encouragement of students who are interested in 3D-technologies (3D-printing, 3D-modeling, 3D-scanning, three-dimensional artistic and technical creativity); improving the quality of education, activity among students; deepening understanding of the physical foundations of the functioning of constructed mechanisms; introduction of new educational technologies in the educational space; development of cooperation between the education system and potential employers; support for professional self-determination of personality; distribution and popularization of information on new digital technologies. Accordingly, a wide range of problems of a didactic and software-technical nature is revealed:

the need to master a new three-dimensional modeling environment, the difficulties of substantive and task filling, the design of an educational environment in accordance with the requirements of the labor market, challenges of the future, etc.

All of the above circumstances determine the significance of the study.

3. Materials and methods

3.1. Theoretical and empirical methods

The authors have analyzed foreign and Russian studies in order to clarify the concepts “engineer of the future”, “engineering thinking” in the conditions of the need to change the training of technical specialists for the formation of Industry 4.0. In particular, they generalized and systematized methodological foundations of applying the competency-based approach to the design of education (Khutorskoy, 2017), the transition of the education system to a personality-oriented learning model (Suvorova, Mikhlyakova, 2020).

The study of the didactic potential of 3D technology tools was carried out using the analysis of specific developments of subject teachers, interdisciplinary projects, generalization of innovative experience in teaching three-dimensional modeling. When organizing the study, the authors have taken into account provisions of the system-activity approach, considering the structure of activity and explaining the process of active assimilation of knowledge by the subject, the formation of methods of its activity through motivated and purposeful solution of the problem system.

When studying the methodological aspects of using 3D technologies in the educational space for the development of engineering thinking, creativity, pragmatism, manufacturability, etc. The authors used praximetric methods to describe, characterize, analyze the methods, means, forms of organization and control; systematization and generalization of ideas and patterns, principles of didactics in teaching.

In the course of work, there were used 3D technology tools (3D pens, 3D printers), 3D modeling environments (Blender, WINGS 3D, 3DReshaper, SketchUp, AutoDesk 123D, MESHMIXER 3.0), MS Office resources for presenting data, and educational constructor tools LEGO Mindstorms EV3, an Arduino-based controller programming environment.

A special group consists of empirical methods (observation, analysis of the results of innovative activities of students) to obtain relevant information on the formation of personality skills and qualities that form the basis of engineering thinking, and improving the quality of education in general.

To divide the participants into the experimental and control groups, the data of input testing was used to demonstrate in each group of the same skills and personality traits that form the basis of engineering thinking, their equal distribution. The sign criterion G was used as a method of statistical processing and verification of the reliability of the results obtained (Ostapenko, 2010).

3.2. The base of research

Assessment of the formation of engineering thinking, analysis of design developments of students using 3D technology was carried out in the course of a pedagogical experiment. 79 students of the direction 02.03.02 “Fundamental Informatics and Information Technologies”, Faculty of Informatics, Mathematics and Physics, Vyatka State University of Kirov, Russia, took part in the experiment. The experimental (40 people) and control (39 people) groups were formed. All students were 21 years old, in the third year of University. The experiment was conducted in the framework of the discipline "Computer Graphics".

To comply with the rules of probabilistic selection, the same teacher conducted training using 3D technology throughout the experiment. The training was conducted in the same classrooms, on the same hardware and software. To carry out control measures, the authors developed test tasks. All questions complied with the requirements of state federal educational standards for the specified area of training.

3.3. Stages of research

The study had three stages.

At the first stage (as part of a stating experiment), various approaches to determining the concepts “engineering thinking”, “engineer of the future”, Industry 4.0 were studied. The urgent problems of the formation of engineering thinking as an important competence of a high-demand professional in the digital society were revealed. Then we analyzed scientific and methodological work on the didactic potential of 3D technology tools for the development of skills and personality traits that form the basis of engineering thinking. At the same stage, we developed and carried out a test, containing of 10 tasks, each task was 2 points. With the help of its results, it was possible to collect experimental data on students of the direction 02.03.02 "Fundamental Informatics and Information Technologies". In the sample, the experimental group had 28 % of girls and 72 % of boys.

Then the participants were divided into groups (40 in the experimental, and 39 in the control group) to demonstrate in each group of the same skills and personality traits that form the basis of engineering thinking, their equal distribution.

At the second stage of the experiment, we formulated the principles and directions of support by the mentor for the research activities of students in 3D modeling. The proposed principles were implemented in the system of work on an interdisciplinary project, which included the identification of methodological, organizational, technical components and the specification of skills that are significant for the formation of engineering thinking.

The third stage of the study was the experimental teaching and improvement of the formulated principles for organizing practice-oriented activities for the design of three-dimensional models, the development of "smart" solutions for Industry 4.0.

4. Results and discussion

4.1. Clarifying the basic concepts

In this study, we will use the following interpretation of the term "Industry 4.0": this is a concept that implies the implementation of the fourth industrial revolution associated with the integration of industrial equipment (or the "industrial Internet of things") and the evolution of automation processes in industry with a qualitative transition of production into the form of a "digital enterprise". An important component of the concept is the emergence of processes for the automated collection, analysis, exchange and use of information in electronic digital form beyond the internal environment of the organization and the creation of a common information system for enterprises engaged in the production, sale and after-sales service of goods, sale of services.

The development of Industry 4.0 necessitates innovative technical developments that support smart solutions. By "smart decision" we mean technologies, objects that support users in finding new ways, improving actions, analytics of current activities, and ensure high-quality interaction with the environment.

A detailed analysis of the definitions "engineering thinking", "innovative thinking", "technical thinking" made it possible to determine the authors' position regarding the studied phenomenon. We will consider engineering thinking as a special kind of thinking that is formed and manifested when solving problems of a technical, design, technological nature, supporting a specialist in making a quick, accurate, original solution for a practice-oriented task and focused on satisfying both technical needs and social needs.

In the presented study, we consider engineering thinking as an integration of technical, economic, research, constructive thinking.

The basis of engineering thinking for a high-demand specialist of Industry 4.0 is RAM, spatial imagination, spatial thinking, and the role of a system-forming factor is performed by intellectual competence. Intellectual competence, as a combination of personal qualities and skills, includes elements of logical, methodological, cognitive activity correlated with real objects. It includes knowledge and skills of goal-setting, planning, analysis, reflection, self-esteem.

The engineer of the future in the conditions of the formation of Industry 4.0 should be ready for professional activity, have demanded professional competencies and engineering thinking. The demanded professional competencies, according to the requirements of the labor market and potential employers, include: a high level of general theoretical technical training; understanding and taking into account broad interdisciplinary relationships; mobility; criticality and rationality; susceptibility to new ideas; ability to see the elements of the system both separately and in unity; ability to independently make responsible decisions and constructive actions in ambiguous situations, predicting and adequately assessing their consequences.

Forming engineering thinking using 3D technology, special attention should be paid to activities, when the future specialist of Industry 4.0 will be able to:

- apply both specialized technical and interdisciplinary knowledge;

– show abilities to see each element of the system separately, relationship between them and the work of the whole system;

– formulate a problem, identify priority tasks and select effective technical means;

– show creativity, independence, non-standard thinking in conditions of restrictions of various nature;

– find rational solutions and compromises in resolving contradictions and conflicts;

– be able to optimally allocate available resources;

– demonstrate, substantiate and justify technically the design solution.

4.2. Design activities of students in the development of engineering solutions

Next, we describe the principles that determine the content of research activities of students in 3D-modeling, contributing to the formation of engineering thinking.

The principle of the need to analyze the requirements of science and industry for engineering and technical personnel of the future. In industries, it becomes possible to choose the materials that are best suited to solve the specific problems of Industry 4.0 (functional prototypes or mass production). A new scientific problem is likely to arise: there will be a need to standardize materials and improve equipment management, especially in industries with high quality requirements, such as the aerospace industry and the manufacture of medical devices. In these conditions, application areas come to the fore rather than technology. When preparing an engineer for the future, we should implement projects which involve the use of 3D technology to profit in specific areas. For example, the improvement of a technical product due to changes in the proportions of the composition, modification of physical and mechanical properties. In this case, we are talking about the implementation of the possibility of constructing the electronic structure of the product according to the 3D model.

The principle of competition, involving the inclusion of students in competitive activities in 3D-modeling, robotics. The implementation of the principle offers participation in seminars, competitions, research laboratories. These organizational forms of training engineers of the future are focused on training specialists who can think outside the box in the face of the uncertainty of the future and work in a team. For example, the international festival "Cyberon", the 3D-modeling contest among schoolchildren and students "Co3Datel", the 3D-printing contest "VZDumay", the "City of 3D-creativity" in 3D-designing and 3D-printing for children and youth.

The principle of taking into account and activation of intersubject communications, involving the implementation of the interdisciplinary didactic potential of three-dimensional modeling activities to form professional skills and the foundations of engineering thinking. For example, in order to restore a historical monument, a specialist of the future must be able to develop a 3D model, design it taking into account the historical context, geographical location, sociocultural significance. Also, an engineer must know biology: to take into account how the human brain perceives depth by merging two images with different perspectives coming from each eye. If innovative materials are used during the reconstruction of the product, then it is necessary to simulate their interaction and environmental impact.

Examples of using 3D scanning and 3D printing are the restoration of the Assumption Cathedral of the Tula Kremlin, the ancient South Gate of the Florentine Baptistery.

The problematic nature of learning. The organization of the corresponding cognitive activity provides a high level of independence in reasoning, in finding solutions in conditions of limitations. For example, you are an employee of a 3D copy center. On October 25, you were sent several orders for the manufacture of products intended for further printing and sale of the finished product for the New Year among the employees of a large holding. The team of your center needs to develop terms of reference for the requirements of the Customer, determine and complete all stages of the project activity in accordance with the available resources, terms.

The principle of training through solving a system of practice-oriented tasks, the key idea is that the concept of "task" can be interpreted quite widely. In this case, the activity of 3D-modeling is presented as a process of resolving contradictions between the proposed course of study, cognitive and practical tasks and the level of formation of engineering thinking and acquired universal skills. The essence of applying the proposed approach to support the development of engineering thinking is that getting new knowledge in solving a technical problem is directed by the teacher through a system of special tasks.

1.1. It is necessary to develop a model of a souvenir mug and print it for sale. Height is no more than 100 mm. Diameter of the upper circle is not less than 100mm. Base diameter is not more than 70 mm. The wall thickness of the cup should be exactly 3 mm. Be sure to apply the image associated with the celebration of the New Year.

1.2. Hedgehog pencil stand with the base in the form of an ellipse. Larger axis of the ellipse is 55 mm. Smaller axis is 45 mm. Clamps for pencils are in the form of hedgehog needles. Be sure to have a hedgehog muzzle on the stand. At least 60 pencils should be placed in the stand. The distance between the needles is 5 mm (pencils should be firmly fixed between the needles of the stand).

1.3. Create a packaging for sweets for a New Year's gift. Parameters are not more than 120 * 120 * 120 mm, but also not less than 100 * 100 * 100 mm. The packaging form should have the New Year theme. Tight contact of one part of the package with another part of it is necessary. Wall thickness should be no more than 3 mm. The application of the name of the holiday is obligatory. It is necessary to think over and calculate the placement on the packaging of the fastener for the gift ribbon, and the packaging can be placed as a pendant.

The principle of continuity between the levels of training of engineering and technical personnel (software, technology, methodological training system). This principle assumes that a chain of cognitive tasks that supports cognition and the formation of engineering thinking takes into account educational results of students at all levels of education. For example, in a preschool, a child masters a 3D pen and with it develops fine motor skills; during the school course, the student receives 3D modeling skills; competitive activity allows to organize the practice of working with 3D printers to protect projects; the learning environment at the university develops universal competencies (collaborations, project activities, programming and work in the face of uncertainty, etc.) and personality traits that form the basis of engineering thinking. For example, in a preschool, a child creates a butterfly using a 3D pen. This is a simple, emotionally vibrant exercise for beginners. The simplicity is that the wings are performed on the plane, can be of various colors and shapes. Hatching is practiced on the wings. Volume can be added to a butterfly body.

At school, a student gets acquainted with the physical structure of butterflies, their habitat, and studies various graphic and text editors. Therefore, the development of the trajectory of knowledge involves the implementation of an interdisciplinary project – to develop a three-dimensional model of a butterfly (for example, Paint 3D), draw up the results and present for discussion. The project is the development of a three-dimensional model of the "Kingdom of the Butterflies", which may be a participant in a competition or Olympiad. In higher education, more technically sophisticated software tools (for example, Maya) act as a tool for 3D modeling. The increasing complexity of theoretical material also supports the development of the trajectory of knowledge (to model a modification of a butterfly model into an elephant). Professional retraining may involve improving an already developed 3D model for new restrictions, new technical capabilities (for example, use them as templates for augmented reality).

The requirements of Industry 4.0 determine that a technician must be able to take on the functions of a designer, marketer, etc. Working with 3D technology allows to get this unique experience. In the course of team work on an interdisciplinary project on 3D modeling, a participant can switch from the role of an idea generator, constructor to the role of a programmer, mechanic, etc. A digital school mentor is required to organize appropriate support and create the conditions for the development of engineering thinking.

The principle of practical application of the obtained prototypes, 3D-models in related promising industries (virtual and augmented reality, neuro-formation).

New training tools, such as the Leica BLK360 compact ground-based 3D laser scanner, allow to get a virtual 3D model of the school for efficient lifecycle management (from design to operation), work in an information modeling environment (BIM-technology), preserve cultural heritage and restoration. The resulting 3D models can be used to organize training sessions in a virtual reality environment as independent objects for subsequent engineering activities.

We will implement these principles using an example of a description of pedagogical support for the development of a prototype of a smart frying pan that does not allow the decomposition of the Teflon layer. The practical problem that the project solves is determined by the following scientific fact: "When the fluoroplastic overheats (even once), thermal decomposition occurs with the release of toxic substances. Cookware with non-stick coatings is considered safe during normal use. Manufacturers consider the norm only heating with water or oil in a pan. The lack of a device for controlling and preventing overheating of pans and other similar utensils leads to overheating of products, premature failure of them, and the release of toxic substances. "Description of the project content: the basic requirement is not to change the essence of the base product (pans), i.e. externally, functionally. It can cook, it can be washed, including in the dishwasher, it should not be "tied with wires". If the temperature of the pan is determined, then it will be possible to modernize the stove, making it more convenient (quick heating of the dishes and its contents to the required temperature, maintaining the temperature at a certain level, etc.). The cooking process will become safer. The dishes will become more durable, it will lead to savings in the family budget, more environmentally friendly (due to the absence of toxic emissions), more economical in terms of energy costs for cooking.

Educational result: a model of "smart frying pan" implemented by various means of 3D technology.

Commercial result: a frying pan with a temperature indicator and with an automatic device that does not allow heating above a given temperature.

The interdisciplinary nature of the project involves interaction with the customer; knowledge of the unique material used in high technology industries – fluoroplastic (properties, features, processing); knowledge of the physics of heat transfer (heating, heat sources, types of heat transfer); temperature measurement (means, features, contact and non-contact method); selection skills of primary measuring instruments (sensors); design of coordination circuits with microcontrollers; programming, regulators (integral, PID); engineering skills: drawing, modeling, circuitry; processing of materials (mechanical milling, manufacturing of cases, soldering, etc.); testing (preparation, plan, execution, processing of results);

Stages of project work organized by a teacher in order to form engineering thinking:

I stage. Field of the problem and forecasting development options. Representation of a problem situation in the form of a physical and engineering constraint (response to an existing need). Analysis of the social significance of the project, generation and discussion of methods for its solution and the possibility of achieving an ideal end result for consumers.

II stage. Multivariate analysis of a problem situation: studying the possibility of introducing a device into operation, minimizing resource costs.

III stage. Circuit assembly: sequencing and connecting components.

IV stage. Assembly of the structure. Making the case.

V stage. Application development. Testing the operation of the device in different operating modes.

VI stage. Design decision. Testing the operation of the device in different operating modes.

VII stage. Engineering book for design solutions. Preparation of speeches and presentations based on the results of work on the project. Reflection. Discussion of the project results.

The functions that the engineer of the future within the framework of the project can perform: a mechanic (designing in 3D, 3D printing, creating simple mechanisms), a programmer (initial skills in programming Arduino-based controllers), an electrician (assembling devices, soldering, connecting sensors), a project manager (organization of interaction, correspondence, maintaining a schedule, reporting results).

4.3. Experimental assessment

4.3.1. The ascertaining stage of the experiment

During the preparatory phase, we defined a set of skills and monitored their formation during the development of 3D models. Then we formulated this set tasks for the assessment. Questions for the control event before and after the experiment took into account the provisions formulated by T.V. Kudryavtsev, I.S. Yakimanskaya (Kudryavtsev, Yakimanskaya, 1964). We developed 5 types of tasks, depending on the prevailing mental operation. A feature of the presented system of tasks for control assessment is that the student needs to demonstrate the skills and qualities of the person that form the basis of technical, economic, scientific research, constructive thinking.

1. Tasks when students showed the ability to generalize and concretize technical phenomena (for example, classification problems). An example of a question: to distribute geometric objects into groups according to a specified attribute (a modification of a task may be a situation when a

student defines a classification attribute on his own). Another option: define an extra object in the presented set of objects.

2. Tasks when students showed constructive and technical skills, involving the combination of objects. An example of a question: there are 15 identical parts in a box. An engineer needs to choose three of them. How many ways can he use to do it?

3. Tasks when students showed the ability to recognize problems. An example of a question: you can see various images of a technical engine problem. You need to choose one that informatively reflects the cause of the problem and allows to predict how to solve it.

4. Tasks involving the operation of spatial images. An example of a question: there are projections for two lines m and n. Lines are located at arbitrary angles relative to the projection planes. You need to choose one that corresponds to their mutual arrangement in space. A modification of the question could be: indicate whether they intersect with each other, and if they do not intersect, then what is their relative position?

5. The task, involving the calculation of economic benefits from the design decision. For example, calculate the reduction in water loss when replacing conventional bathroom taps with automatic touch taps.

Thus, the system of tasks for the control assessment consisted of 10 test questions, it was possible to get 2 points for each one.

4.3.2. Forming stage of the experiment

At the forming stage of the experiment, the teacher analyzed the requirements of Industry 4.0 for engineers of the future. The following areas were identified: mobile devices, augmented reality, interaction with the client, “Internet of things”, analysis of large data arrays, location technologies, human-computer interaction interfaces, 3D printing, “smart” solutions for consumers of social services. In each direction, the mentor developed topics for design. For example, as part of the direction of "location technology," students were asked to develop a 3D model of the school, a natural site. Another variations of such a project are the design of a souvenir, landscape for a computer game.

The control and experimental groups had classes "Computer Modeling". The students of the experimental group were offered possible subjects for projects, they selected those that corresponded to their professional aspirations, cognitive interests, abilities, and educational achievements. They started a software implementation after studying the corresponding theoretical material on 3D modeling, and gaining practice in the design environment. They had one or two months for practical implementation of the concept/idea of the project.

The control group had the traditional mode of studying: basic concepts and stages of working with the model, compilation of information and computer models, their implementation in software environments, analysis and discussion of the results.

When processing and interpreting the materials of the control event, the level of formation of skills that form the basis of engineering thinking was determined according to the following scale: high level – if the student scored more than 19 points; average level – from 18 to 9 points (inclusive); all other test results corresponded to the "low level".

"High" level: the student is independent in determining the objectives of the study; rationally fits the definition of restrictions of various nature (material, social, etc.); recognizes the social significance of the simulated object/phenomenon; effectively allocates available resources in the course of practical implementation; applies interdisciplinary knowledge that goes beyond the scope of a technical profile; highlights the relationship between the elements in the designed system and the conditions for their manifestation; defends its presentation of the model, the concept of the project, the design decision with reason; owns techniques, methods of working with 3D technology; can reasonably select the most effective (both 3D technology tools and techniques) for designing, developing a “smart product”; qualitatively prepares the results in the form of an engineering book or technical task for the Customer.

"Average" level: the student is not always able to independently formulate research objectives; not for all resource constraints is able to carry out model development; not fully aware of the potential of the simulated object/phenomenon; shows insufficiently deep and systemic interdisciplinary knowledge; highlights not all the relationships between elements in the designed system and the conditions for their manifestation; not always reasonably defends his view of the model, project concept, design solution; knows the techniques, methods of working with 3D technology, but makes one or two non-critical errors in reasoning when substantiating their choice for designing, developing a "smart product"; when processing the results, he fulfills the basic technical requirements.

In other cases, the level of engineering thinking was defined as "low".

4.3.3. Control stage of the experiment

At the control stage of the experiment, we carried out another assessment, which also contained 10 test questions developed according to the previously described principle. In the final control testing, the teacher took into account the difficulties faced by the participants when formulating the questions. For example, to determine those functions of the designed engineering solution that will be redundant; what 3D technology tools are best used in the restrictions specified by the Customer; choose from the list those compromises that you are ready to make when developing; choose the model from a set of three-dimensional images, which may be the prototype of some product; suggest options for improving the mechanism, etc.

To verify the reliability of results, we applied the criterion of G characters and used an online calculator and statistical tables (Ostapenko, 2010). Let us formulate hypotheses for the experimental group:

H0: the shift in increasing the level of formation of personality skills, which form the basis of engineering thinking, after the teacher implements directions for supporting the research activities of students in 3D modeling, is random.

H1: a shift in increasing the level of formation of personality and personal skills, which form the basis of engineering thinking, after the teacher has implemented areas of support for the research activities of students in 3D modeling, is not random.

The results of the control assessment for students of the experimental group are presented in Table 1.

Table 1. The results of the test in the experimental group

Level	Before the experiment	After the experiment	Positive Shifts	Negative shifts	Null shifts	Total of non-null shifts
High	1	4	0	0	1	0
Average	28	34	22	2	4	24
Low	11	2	11	0	0	11
Total of shifts			33	2	5	35

The values in the columns "Positive shifts", "Negative shifts", "Null shifts" allow to present in dynamics the qualitative changes in the level of formation of personal skills, which form the basis of engineering thinking. In the corresponding parts of the table we have 5 «null» (discarded shifts), 33 «positive» (typical shifts), 2 negative (atypical) shifts. According to the requirements of the criterion, only "non-null" shifts are taken into account, and null shifts are discarded. Performing the analysis of the values of the statistical tables for the criterion of G characters and online calculations, we conclude that for n=33 (in accordance with the number of "typical" shifts) the following is true:

$$G_{cr} = \begin{cases} 11, \text{if } p = 0.05 \\ 9, \text{ if } p = 0.01 \end{cases}$$

According to empirical measurements, Gemp = 2. Thus, Gemp < Gcr. Therefore, the hypothesis is inclined to the alternative hypothesis H1, i.e. a shift in increasing the level of formation of personal skills that form the basis of engineering thinking, after the teacher has implemented areas of support for research activities of students in 3D modeling in the experimental group, is not random.

Let us formulate hypotheses for the control group:

H0: a shift in the increase in the level of formation of skills of the personality, which form the basis of engineering thinking, after training, is random.

H1: a shift in increasing the level of formation of skills of the personality, which form the basis of engineering thinking, after training, is not random.

The test results for the control group are presented in Table 2.

Table 2. The results of the test in the control group

Level	Before the experiment	After the experiment	Positive shifts	Negative shifts	Null shifts	Total of non-null shifts
High	1	1	0	0	1	0
Average	27	34	13	7	7	20
Low	11	4	9	0	2	9
Total of shifts			22	7	10	39

In the corresponding parts of the table we have 10 "null" (discarded shifts), 22 "positive" (typical shifts), 7 negative (atypical) shifts. According to the requirements of the criterion, only "non-null" shifts are taken into account, and null shifts are discarded. Performing an analysis of the values of the statistical tables for the criterion of G characters and online calculations, we conclude that for n = 22 (in accordance with the number of "typical" shifts) the following is true:

$$G_{cr} = \begin{cases} 6, \text{ if } p = 0.05 \\ 5, \text{ if } p = 0.01 \end{cases}$$

According to empirical measurements, Gemp = 7. Gemp > Gcr, then the hypothesis H0 is accepted, that is, a shift in increasing the level of formation of personal skills, which form the basis of engineering thinking, after training in the control group, is random.

Discussion

The sample was not probabilistic, since the experimental and control groups were formed in such a way as to ensure the presence of the same skills and personality traits that form the basis of engineering thinking, their equal distribution in each group.

Throughout the experiment, work on three-dimensional modeling, attracting students to research with 3D technology was carried out by the same teacher, on the same software equipment in special informatics rooms.

Performing a quantitative analysis of the above results, we can conclude that after the experiment was completed, 10 % of the students in the experimental group had a high level of formation of basic properties that form the basis of engineering thinking, while initially this percentage was 3 %. In the control group, the proportion of students with a high level of development of engineering thinking remained unchanged (the value of the indicator is 3 % before and after the experiment). The dynamics of values at other levels in the experimental group also testifies to a qualitative improvement in learning indicators and the formation of monitored personality traits (see Figure 1).

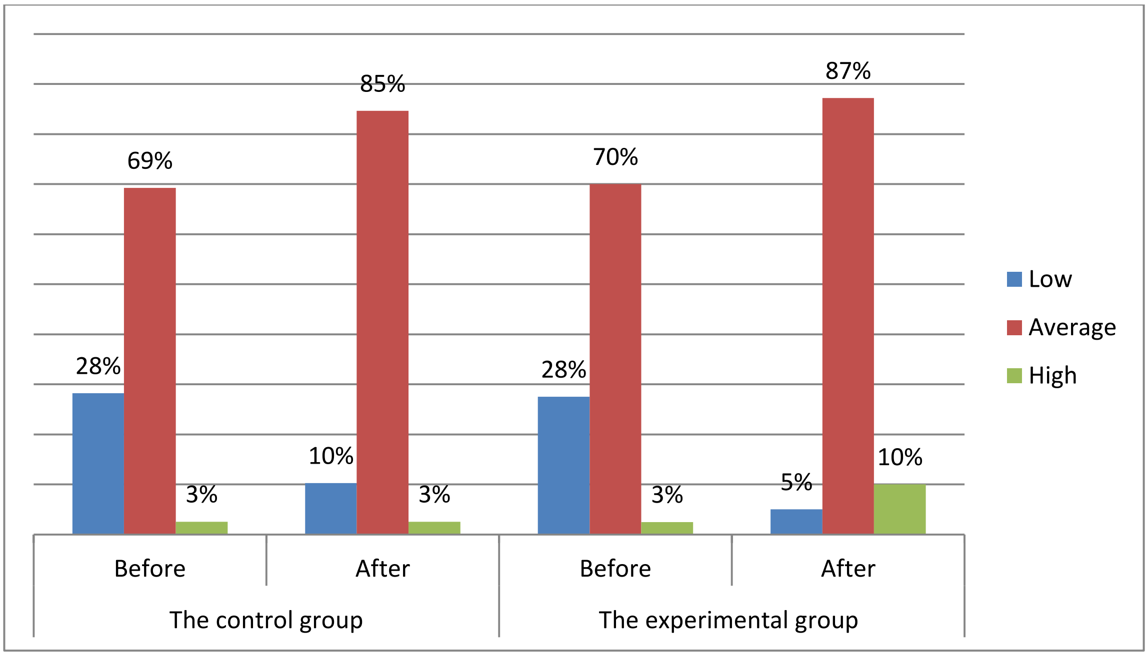

Fig. 1. Dynamics of changes in the level

Thus, in the course of completing technical tasks on three-dimensional modeling, students systematized the necessary conceptual apparatus, studied various functional capabilities of software environments and 3D printing devices, got the opportunity to solve specific practical and socially significant problems of the future, while showing independence in choosing 3D tools, methods of cognition. We can conclude that the differences in the levels of engineering thinking are due precisely to the use of 3D modeling tools and methods as an effective pedagogical teaching technology. The presentation of ready-made three-dimensional models to potential employers of the city of Kirov confirmed the importance of inventions, as many of them expressed their willingness to assist in organizing and conducting industrial internships, student training practices, as well as to collaborate in the development and implementation of new educational programs for future professions to prepare highly qualified specialists Industry 4.0 when providing additional information.

5. Conclusion

In the process of three-dimensional modeling, students create 3D objects according to working drawings and technical documentation, participate in the development of design documentation for the product; perform visualization and texturing of objects, analyze simulated products for technicality, generate and improve engineering solutions; carry out the presentation of the project with oral support and justification of social significance. Objects for 3D modeling can be abstract, or they can correspond to the real problems of society, economics, science (resource saving, life safety, architecture, film and video industry, etc.). Work in 3D spaces is emotionally attractive for students, supports the development of high-order thinking processes, professional self-determination and allows to get skills that are in demand on the labor market.

Thus, the results of the study prove that 3D technologies have a powerful educational potential in terms of improving the training of a high-demand “engineer of the future”, capable of self-development and professional self-realization, ready to solve non-standard tasks of Industry 4.0, with experience in predicting the results of upcoming activities and oriented towards universal human values.

For the successful implementation of the proposed areas and the use of 3D technology in the formation of engineering thinking, it is recommended to have the following set of conditions: building the educational process based on the integration of fundamental scientific theories and software/digital technologies; implementation of interdisciplinary research tasks of a problematic nature with a focus on the challenges of Industry 4.0; actualization of the needs of students in obtaining a high-demand profession of the future through the practice of 3D modeling activities, collaboration. When forming engineering thinking using 3D technology, we should remember that the corresponding activity involves the integration of innovative, technical, economic and constructive components. Distinctive features of the "engineer of the future" are:

– the ability to see the structure when it is not visible to humans, without engineering thinking. The engineer of the future should see all sorts of interconnections between elements in the system, as well as the conditions in which they appear and disappear;

– the ability to be effective in conditions of restrictions that may be determined by nature (climate, physical laws, resistance of materials) or by a person (human behavior, constitution, finances);

– ability to identify priority tasks in the project and efficiently allocate resources.

The results can be used to improve the quality of teaching 3D modeling in a digital school due to specially organized areas of support for creative, intersectoral, cognitive research activities of students, focused on the development of engineering thinking, and carried out in the conditions of training for the formation of Industry 4.0.

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