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Modeling and visualization of functional 3D objects in the professional training of future vocational education teachers

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Abstract: The article presents a methodology for implementing comprehensive STEM projects in the training process of higher education learners in engineering-pedagogical specialties of a general technical or technological (in the field of mechanical engineering) profile. As an example, the study proposes teaching students how to build and analyze models of functional 3D objects, as well as how to visualize them as part of comprehensive STEM projects. The active integration of 3D modeling and 3D visualization into the educational process aims at integrating scientific knowledge in technology, engineering, and mathematics through solving practical tasks and analyzing real challenges of professional activity. Modeling and visualization of 3D objects, in particular, make it possible to gain deeper insight into the study of the features of functional 3D objects and contribute not only to mastering abstract mathematical concepts but also to the development of logical and spatial thinking. As an example of a possible way to implement comprehensive STEM projects in the educational process, the stages of the project "Modeling and Visualization of Functional 3D Objects" are highlighted. The project includes the analysis, modeling, and visualization of functional 3D objects in the SolidWorks Simulation software suite and the printing of a physical model on a 3D printer.

Keywords: *3D modeling, Digitization of education, Mechanical engineering, STEM education, STEM projects, Visualization, Vocational education teachers.*

1. Introduction

In the context of rapid changes in industrial production technologies, today's labor market faces a significant skills gap problem. It arises due to workers' lack of certain competencies associated with the requirement to possess the latest specific skills, which cannot be acquired within traditional vocational training programs. This causes an imbalance between labor market demand and supply, slows technological progress and the economic development of society, and therefore requires changes in the programs and methodologies for training future specialists.

A study of labor market trends has revealed that, in the ranking of the most in-demand skills, employers highlight the following: analytical thinking, creativity, resilience and flexibility, the ability to adapt to change, motivation and self-awareness, a commitment to continuous learning, reliability and attention to detail, active listening, leadership qualities and social influence, technological literacy, and others [1]. This, in turn, underscores the role of educational institutions in preparing a new generation of competitive workers. This result can be achieved by adapting educational programs to the requirements of the modern labor market, providing vocational education learners not only with theoretical knowledge but also with practical skills that are key to a successful career [2, 3]. The implementation of the latest technologies, teaching methods, and assessment approaches is also relevant [4-6]. Cooperation between vocational education institutions and industry and business is also

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important to provide learners with opportunities to gain practical experience and internships, as well as support for non-formal education.

Technological development has fundamentally changed professional activity in many fields. Modern professions are becoming increasingly knowledge-intensive, which requires specialists to possess skills of objective analysis and to make well-founded decisions. The ability to reasonably forecast the results of practical activity is achieved, in particular, through methods of modeling various scenarios, which significantly increases productivity and reduces risks. For example, the main task of engineering sciences is to study the patterns that manifest themselves in the process of manufacturing products (machines, mechanisms, instruments, or devices) in order to use them to ensure the required product quality, as well as the necessary quantity at the lowest cost. The achievement of this goal is facilitated by the use of computer modeling tools, which make it possible to create virtual models (prototypes) and test them before mass production.

In turn, this highlights the problem of professional training of higher education learners in engineering-pedagogical specialties through the introduction into the educational process of studying computer modeling methods and their practical application in subsequent professional activity. This is explained by the recognition of the potential of this approach for deepening students' perception of professional disciplines and for better understanding the essence of complex engineering solutions and technological processes.

To increase the effectiveness of educational activity, various types and methods of modeling are used. For example, computer modeling methods can be used to create virtual laboratories [7], simulations for studying problem-based and role situations, and a programmable virtual environment for performing practical educational and technological-production tasks [8, 9]. Modeling can also be used to analyze data on learners' academic performance, which helps identify problem areas and individualize the approach to learning. In this way, modeling becomes an integral part of the professional training of both engineers and teachers. In terms of educational activity, the acquired knowledge, abilities, and skills will be of significant importance for forming the foundations of their professional future. The use of computer modeling methods during the training of future teachers contributes to the development of a number of key competencies that determine their ability to teach and that are not available within the traditional learning model. For this reason, building models of various pedagogical processes is a relevant area and subject of scientific and pedagogical research.

The purpose of this article is to present one of the possible ways to introduce computer modeling methods into the process of training higher education learners in engineering-pedagogical specialties. The idea is to apply project-based learning technology using the preparation and step-by-step implementation of comprehensive tasks for modeling, visualization, and manufacturing or 3D printing of functional objects, models of real-world products, or products created during the design process that can perform functions inherent to the corresponding original. The process of implementing this type of educational project is demonstrated using the example of modeling, visualization, and preparation for 3D printing of a functional 3D object from the field of transport machine building, a non-swiveling brake shoe for freight cars. All stages of such a project are considered; the didactic purpose and the possibility of incorporating each of them into the content of the training program for higher education learners in the specialty "Professional Education (Mechanical Engineering)" at Yuriy Fedkovych Chernivtsi National University are determined.

2. Computer 3D Modeling in Mechanical Engineering and Engineering-Pedagogical Education

Information and communication technologies (ICT) and project-based technologies are recognized as important tools for increasing the effectiveness of the educational process [3, 4, 10]. Accordingly, all modern training programs for specialists in the engineering-pedagogical field provide for the use of teaching and learning methods based on ICT. First of all, they are considered a means of teaching students of any specialty. However, for training future teachers, it is important to provide them with the abilities and skills to apply ICT in practical educational activities.

This goal can be achieved through the introduction of creative learning tasks (STEM projects) related to the design and modeling of self-selected functional 3D objects. In the course of their implementation, students have the opportunity to deepen their perception of engineering concepts studied in the relevant courses and their understanding of design and technological solutions, since modeling, by definition, is a process of adequate representation of the simplest properties of the object or phenomenon under study with the accuracy required for practical needs. Approaches to organizing learning through project-based technologies, which involve the practical implementation of the stages of design and modeling, usually intensify students' cognitive activity because the interactions revealed in the process of constructing and transforming three-dimensional geometric objects eliminate their passive attitude, which is often observed in the case of traditional learning technologies [11]. In addition, project work that includes graphical constructions with elements of 3D modeling significantly improves the assimilation of precise technical information and understanding of spatial configurations. This way of graphical representation surpasses the traditional use of a drawing, blueprint, or diagram and makes the understanding of the real world more intuitive [12].

Computer modeling makes it possible to create a model of a real or imaginary object using computer technology based on the analysis of mathematical, physical, and other logical constructions. The result is computer models that can be presented in 2D and/or 3D image formats; they can be static or gamified (with animation elements) [13].

The use of projects implemented through computer modeling within STEM education differs significantly from traditional learning [14]. This system creates conditions for the development and improvement of learners' analytical and creative abilities, allows them to try themselves in teamwork, and develops their independence in acquiring new knowledge. Such activity promotes the integration of academic disciplines and the formation of skills in using modern technologies and modeling. Independent creation of models allows learners to better understand the basic properties of objects, phenomena, and processes, their components, and the relationships between them. Studying models forms in future specialists the skills of analysis, synthesis, critical thinking, and a methodological approach to implementing content by means of computer modeling within project-based activity [15].

In the professional training of future specialists in engineering-pedagogical specialties, it is advisable to carry out the modeling and visualization of complex 3D objects using the example of functional objects intended to perform specific tasks or functions. This approach has a significant advantage: typical, appropriately classified functional objects that have the same purpose but differ in size or other design or operational parameters do not need to be studied from scratch with each new class [16]. As a result, the process of training students is significantly accelerated.

The process of teaching students to model functional 3D objects includes relevant stages that play a key role in the process of preparation and in forming the necessary competencies in future specialists. This enables them to better master the theoretical foundations of the learning material and will allow the practical application of innovative software suites for computer modeling, the study of design features, and the mechanical characteristics of the structure of specific functional 3D objects.

The initial stage of modeling any functional 3D object involves the preliminary formation of an understanding of it, its purpose, operating conditions, possible design variants, and its graphical representation, the nature of static and dynamic loads, requirements for mechanical properties, types and physical characteristics of structural materials, cost-effectiveness, and environmental risks. Such understanding should be based on theoretical knowledge acquired during the study of academic disciplines provided by the educational program. Specifically, the two-level educational and professional program "Mechanical Engineering," which offers training at the first cycle of higher education (bachelor's) and the second cycle (master's) in the specialty "Professional Education" at Yuriy Fedkovych Chernivtsi National University (Ukraine), includes, among professionally oriented educational components, disciplines such as "Engineering Graphics," "Mechanical Engineering Drawing," "Computer Graphics," "Theoretical Mechanics," "Strength of Materials," "Theory of

Mechanisms and Machines," "Machine Elements," "Materials Science and Materials in Mechanical Engineering," "Mechanical Engineering Technology," "Technologies of Technical Design and Modeling," "Computer-Aided Design Systems in Mechanical Engineering," "Advanced Structural Materials in Mechanical Engineering," "Computer Technologies of Engineering Design and Development," "Technical Measurements, Interchangeability, Standardization and Certification in Mechanical Engineering," and "Economics, Entrepreneurship, and Marketing." Mastering the material presented in these disciplines ensures that the learner acquires the necessary theoretical knowledge and practical skills to carry out an educational project on modeling a functional 3D object of their choice. The practical implementation and presentation of results at each project stage are conducted through individual assignments, course projects, and graduation theses.

3. Visualization of 3D Modeling Objects

Visualization has long been considered an effective way of teaching, a method of using a graphical image of the object of study to give it a perceptible form and maximize convenience for describing its structure and characteristic properties.

With the invention of computer graphics tools, this method acquired new, potentially more powerful possibilities and, as a result, significantly influenced all levels of modern education. Visualization carried out in parallel with the modeling process makes it possible to significantly facilitate the explanation of educational material due to the ability of this method to present information compactly at an accelerated pace compared to traditional approaches, while preserving its semantic completeness. In addition, studies by a number of psychologists and educators have proven that this improves the conditions for students' assimilation of educational material, as it reduces their time and energy expenditures on perceiving and understanding a large volume of information. This is explained by the possibility of simultaneous activation of both hemispheres of the brain, which significantly contributes to the creative and professional development of the individual [17].

Visualization occupies a particularly important place in engineering education, since this type of education is a specific form that requires a focus on the practical aspect of design and technological processes [18]. The use of visualization in training learners in higher engineering-pedagogical education aims to solve a range of pedagogical tasks, including: activating cognitive activity, intensifying learning; forming skills of visual perception, spatial imagination, and technical creativity, developing critical thinking and figurative representation of ideas, knowledge, and learning activities; and acquiring the ability to recognize images and effectively transfer knowledge.

At present, many means of visualization in the process of transmitting information are known: traditional and interactive boards, posters, diagrams, a television screen, a computer monitor, a multimedia projector, and others. The task of training a qualified teacher is to provide them with the knowledge, abilities, and skills to use such forms of visual aids that would not only supplement verbal information but also serve as carriers of information. The higher the level of competence of the future teacher regarding visualization tools, the higher the quality of their professional activity will be in the future. The formation of such competence in learners of higher engineering-pedagogical education under the above-mentioned educational and professional program "Mechanical Engineering" is envisaged through the performance of educational and creative tasks within such academic disciplines as "Computer Graphics," "Creative Technologies of Vocational Training," "Computer-Aided Design Systems in Mechanical Engineering," "Theory and Methodology of Vocational Education," and "Digital Technologies in Vocational Education." The student acquires the necessary practical skills and abilities in the process of completing the stages of an educational project on modeling a functional 3D object of their own choice.

4. Example of Implementing a Comprehensive Project on Modeling and Visualization of Functional 3D Objects

In order to provide practical training in the methods and tools for modeling and visualizing functional 3D objects, the authors have developed a number of comprehensive projects. One of them is the project "Modeling and Visualization of a Non-Swiveling Brake Shoe for Freight Cars." For the practical implementation of this and similar projects, it is proposed to use the SolidWorks computer suite, a design system for solid-body parametric modeling of mechanical engineering structures [19]. The methodology for implementing this type of educational project, as well as the stages of its completion, is described in the next section of this article.

4.1. Analysis of the Graphic Image of a Functional 3D Object

In the above-mentioned project, the object of modeling is a complex functional 3D object, a non-swiveling brake shoe, which belongs to the components of the brake lever transmission (BLT) of a freight railway car bogie.

The brake shoe receives the load developed by the brake cylinder and transmitted to it through the system of rods and levers of the BLT, then to the brake pad, which performs the braking of freight rolling stock.

The non-swiveling brake shoe (Figure 1) belongs to the class of parts with a complex geometric shape. It consists of upper and lower stiffening ribs that firmly connect the supporting surface. Its middle part has a slot for installing a pendulum suspension, which allows it to move freely during brake operation. The supporting surface of the non-swiveling brake shoe and its stiffening ribs are connected to the faces of a four-sided slot intended for mounting it on the triangle beam.

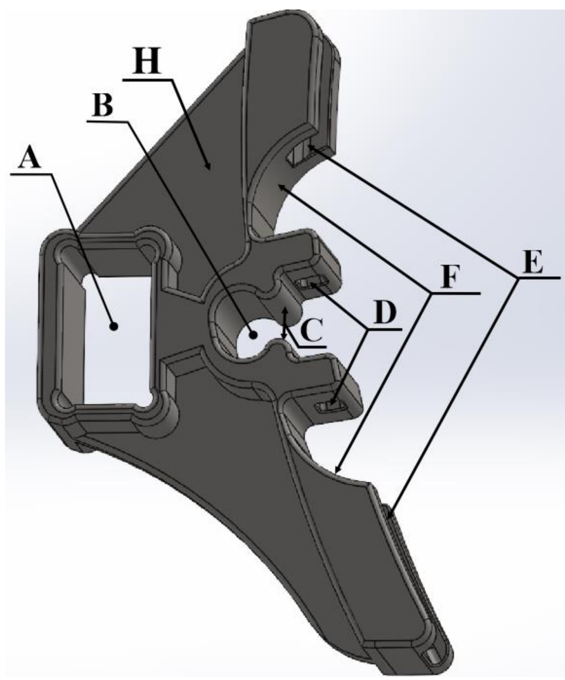

Figure 1.
Star octahedron Elements of the non-swiveling brake shoe for freight cars: A – triangular mounting hole; B – suspension hole; C – shoe slot for the pad lug; D – hole for fastening the brake pad; E – brake pad guide; F – functional cutout; H – stiffening ribs.

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The entire structure of the non-swiveling brake shoe is rigidly connected by at least one stop made in the form of a plate or rod, intended to limit the rotation of the shoe relative to its pendulum suspension.

4.2. Determining the Features of Building and Editing a Computer Model of a Functional 3D Object

The initial data for carrying out the project are the instruction manual and technical documentation for the product being designed, which specify its nominal dimensions. The final result of work on the project is 3D printing and presenting a physical model of the product developed using the SolidWorks computer suite.

The construction of the computer 3D model of the design object is carried out in the following sequence: constructing the contour sketch of the computer model of the object; creating and editing its solid structural elements on the constructed computer 3D model.

4.2.1. Constructing the Contour Sketch of the Model of a Non-Swiveling Brake Shoe for Freight Cars

The construction of the base sketch of the computer 3D model of the non-swiveling brake shoe is performed in the SolidWorks software suite.

When creating the contour sketch of the computer 3D model, learners use geometric construction tools. To ensure consistency in the placement of geometric primitives, they apply such constraint operations as tangency, parallelism, perpendicularity, horizontality, verticality, concentricity, etc. The construction process is considered complete after applying geometric dimensions, in automatic or manual mode, both for the object itself and for its orientation relative to the coordinate system.

As is known, a computer 3D model consisting of several elements can be built in different ways. Construction options are chosen based on an analysis of construction complexity, an analysis of the model's functional properties, and consideration of the developer's experience in technical drawing.

The result of the construction will be, as in our case, a flat two-dimensional image of the contour of the part (Figure 2).

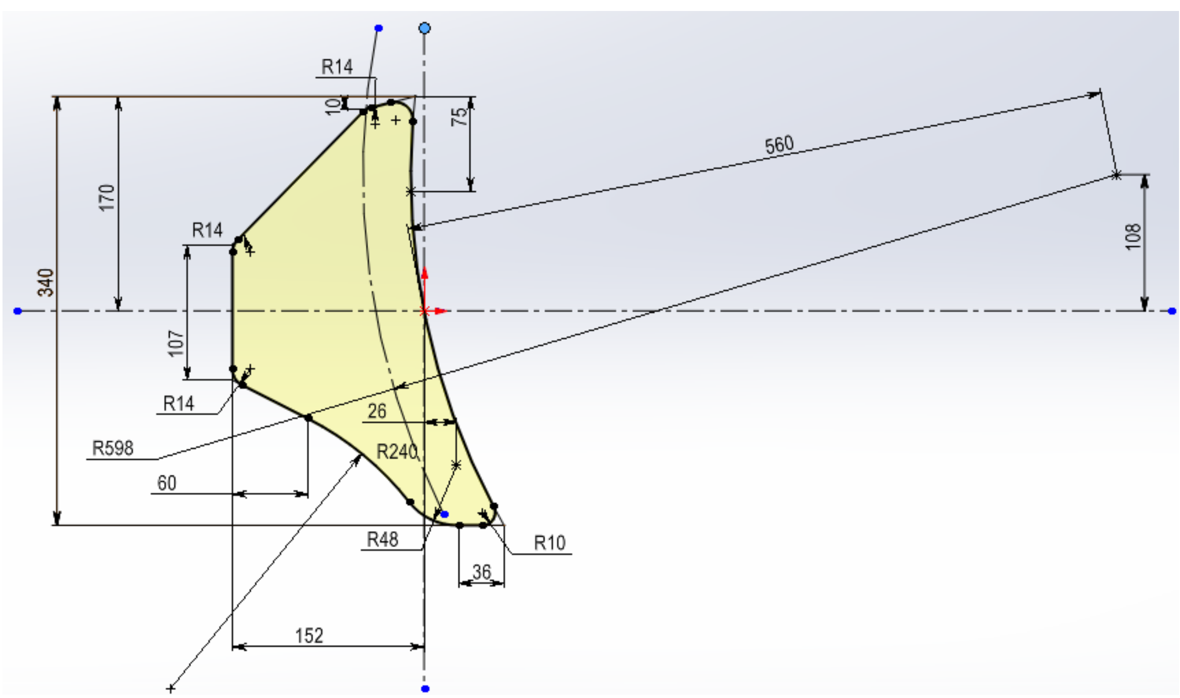

Figure 2.
Dimensional Parameters of the Contour of the Model of a Non-Swiveling Brake Shoe for Freight Railway Cars.

After completing the contour sketch of the model of the object being modeled, we move to the mode of creating and editing solid structural elements on the constructed model.

4.2.2. Creating and Editing Solid Structural Elements on the Constructed Computer 3D Model

To create a solid computer 3D model of the non-swiveling brake shoe for freight cars, we apply the "Extruded Boss/Base" extrusion operation. On the selected model, we apply the extrusion to the appropriate depth, completing the process of forming the three-dimensional representation of the contour sketch.

The process of constructing and editing the components of the computer 3D model of the non-swiveling brake shoe for freight cars involves creating the following structural elements: the triangular mounting hole – A; the suspension hole – B; the shoe slot for the pad lug – C; the hole for fastening the brake pad – D; the brake pad guide – E; the functional cutout – F; the stiffening rib – H (Figure 1).

All the listed elements are built using operations for constructing the corresponding sketches and applying the "Cut-Extrude" feature. The sequence of operations involves creating sketches on the model's frontal projection plane for elements A, B, C, and F. To create the brake pad mounting holes D, the corresponding plane was activated, and rectangles with the required dimensions were constructed using the "Midpoint Line" primitive. A specific feature of constructing the brake pad guide E was the use of auxiliary planes perpendicular to the shoe guide. For sketches created on the auxiliary planes, the "Swept Cut" and "Cut-Extrude" cutting operations were applied.

To reduce the weight of the non-swiveling brake shoe for freight cars without changing its mechanical properties, the technology provides for the procedure of cutting out a part of the shoe body that does not participate in technical operations.

Creating element H – the stiffening rib- was accompanied by removing part of the body of the non-swiveling brake shoe for freight cars. The sequence of performing this operation is traditional: creating a sketch of the upper part, creating a mirror pattern relative to the centerline in the lower part, "Linear Pattern," performing the "Cut-Extrude" operation to the appropriate depth, and mirroring the resulting face to the opposite side of the non-swiveling brake shoe for freight cars.

In order to analyze the strength of the non-swiveling brake shoe under a uniformly distributed load from the brake pad, its 3D model was built. The graphical work was reproduced in SolidWorks using the drawing album of the shoe, which made it possible to create an accurate model (Figure 3).

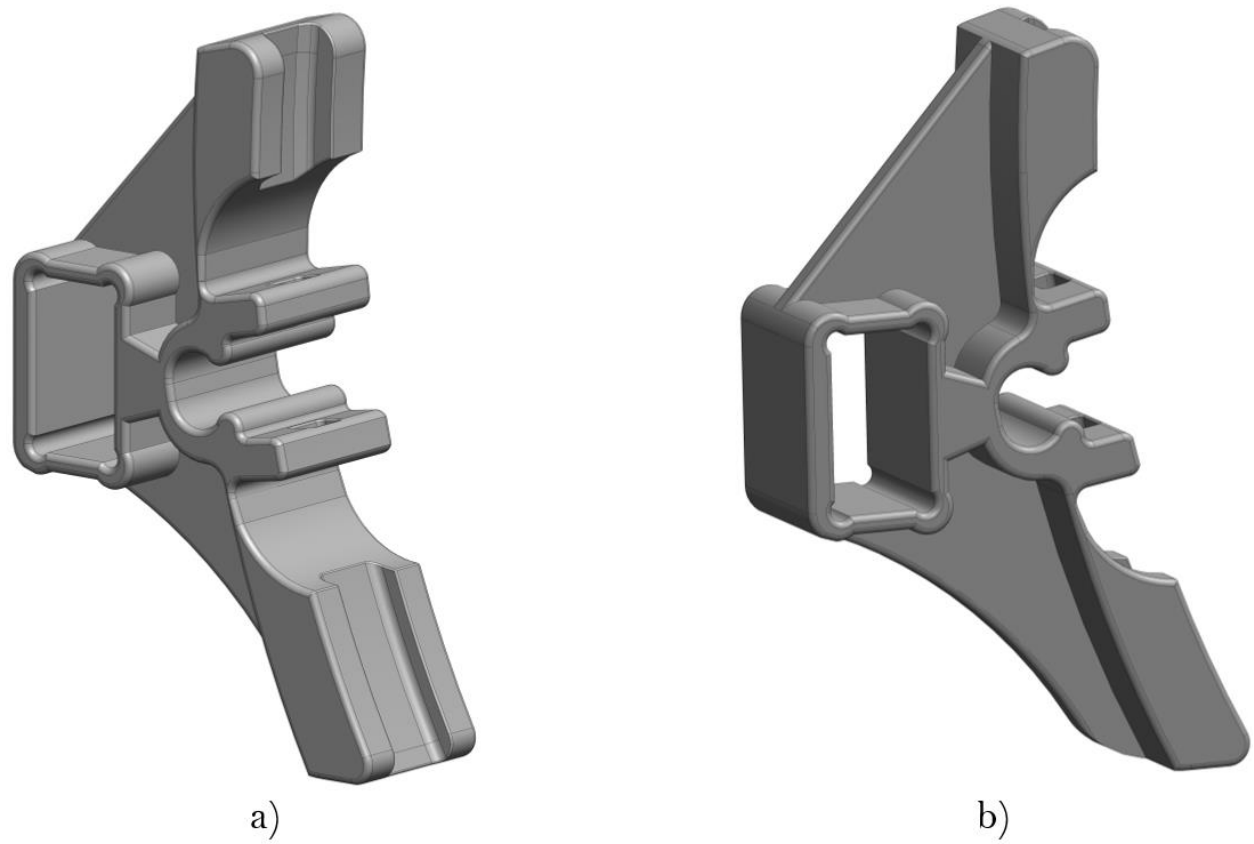

Figure 3.
Graphs of the mathematical calculation of the star octahedron.

4.3. Analysis of the Mechanical Properties of Functional 3D Objects Based on Visualization in the SolidWorks Simulation Software Suite

In the educational process, 3D data visualization is quite effective as it helps to quickly stimulate students' interest in learning, improve material assimilation, and focus attention on key areas of a functional 3D object.

Data visualization involves using graphs, charts, images, diagrams, maps, 3D models, and other visual tools to present data understandably. Visualization helps quickly identify patterns, trends, templates, and outliers (anomalies) in data.

The strength calculation of the studied object was performed using the finite element method in the SolidWorks Simulation software suite. To create the finite element model, isoparametric tetrahedra were used (Figure 4).

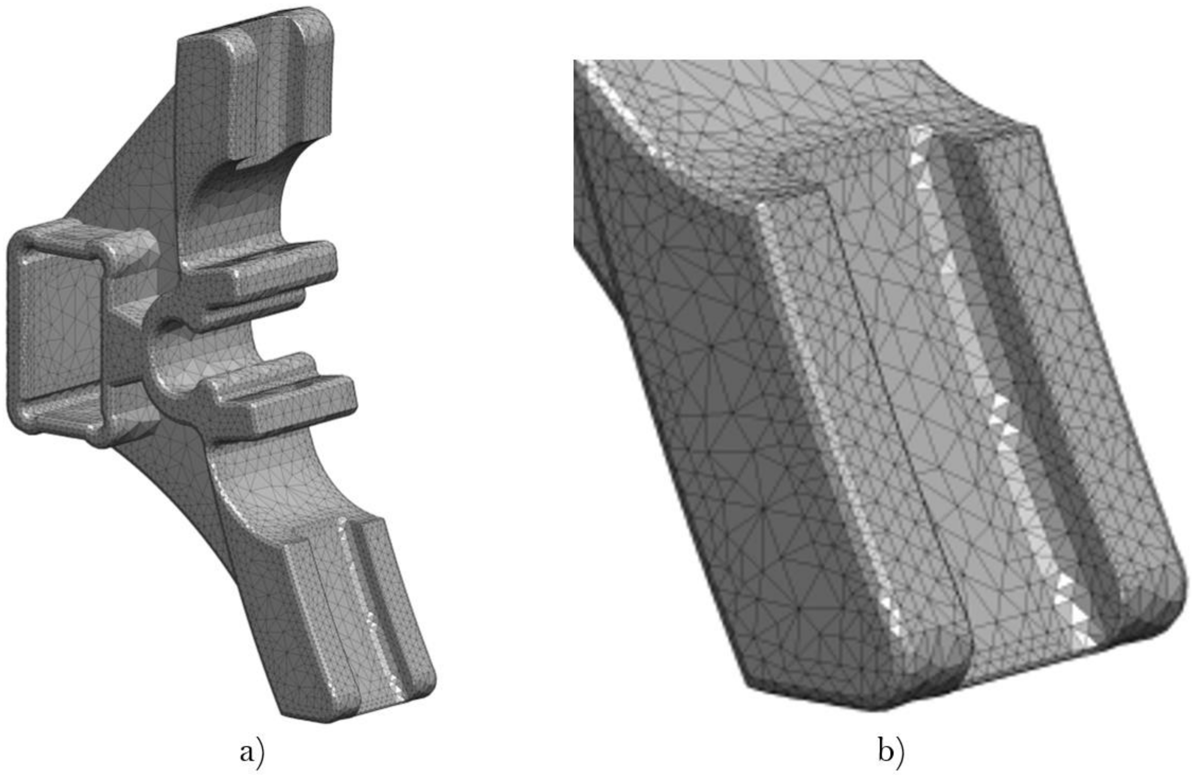

Figure 4.
Finite Element Model of the Non-Swiveling Brake Shoe.

Under this condition, their number was determined using the graph-analytical method. The essence of this method lies in constructing the dependence of maximum stresses on the number of finite elements. When this dependence begins to be described by a horizontal line, it indicates the optimum number of finite elements. Based on the calculations performed, the model includes 77,898 elements and 18,467 nodes. The largest element size in the model was 15 mm, and the smallest was 3 mm.

The fixation of the shoe was modeled by applying rigid constraints in the zone of its interaction with the bogie triangle. In Figure 5, they are shown in green.

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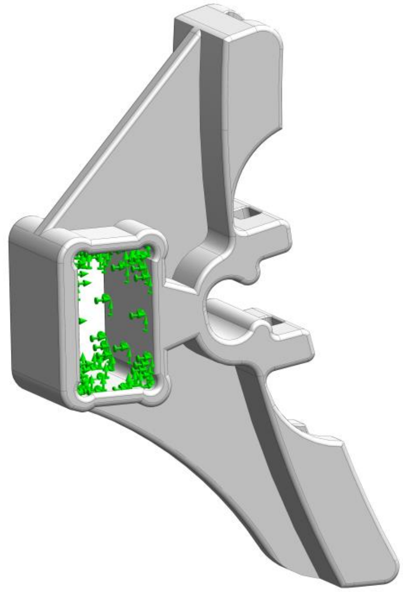

Figure 5.
Fixation of the Non-Swiveling Brake Shoe.

The strength calculation was performed taking into account the operating loads, which correspond to an external load of 35.35 kN. The calculation scheme is shown in Figure 6.

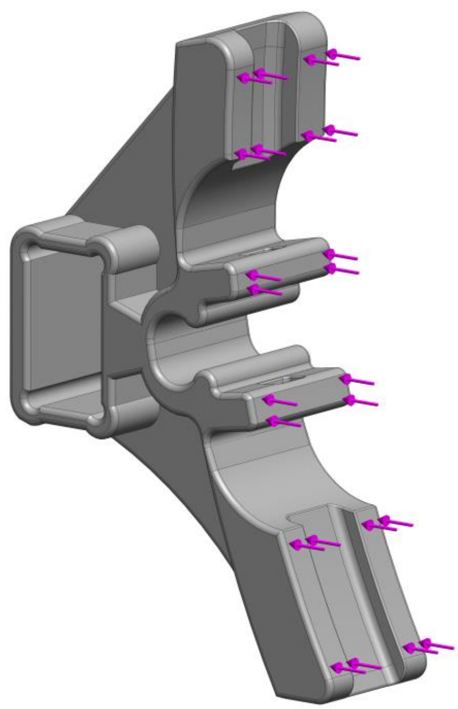

Figure 6.
Computer Model of the Non-Swiveling Brake Shoe with Applied Calculation Loads.

The results of the strength calculation are presented in Figures 7–9. The maximum stresses were recorded in the reinforcing rib (Figure 7). They amounted to 112 MPa (Fig. 8), which does not exceed the allowable values.

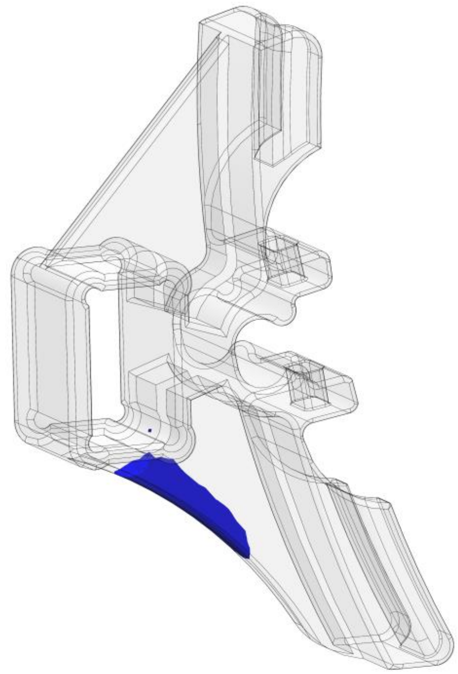

Figure 7.
Zone of Maximum Stress Distribution in the Non-Swiveling Brake Shoe (Focusing Attention on Key Areas)

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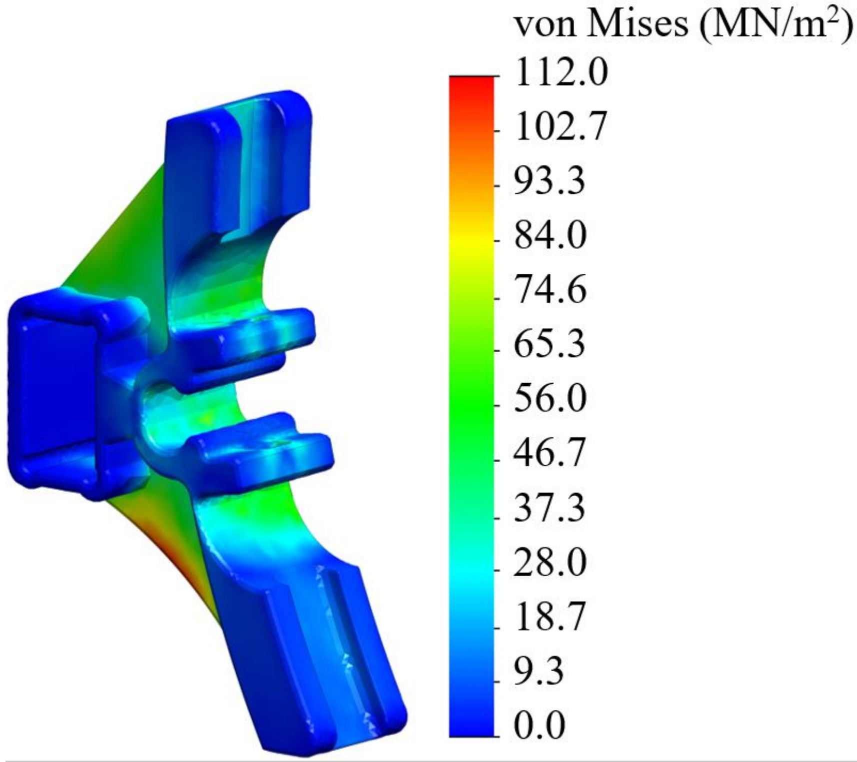

Figure 8.
Stress State of the Non-Swiveling Brake Shoe (3D Visualization).

The maximum displacements in the non-swiveling brake shoe were 0.67 mm and occurred in its lower part (Figure 9).

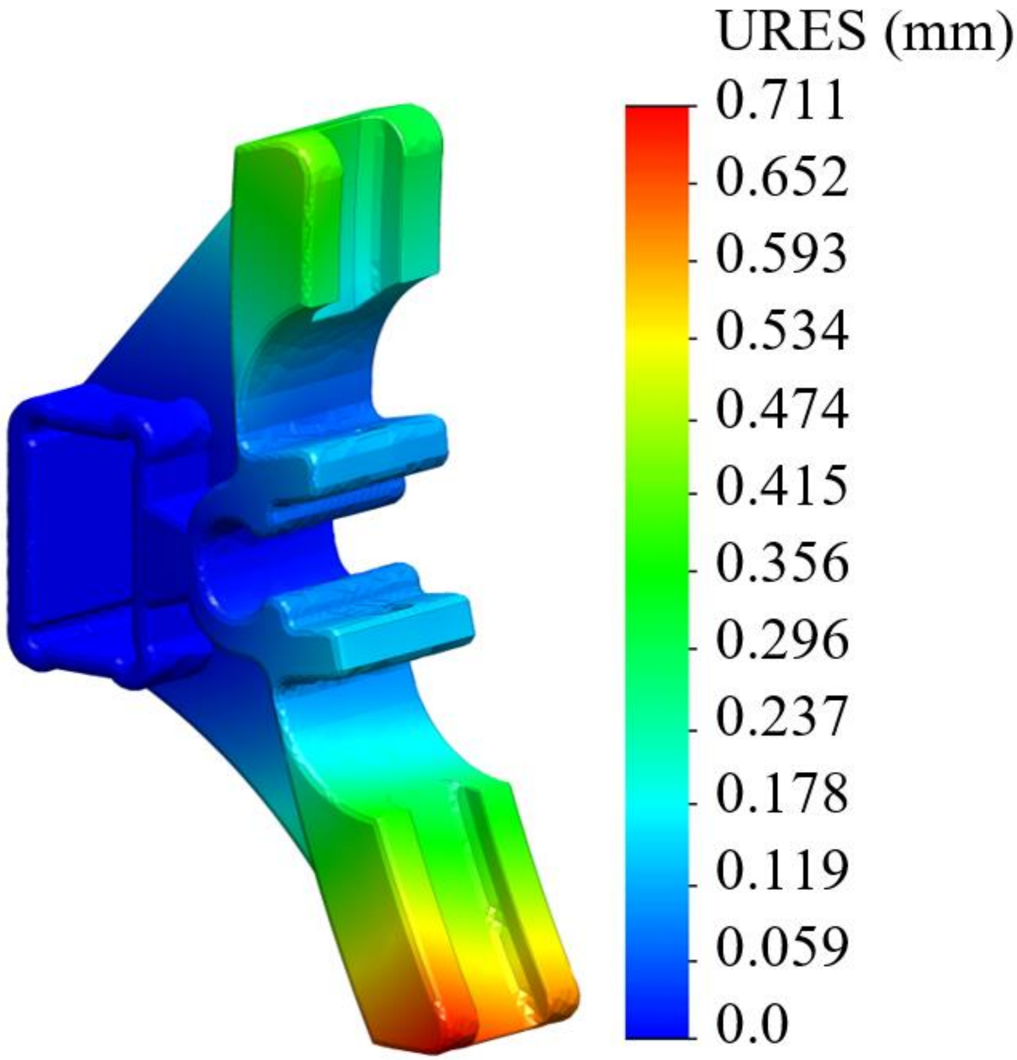

Figure 9.
Displacements in the Non-Swiveling Brake Shoe.

The results of the calculation allow us to conclude that the strength of the non-swiveling brake shoe under the specified loading mode is ensured.

4.4. 3D Printing of Three-Dimensional Models on a 3D Printer

At the final stage of design, the digital model is physically reproduced using 3D printing, which involves preparing the model file, selecting the material, configuring the 3D printer, performing the printing process, and addressing possible deviations that may arise during fabrication [20].

Manufacturing a part using 3D printing involves several successive stages: creating a 3D model and preparing it for printing (selecting the material and parameters, choosing the orientation, generating supports, and setting the infill), the actual printing of the object on a 3D printer, and, if necessary, mechanical post-processing of the part (removing supports, surface finishing, sanding, and bringing dimensions to the specified values) [21, 22].

The previously designed model is exported in the (.stl) format for further slicing into layers in the appropriate software package. To export the created brake shoe model to STL format, in the "Save As" mode, it is necessary to specify the file type (*STL) [23].

The Repetier-Host software interface displays the brake shoe model prepared for 3D printing (Figure 10). The visualization of printing speed in the Repetier-Host environment is shown in Figure 11. Model preparation for printing (slicing) within the Repetier-Host software package was performed using the PrusaSlicer plugin [24]. PrusaSlicer software converts 3D models into control commands for a 3D printer and configures printing parameters.

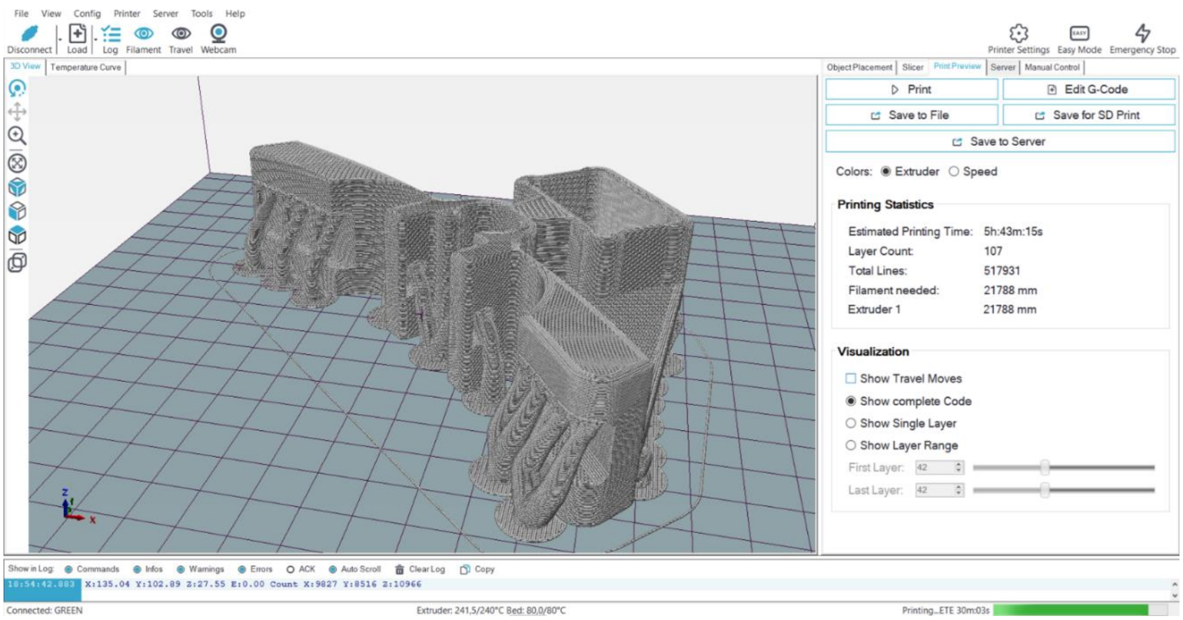

Figure 10.
The Sliced Model of the Non-Swiveling Brake Shoe for Freight Cars in the Repetier-Host Program Window.

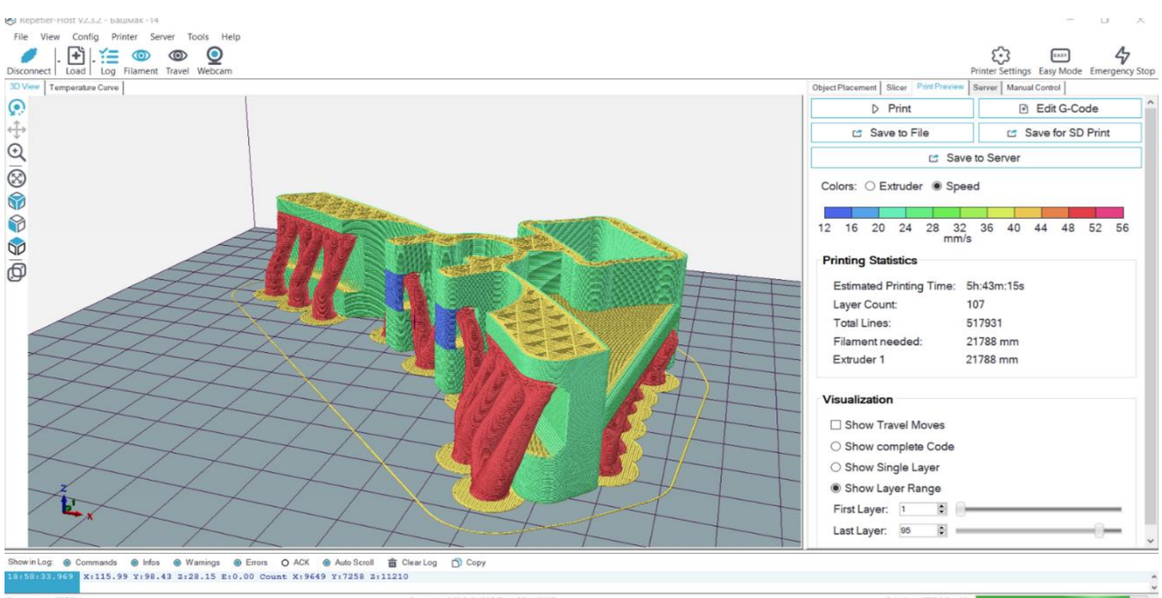

Figure 11.
Visualization of Printing Speed in the Repetier-Host Program Window.

Additionally, it should be noted that for successful printing of the model, it is necessary to enable support generation, since the model contains elements positioned at an angle greater than 45 degrees relative to the previous layer. There are several variants of support generation algorithms; however, one of the most convenient to remove from the finished part is the tree-support algorithm. This also makes it possible, unlike grid supports, which are generated only vertically, to bypass already printed parts of the model and subsequently simplify support removal. PrusaSlicer also allows specifying which areas of the model require supports, whereas automatic support generation may additionally produce support material in areas where it can be avoided, for example, by using bridges.

The model also has rounded chamfers, which are very convenient for manufacturing the model by casting; however, due to the specifics of building a model with FDM printing, the rounded chamfers of the printed part will have noticeable stepping because the slicer attempted to approximate the rounding radius with layers of fixed thickness. To reduce this effect, the layer thickness can be decreased, but this will immediately lead to a significant increase in printing time. To achieve a satisfactory printing result, variable layer thickness can be used, which will allow the slicer to reduce the layer thickness in areas of the model where greater detail is required; that is, for example, to print the vertical walls of the part with a 0.25 mm layer, and in the areas of rounded chamfers to reduce the layer thickness to 0.1 mm. This will reduce the stepping effect and produce a printed part that is more similar to a model cast from metal.

The printing process and the printed model of the non-swiveling brake shoe for freight cars are shown in Figure 12.

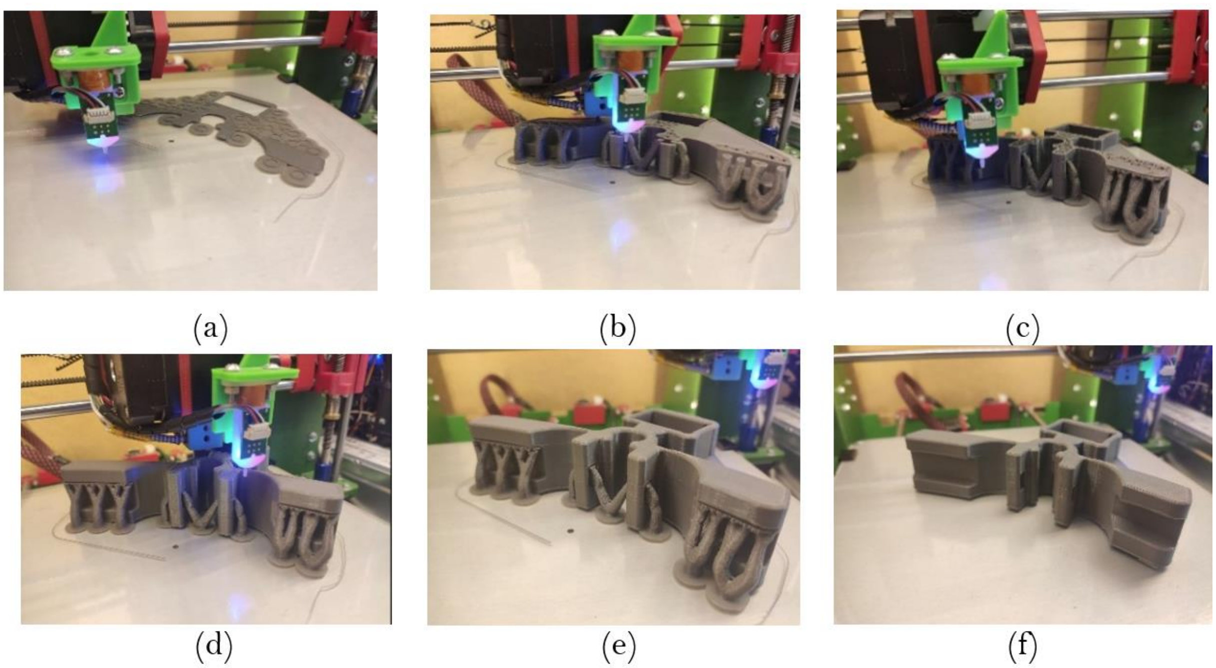

Figure 12.
Process of Printing the Non-Swiveling Brake Shoe for Freight Cars

Quality control of 3D-printed models can subsequently be carried out, see by digitally processing their images.

5. Results and Discussion

Thus, we proposed a consistent approach to implementing elements of STEM education in the training of higher education learners of an engineering-pedagogical profile through their completion of comprehensive STEM projects using modeling and visualization technologies in the SolidWorks environment, software tools for 2D and 3D design, and printing models on a 3D printer.

The implementation of STEM projects in the training of future teachers and engineers for the mechanical engineering sector is a promising direction for improving the quality of education. The implementation and dynamic development of this direction are necessary for forming in the future specialists a comprehensive approach to solving professional problems, readiness for continuous self-education, and the ability for innovative thinking. This contributes to increasing their competitiveness in the labor market, since in the modern world specialists are required not only to have deep knowledge in their field but also the ability to apply this knowledge in a broader context.

The impact of the teaching methodology, which uses a thematic STEM project, on learning outcomes was studied using a group of master's learners (30 learners in the specialty "Professional Education (Mechanical Engineering)" at Yuriy Fedkovych Chernivtsi National University) during their study of the course "Digital Technologies in Vocational Education." The learners' learning outcomes were assessed by testing them (4 tests) before and after completing the STEM project. The maximum number of points for each test is 100. The topics of test tasks No. 1–4 corresponded to the topics of the STEM project stages:

1. Constructing the contour sketch of the object model.
2. Creating and editing solid structural elements on the constructed computer 3D model.
3. Analysis of the mechanical properties of the functional 3D object based on visualization in the SolidWorks Simulation software suite.
4. 3D printing of the model on a 3D printer.

The tests contained questions of both theoretical and practical orientation. The analysis of the test results involved calculating, for each test, the group mean score (Mean), the standard deviation of scores relative to the Mean, and the skewness of the score distribution relative to the Mean (Fig. 13). Skewness determines the symmetry of the score distribution relative to the Mean [25]. If skewness values are close to zero, the scores are symmetrically distributed around the Mean. If deviations above the Mean are more prevalent than deviations below, skewness is positive, indicating individual high scores significantly exceeding the Mean. Conversely, if the distribution is characterized by individual low scores, skewness is negative. Therefore, the smaller the absolute value of skewness, the more symmetric the score distribution.

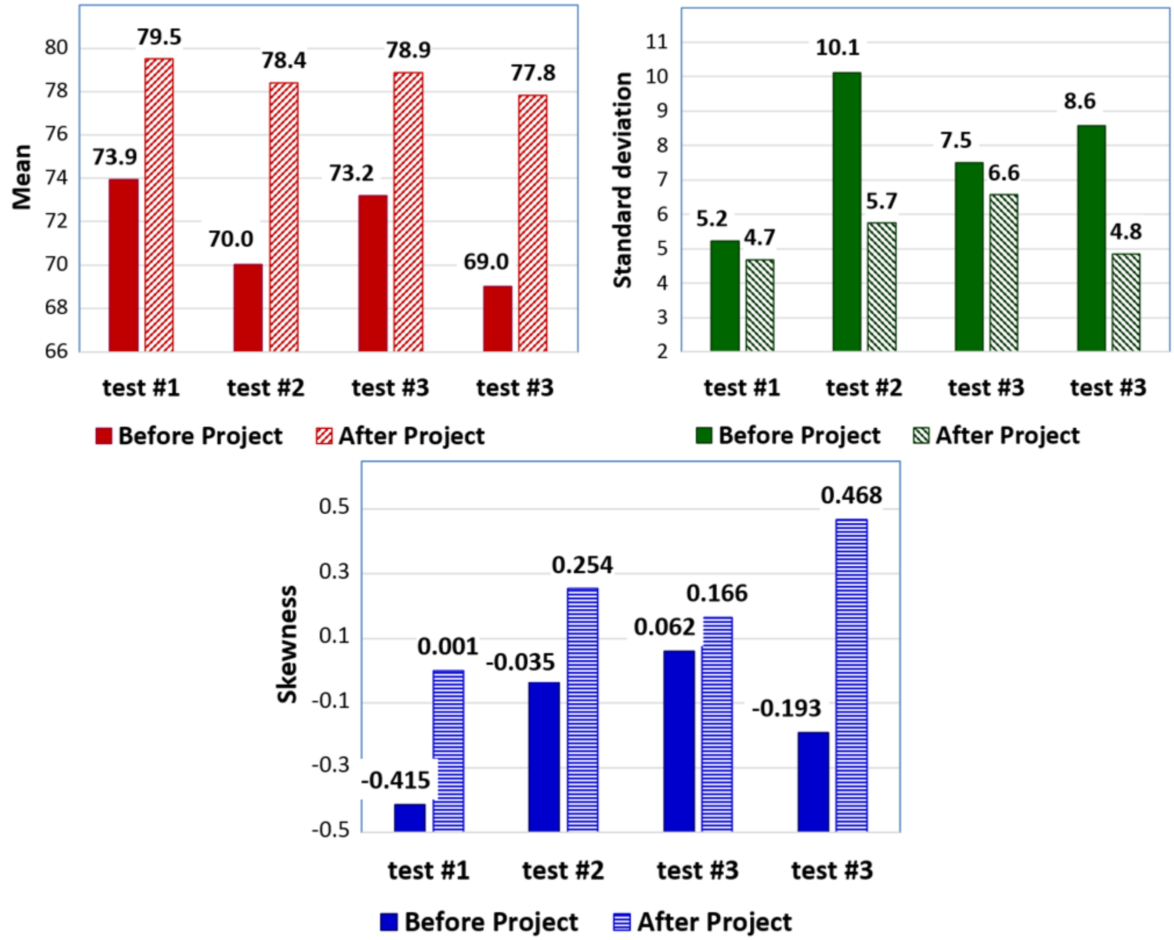

Figure 13.
Students' Test Results Before and After Completing the STEM Project

After completing the STEM project, for tests No. 1–4, the group mean score increased by 5.57, 8.37, 5.67, and 8.83 points, respectively (on average by 7.11%). The standard deviation of scores after completing the project decreased for all tests; the largest decrease was obtained for test #2 by 4.37 points and for test #4 by 3.72 points. This can be explained by a significant improvement in the results of learners who had the lowest results before completing the project, especially for topics #2 and #4, which required practical reinforcement of the material during project implementation. For all tests, an increase in the skewness of the score distribution after completing the project is observed (on average by 0.37). The increase in skewness is due to the fact that the number of learners with scores significantly below the mean decreased, and the number of learners with scores significantly above the mean increased. As a result of the project, the greatest improvement in learning outcomes was obtained for test #4, according to the topic of project stage #4, "3D printing of the model on a 3D printer." This is explained by the practical skills learners acquired while mastering 3D printing technology, which significantly simplifies the perception of educational material for learners. Improvements in learners' learning outcomes were obtained for all stages of the project; therefore, in general, the implementation of the STEM project was successful.

6. Conclusion

The implementation of the STEM project "Modeling and Visualization of Functional 3D Objects" offers significant opportunities for training future specialists in engineering-pedagogical fields. During its implementation, elements of key professional competencies are formed in learners in a consistent manner, in particular, practical skills and abilities, the achievement of which is impossible under traditional learning conditions.

Learners learn to apply mathematical methods for analyzing and modeling complex spatial objects and acquire three-dimensional modeling skills when building wireframe, surface, and solid models of objects in the SolidWorks software suite. Learners also gain practical skills in printing models of objects on a 3D printer.

While carrying out the project, learners learn to analyze problems and find optimal solutions, approach tasks creatively, and develop communication skills.

Learners were tested on the topics of the three stages of the project before and after completing it, resulting in an average improvement of 6.6% in learning outcomes across all stages. In our opinion, this suggests that the teaching methodology based on learners' participation in implementing comprehensive STEM projects was successful, as improvements in learning outcomes were observed at every stage of the project presented here.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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