

Modeling and Manufacturing 3D Geometric Figures for STEM Training of Engineering Students: A Staged Methodology and Case Study

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Received: January 12, 2026; Revised: March 4, 2026; Accepted: June 14, 2026; Published: October 8, 2026

Abstract: This article presents a methodology for modeling and manufacturing three-dimensional (3D) geometric figures. The need for developing the methodology is substantiated, and its significance for the STEM training of future specialists in engineering specialties is demonstrated. An advantage of the methodology is the clear structuring of all its stages, levels, and steps, which simplifies the process of implementing STEM projects. Structurally, the methodology includes a preparatory stage and four main stages. Stage 1 involves designing the object model, which includes collecting information about its characteristics and developing a mathematical model. Based on the mathematical model, the main parameters of the investigated object (part) are determined and calculated. At Stage 2, the computer-aided construction of a three-dimensional model of the object is performed, taking into account the parameters determined at the first stage. The development of drawings and the 3D model is carried out in an appropriate software environment, in particular, in the AutoCAD computer-aided design (CAD) system. Based on the calculated parameters, different types of three-dimensional models of the object are created: wireframe, surface, and solid. Stage 3 involves the implementation of additive manufacturing, that is, the manufacture of a physical prototype of the investigated object using 3D printing. For models of significant overall dimensions or complex geometric shapes that complicate printing, preliminary decomposition of the model into separate parts is performed. After printing, the individual components are joined, and the resulting physical prototype undergoes appropriate post-processing. Stage 4 involves the validation of the

manufactured physical 3D model by assessing its conformity with the digital model of the object. Comparison of the physical and software models can be carried out based on the analysis of their photographic images using digital image processing methods. In addition, a visual assessment of the prototype and measurements of its main geometric parameters are performed. An example of the implementation of a STEM project aimed at the creation, investigation, and physical reproduction of a three-dimensional model of a small stellated dodecahedron by means of 3D printing is presented. According to the developed methodology, at the first stage, a mathematical model of the dodecahedron was developed. At the second stage, based on this model, wireframe, surface (polygonal), and solid (volumetric) models were sequentially developed. An important advantage of the proposed methodology is the step-by-step construction of the wireframe model, which begins with the construction of simple geometric primitives. At the subsequent stages, individual primitives and their groups are sequentially combined into more complex structural elements. This approach simplifies the construction process and enables the step-by-step creation of complex three-dimensional models. At the third stage, the model was decomposed, prepared for printing, and its individual components were manufactured using an FDM 3D printer. After that, the printed parts were assembled and the resulting product was post-processed. As a result, a physical model of the small stellated dodecahedron was manufactured, whose geometric dimensions and surface quality meet the requirements and objectives of the STEM project. A physical model of the small stellated dodecahedron was fabricated, with a pentagon edge length of $b = 25.3$ mm and a circumscribed sphere diameter of $D_s = 127.2$ mm. The maximum dimensional deviation of the dodecahedron was 0.3 mm.

Index Terms: STEM projects, 3D model, AutoCAD, 3D printer, additive manufacturing, small stellated dodecahedron, engineering specialties

1. Introduction

In the current conditions of social transformations, the importance of the systematic development of the professional competencies of specialists, necessary for their effective professional activity and adaptation to new requirements, is increasing [1]. Engineering tasks are characterized by increasing complexity, which necessitates the use of modern approaches and tools for their solution, among which mathematical and computer modeling occupy an important place [2]. Computer modeling and virtual prototyping make it possible to create digital representations of real technical objects [3], investigate their behavior under different parameters and conditions [4], as well as perform analysis, testing, and optimization prior to the stage of physical implementation, which contributes to reducing costs and risks during design [5]. Modeling contributes to the integration of modern digital technologies into design and manufacturing processes. The use of specialized software packages makes it possible to automate individual stages of modeling and analysis, reduce the duration of design operations, and increase the efficiency of engineering decision-making.

Computer modeling makes it possible to investigate the geometric and functional characteristics of technical systems [6, 7], while three-dimensional (3D) graphics tools enable the visualization of objects with complex spatial forms. Modern artificial intelligence and machine learning technologies integrated with computer modeling tools expand the possibilities for analyzing large datasets [8], predicting the technical condition of objects, and optimizing engineering solutions [9].

The spread of such technologies increases the requirements for the digital and analytical competencies of future specialists and strengthens the role of modeling in the professional training of engineering students as a tool for the comprehensive solution of professional tasks. The use of models makes it possible to investigate complex technical objects, analyze their geometric and functional characteristics, as well as develop students' understanding of the principles of their functioning and skills in the practical application of the acquired knowledge [10].

One of the effective approaches to integrating modeling into the educational process is the implementation of STEM projects focused on solving practical engineering tasks [11, 12]. STEM education integrates science, technology, engineering, and mathematics and is based on the interdisciplinary nature of learning [13]. The use of project-based and problem-oriented approaches contributes to the development of critical thinking, creativity, and the ability to apply acquired knowledge to solve practical tasks. In addition, participation in STEM projects contributes to the development of cognitive flexibility and the ability to engage in interdisciplinary collaboration [14]. One of the important areas of STEM education is the practical mastering of computer modeling technologies and the manufacture of three-dimensional objects, in particular, models of geometric figures. This approach enables students to master the fundamentals of engineering activity, analyze and design objects, create and process their 3D models, and manufacture physical prototypes using 3D printing. Participation in STEM projects contributes to the development of the ability to solve complex problems, creative and logical thinking, as well as to integrate knowledge from different fields [15].

However, despite the obvious advantages of using computer modeling and manufacturing parts in STEM education, there are significant challenges and barriers that slow down the process of their integration into educational programs. These include insufficient experience of teachers in implementing STEM technologies and the lack of adapted methodologies for different levels of student training. At the same time, it is important that the developed methodology establish a clear sequence for the application of tools and technologies for constructing 3D models and manufacturing

them. Therefore, the aim of this study is to develop a methodology for modeling and manufacturing three-dimensional geometric figures. The aim of the study is relevant because the developed methodology can be effectively applied as a means of STEM training of future engineering specialists. The methodology is designed to enhance students' skills in mathematics, computer-aided design (CAD) and 3D printing.

2. Literature Review

A review of current research indicates the growing role of models and modeling as integrative components of STEM education. Hallström and Schönborn [16] note that, despite differences in the use of models across various STEM disciplines, common elements of modeling activities include the construction, evaluation, improvement, and reuse of models. In technology and engineering education, working not only with conceptual and visual models but also with physical models is of particular importance, while the modeling process should be integrated into authentic engineering activities.

The practical implementation of such an approach was demonstrated in the study by Zárate-Navarro et al. [2], where STEM education of engineering students was based on the comprehensive use of mathematical modeling, computer simulation, and experimental validation. The STEM workshops proposed by the authors involved the use of MATLAB and COMSOL for modeling and visualizing heat transfer processes, as well as Arduino-based experimental equipment for verifying the obtained results. Testing of the approach in student groups during 2020–2023 showed an improvement in the understanding of the fundamentals of computer modeling of processes and the corresponding practical skills [2].

The effectiveness of combining project- and problem-oriented learning with an integrated STEM approach in engineering education was investigated by Gutierrez-Berraondo et al. [11]. The authors developed and implemented a long-term interdisciplinary STEM project over three years within the training of engineering students. The evaluation results showed that the application of this approach contributes to the use of basic engineering skills for problem solving and to a deeper understanding of concepts, laws, and models of different disciplines [11].

An important direction of modern engineering education is the integration of digital design with practical manufacturing technologies. Fidan [17] considers the training of future engineers through the use of modern design and sustainable manufacturing tools. The practical training modules proposed by the author include generative design in Autodesk Fusion, casting technologies, and the processing of plastic waste into filament for 3D printing. Testing of such modules with STEM students and teachers confirmed the prospects of a practice-oriented combination of design and manufacturing technologies in engineering education [17].

Further development of this approach is presented in the work of Shen et al. [18], where an interdisciplinary educational framework is proposed that integrates additive manufacturing, 3D printing, and digital technologies with academic learning and industrial practice. The approach is based on learning through practical activities, within which students perform project tasks related to 2D and 3D modeling, optimization of material properties, and collaborative solving of engineering problems. Such an organization of learning is aimed at developing critical thinking, technical skills, and interdisciplinary interaction [18].

The features of project-oriented learning in additive manufacturing were studied in detail by Sardinha and Leite [19]. The course proposed by the authors combines theoretical training with practical laboratory work and concludes with a comprehensive project in which students integrate the acquired knowledge and skills. The results of the study demonstrated the effectiveness of a holistic practice-oriented approach for deepening the understanding of additive manufacturing technologies and developing students' readiness for innovative engineering activities [19].

Thus, current research demonstrates a trend toward the integration of digital design, computer modeling, and additive manufacturing within practice-oriented engineering training. At the same time, the effectiveness of this approach largely depends on the consistency between the stages of computer-aided design (CAD) modeling and the subsequent physical manufacturing of an object.

The relationship between computer-aided design processes and the subsequent manufacturing of objects was investigated by Velikonja et al. [20]. The authors showed that previous manufacturing experience influences the nature of CAD modeling and the choice of an additive or subtractive design approach. Differences were identified between the behavior of novice students and professional engineers, with students more often focusing on 3D printing and additive methods of model formation. The obtained results emphasize the need for closer integration of design and manufacturing processes in the training of future engineers [20].

The practical significance of computer modeling for solving applied engineering problems was demonstrated in the works of Lovska and co-authors. In particular, study [21] calculated the loads on the load-bearing structures of articulated tank cars equipped with new concepts of draft gears, while study [22] analyzed the loading and strength of a removable FLAT RACK module with viscoelastic connections in the fittings. These studies confirm the importance of mathematical and computer modeling for assessing the stress-strain state, loading, and strength of complex technical structures [21, 22].

A separate important aspect of additive manufacturing is the control of the geometric accuracy of physical models. Bushra et al. [23] proposed an integrated approach combining 3D scanning, process modeling, and analysis of geometric distortions of additively manufactured parts. The authors performed a quantitative comparison of predicted and actually measured geometric parameters and demonstrated the advantages of a CAD-oriented approach compared with the use of

STL models [23].

A hybrid laboratory framework based on CAD/CAE/CAM projects, integrating topology optimization and laser powder deposition for the fabrication of three-dimensional parts, was presented in [24]. The study demonstrated that the developed laboratory framework can be used for training students in engineering disciplines. In [25], an approach for improving 3D printing accuracy through the compensation of geometric deviations using a convolutional neural network was described. The dimensions of the object are determined during the printing process using a structured-light 3D scanner. When necessary, the printing parameters are adjusted to improve the dimensional accuracy of the fabricated 3D model. The role of 3D printing in modern engineering education was examined in [26]. The study demonstrated that 3D printing technology contributes to the development of creativity and critical thinking and improves students' spatial visualization skills.

Optical analysis methods are characterized by high informativeness in the study of spatially inhomogeneous structures. In particular, studies [27, 28] proposed methods for the spatial reconstruction of biomedical structures. Although these methods were developed for biomedical objects, they demonstrate the capabilities of optical analysis for obtaining quantitative information about the complex spatial structure of the investigated objects.

In the professional activities of engineering specialists, methods of digital image processing, computer modeling, and visualization of technical objects are widely used. For digital image processing, methods of filtering [29], profile extraction [30], segmentation [31], contrast enhancement [32, 33], and recognition [34] are used, in particular.

The need to control the results of additive manufacturing is also confirmed by recent review studies. Ali et al. [35] note that, despite the significant capabilities of additive manufacturing for creating objects with complex geometries, the technology remains sensitive to problems of repeatability, geometric and structural defects, and variability of technological processes. This necessitates the validation of manufactured models and control of the conformity of their parameters [36]. Optical methods are often used to control the parameters of the investigated objects [37].

The conducted review of current scientific research confirms that current studies cover modeling in STEM education, project-oriented learning in additive manufacturing, the integration of CAD design with manufacturing technologies, and the assessment of the geometric accuracy of additively manufactured parts. At the same time, a comprehensive practice-oriented approach remains insufficiently studied, in which, within a single STEM project, mathematical modeling of a geometrically complex object, its CAD design, technological adaptation for 3D printing, manufacturing of a physical prototype, and subsequent geometric validation are sequentially combined.

3. Methodology

According to the developed methodology, the modeling and manufacturing of three-dimensional geometric figures include Stages No. 0–No. 4 and are carried out in the following sequence (Fig. 1.).

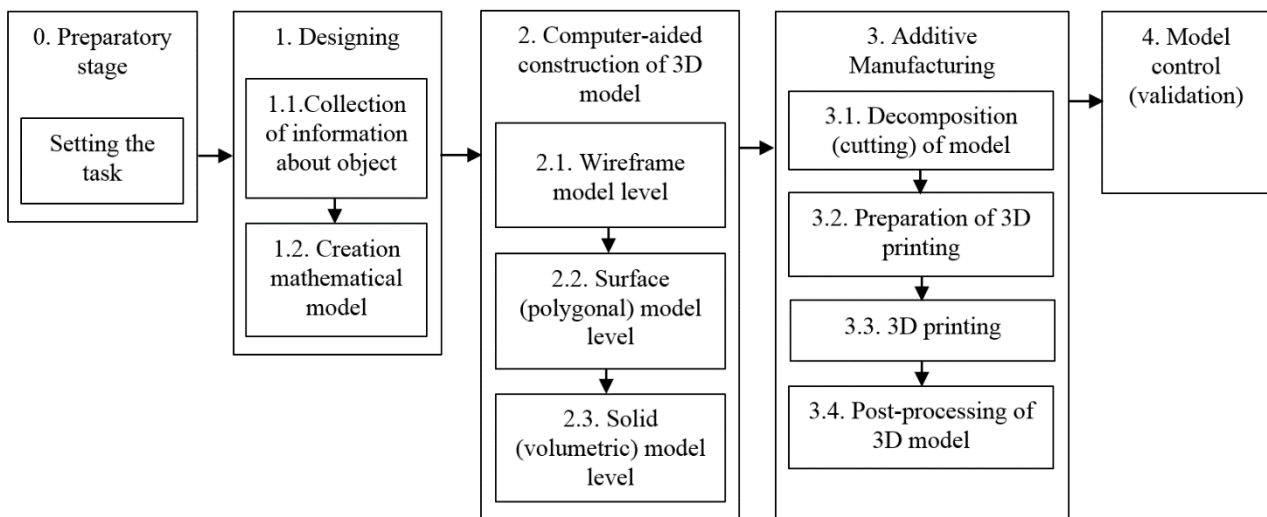


Fig. 1. Scheme of the Methodology for Modeling and Manufacturing Three-Dimensional Geometric Figures

The developed methodology is intended for use in STEM projects. The pedagogical definition of the concept of a “project” in the educational context is characterized by multidimensionality, where an “educational project” is considered a problem-oriented task that involves independent search and research activities of higher education students using a heuristic approach. The implementation of STEM projects in the educational process of higher education institutions is aimed at solving socially significant problems through the implementation of information-search, research, and practice-oriented activities of students. The practical application of theoretical knowledge in STEM projects is a fundamental element of the training of future engineers.

The theoretical basis of STEM education is the clear structuring and methodological substantiation of the process of implementing STEM projects. Pedagogical studies show that the effectiveness of the formation of professional competencies directly depends on the systematic and consistent implementation of project activities in the educational process. In this context, the phased implementation of STEM projects is of particular importance, as it ensures a logical sequence in the formation of both technical and pedagogical competencies of future specialists.

A STEM project involving the implementation of technologies for designing, modeling, and manufacturing three-dimensional geometric figures has a number of specific features, which are reflected in its structure. Taking into account the possibilities of STEM education and the requirements for the training of future specialists in engineering specialties, the following generalized sequence of STEM project stages was developed.

Preparatory stage (stage 0). Setting the task, formulating the project aim, and planning its stages. At this stage, the teacher together with the students determines the aim and objectives of the STEM project. In general, the aim of the project is the computer modeling and manufacturing of the investigated object (part), while during the practical implementation of the project, the aim is specified. The problem that needs to be solved is formulated; the knowledge and skills required for its implementation are determined. The pedagogical aim is to create a learning situation that will motivate students to conduct research, experiment, and actively participate in the educational process. Planning the project stages consists in determining the sequence of actions (stages) required to achieve the project objectives. Together with the teacher, the students create a project plan that includes identifying the necessary resources and technologies, distributing responsibilities, and establishing time frames for completing each stage.

Stage 1. Designing the object model. This stage is theoretical; its components are the collection of information about the object and the creation of its mathematical model. Based on the mathematical model, the parameters of the investigated object (part) are calculated. Students study the theoretical foundations related to the project, collect information from various sources, and analyze scientific articles and studies. This stage contributes to the development of analytical thinking and the ability to find the necessary information.

Stage 2. Computer-aided construction of a three-dimensional model of the object (part). At this stage, students apply the acquired knowledge to solve practical tasks, namely, to construct drawings of the object based on its previously calculated dimensions (Stage 1). An environment for constructing drawings and a 3D model of the object is selected, for example, the AutoCAD computer-aided design (CAD) system. Based on the parameters of the object, its 3D models are constructed: wireframe, surface, and solid. An important aspect of this and the following stages is interactivity and the involvement of students in active activities, which allows them to acquire practical skills and develop critical thinking.

Stage 3. Additive manufacturing, that is, manufacturing a prototype of the investigated object (part) by means of 3D printing. If necessary, decomposition (cutting) of the model into parts is performed. After 3D printing, these parts are joined, and post-processing of the physical prototype is carried out (for example, mechanical processing).

Stage 4. Model control (validation). An analysis is performed to determine the conformity of the physical model of the object, printed on a 3D printer, with its software model. The models are compared, in particular, by analyzing their photographs using digital image processing methods.

After the completion of all project stages, reflection is provided, which makes it possible to draw conclusions about the achievement of the project objectives, identify difficulties, and determine ways to overcome them. The project results are presented to the audience. Students prepare presentations in which they demonstrate their achievements, share the experience gained, and answer questions from the audience. This stage contributes to the development of communication skills, the ability to present research results, as well as the ability to defend their scientific ideas and justifications.

4. Example of STEM Project Implementation

4.1. Preparatory Stage of the Project

The aim of the STEM project is defined as constructing a three-dimensional model of a small stellated dodecahedron, studying the obtained model, and manufacturing it by means of 3D printing. In accordance with the aim, the project task is formulated (the type of polyhedron, whose dimensions are specified by the polygon edge length b), and its Stages No. 1–4 are planned.

4.2. Stage 1. Theoretical Foundations

Students collect information about the object under study (the small stellated dodecahedron) and construct its mathematical model. The parameters of the investigated object are calculated using analytical formulas. It is established that the small stellated dodecahedron is constructed on the basis of a regular dodecahedron; therefore, both models of regular polyhedra are considered (Fig. 2.).

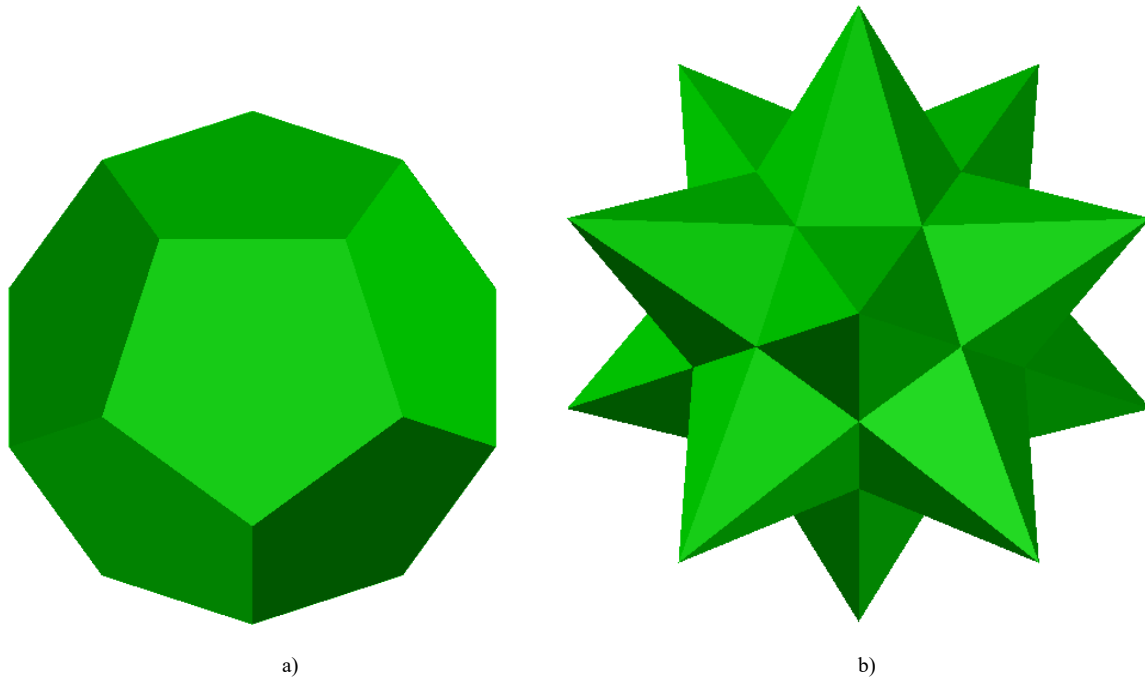


Fig. 2. Regular Dodecahedron (a) and Small Stellated Dodecahedron (b)

The use of regular polyhedra as modeling objects for educational purposes provides a number of advantages: well-developed mathematical models exist for such polyhedra, making it easy to control the correctness of their construction; during the project, interdisciplinary connections between mathematics, computer graphics, and other disciplines are used. The choice of a three-dimensional model of the small stellated dodecahedron is explained by the relative complexity of its structure, which will allow students to acquire useful skills in modeling and 3D printing such an object.

A regular dodecahedron (Fig. 2.) is constructed by spatially combining 12 regular pentagons (faces), which are the basic elements (primitives) of the three-dimensional model. The proportions of the “golden ratio” are used in the construction of the dodecahedron.

$$\varphi = \frac{1+\sqrt{5}}{2} \approx 1.6180339887 \quad (1)$$

Let the length of the pentagon edge be denoted by b . Then the radius r of the circumscribed circle passing through all vertices of the pentagon is equal to:

$$r = \frac{b}{2\sin(\beta)} = 0.850651 \cdot b \quad (2)$$

where $\beta = 36^\circ$ is half of the central angle of the pentagon.

The radius R_D of the circumscribed sphere passing through all vertices of the dodecahedron is calculated by the formula:

$$R_D = b \cdot \varphi \cdot \frac{\sqrt{3}}{2} \approx 1.395863 \cdot b \quad (3)$$

The value of the radius R_D describes the overall dimensions of the regular dodecahedron, which are very important for its 3D printing. The overall dimensions of the regular small stellated dodecahedron exceed those of the regular dodecahedron by two heights of the pyramids extended on the faces, which is taken into account when manufacturing physical models of the objects.

The angle between two adjacent faces of the dodecahedron (dihedral angle) is calculated by the expression:

$$\theta = \arccos\left(\frac{\sqrt{5}}{5}\right) \approx 116.565^\circ \quad (4)$$

Accordingly, the rotation angle of the dodecahedron faces is approximately $\theta_2 = 180 - \theta = 63.435^\circ$. It is this angle that determines how the planes of the dodecahedron faces are “inclined” in space.

After construction, the regular dodecahedron is transformed into a small stellated dodecahedron by extending its edges until they intersect, that is, each face of the regular dodecahedron is replaced by a stellated pentagon. To simplify the construction, in this study we will consider the small stellated dodecahedron as a polyhedron formed by extending regular pentagonal pyramids on the faces of the dodecahedron.

The height H of the pyramid extended on a face of the dodecahedron with side b (Fig. 3.) is determined by the formula:

$$H = \frac{b}{\tan(\beta)} = 1.376382 \ b \quad (5)$$

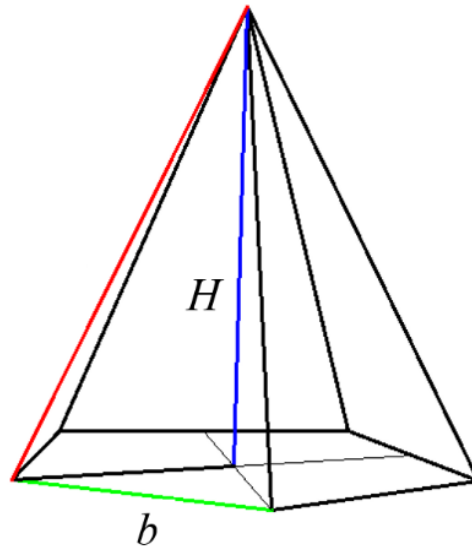


Fig. 3. Structure of the “Extended Pyramid” on a Dodecahedron Face

The radius of the circumscribed sphere of the small stellated dodecahedron is calculated using the following formula:

$$R_S = \frac{\sqrt{50 + 22\sqrt{5}}}{4} b \approx 2.489898 \ b \quad (6)$$

where b is the edge length of the pentagon.

Accordingly, the diameter of the circumscribed sphere of the small stellated dodecahedron is given by:

$$D_S = \frac{\sqrt{50 + 22\sqrt{5}}}{2} b \approx 4.979797 \ b \quad (7)$$

The overall dimensions of the small stellated dodecahedron, which are important for 3D printing, can be approximately determined from the diameter of its circumscribed sphere as $D_S \times D_S \times D_S$.

Based on the pentagon edge length b of its face, the presented mathematical model (1-7) makes it possible to calculate the main geometric dimensions of the small stellated dodecahedron, which are sufficient for its construction. However, the considered mathematical model also makes it possible to determine the dimensions of the small stellated dodecahedron based on the radius R_D of the circumscribed sphere or its other geometric parameters.

4.3. Stage 2. Construction of the 3D Model

At this stage, the technological design of the small stellated dodecahedron is carried out using three-dimensional computer modeling tools. First, drawings of the regular dodecahedron and its three-dimensional model are constructed. After that, the 3D model of the regular dodecahedron is transformed into a 3D model of the stellated dodecahedron by “extruding” the faces of the regular dodecahedron into pyramids. The practical construction of the regular dodecahedron is performed in the AutoCAD 2019 (system version 23.0) computer-aided design system. The drawing of the regular dodecahedron is created on the basis of its known dimensions in the following hierarchical sequence.

1. Wireframe model level, which consists only of vertices and edges. The wireframe model is constructed in the following sequence:

Step 1. Construction of geometric primitives. A face of the dodecahedron is constructed as a polygon (regular pentagon) with an edge length b , inscribed in a circle of radius r (2) (Fig. 4a).

Step 2. Construction of groups of geometric primitives. Adjacent faces are connected so that their planes form a dihedral angle $\theta = 116.565^\circ$ with each other (Fig. 3b–c).

Step 3. Construction of the wireframe model of the regular dodecahedron (Fig. 4d), which is obtained by combining groups of geometric primitives (the lower and upper parts of the model).

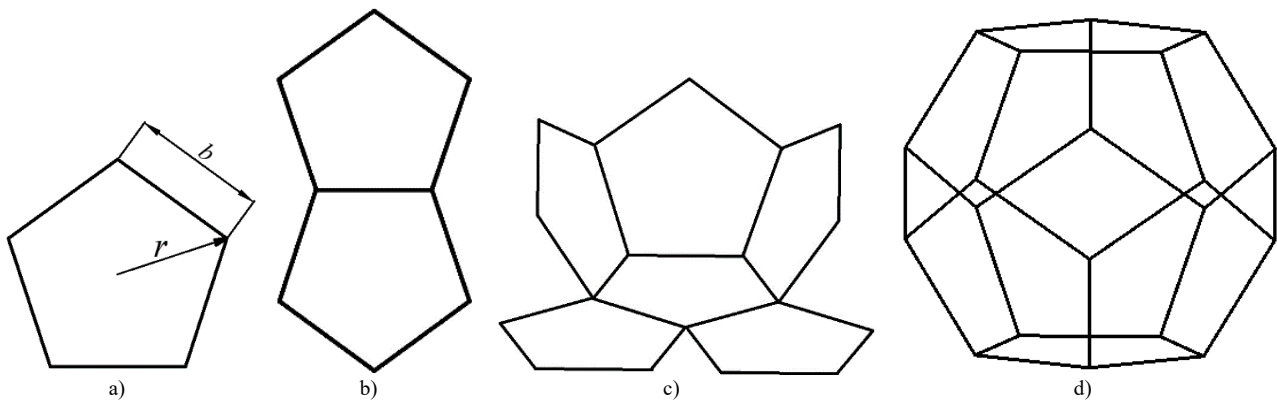


Fig. 4. Creation of the wireframe model of the dodecahedron: (a) regular pentagon, $r = 100$ mm; (b) joining two faces; (c) construction of the lower part of the wireframe model; (d) wireframe model of the dodecahedron

2. Surface (polygonal) model level, which consists of polygons (pentagons).

Step 1. Construction of the surface model of the regular dodecahedron by forming a surface (as a fragment of a plane) for each face. The color of the surface material is set (Fig. 5a).

Step 2. Modification of the surface model. Construction of the surface model of the small stellated dodecahedron by “extruding” regular pentagonal pyramids of height H on each face of the regular dodecahedron (Fig. 5b)

Step 3. Changing the color of the surface material and lighting conditions (if necessary), visualization of the surface model of the small stellated dodecahedron.

Step 4. Saving the polygonal model to a file (for example, in .stl or .obj format).

Step 5. Correction of the polygonal model, for example, using the “Free Online STL Repair” web service by Formware [38]. Model correction can also be performed in the Repetier-Host environment or in the Meshmixer software package (by Autodesk).

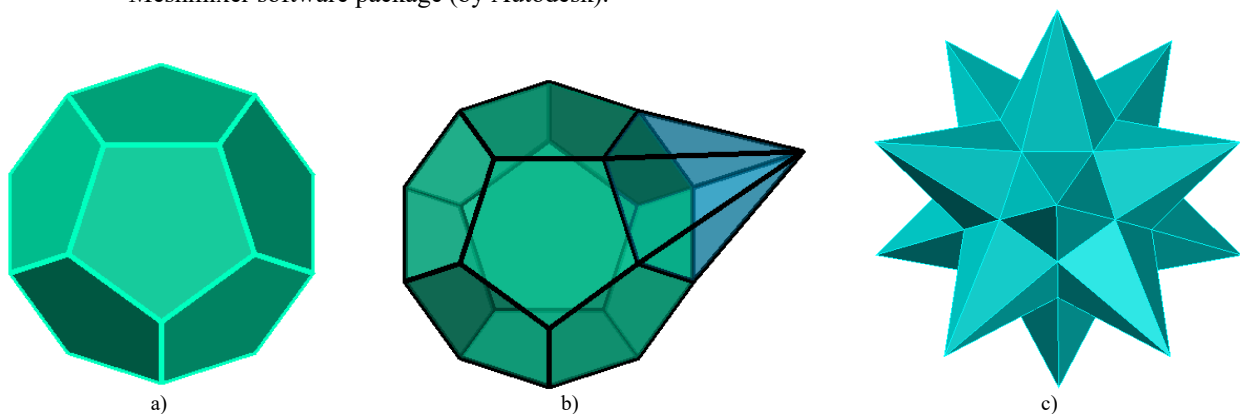


Fig. 5. Process of constructing the surface model: (a) regular dodecahedron; (b) regular pentagonal pyramids on the faces of the regular dodecahedron; (c) small stellated dodecahedron

3. Solid (volumetric) model level, which contains not only the shell but also a filled internal structure. During the correction of the surface model, a 3D model with a closed volume (watertight solid) is obtained, which is suitable for 3D printing. Therefore, the creation of a solid (volumetric) model is not mandatory.

4.4. Stage 3. Additive Manufacturing

This stage consists of 3D printing the solid (volumetric) model of the object and includes the following steps [39].

Step 1. Decomposition (cutting) of the solid model into parts is performed if the dimensions of the model exceed those permitted for the selected 3D printer or if the model does not contain sufficiently large flat areas (for reliable contact with the surface of the 3D printer platform (bed)). In the considered case, the 3D model of the small stellated dodecahedron does not contain flat areas for contact with the platform (the pyramid faces cannot be used for this purpose because, in this case, the other pyramids would interfere). Printing such a model on an FDM (Fused Deposition Modeling) 3D printer as a single object is a complex task that requires a significant number of mechanical supports for the 3D model and does not guarantee an accurate printing result [42]. Therefore, to simplify printing, the three-dimensional model is divided (cut) into parts by planes. The resulting cutting planes are used as the bases from which printing begins.

The three-dimensional model of the small stellated dodecahedron was divided in half, resulting in two symmetrical parts with flat sides (Fig. 6., Fig. 7.). The overhanging parts of the model halves are inclined to the plane of the 3D printer bed at angles that exceed the threshold (45°) and do not require the generation of additional supports.

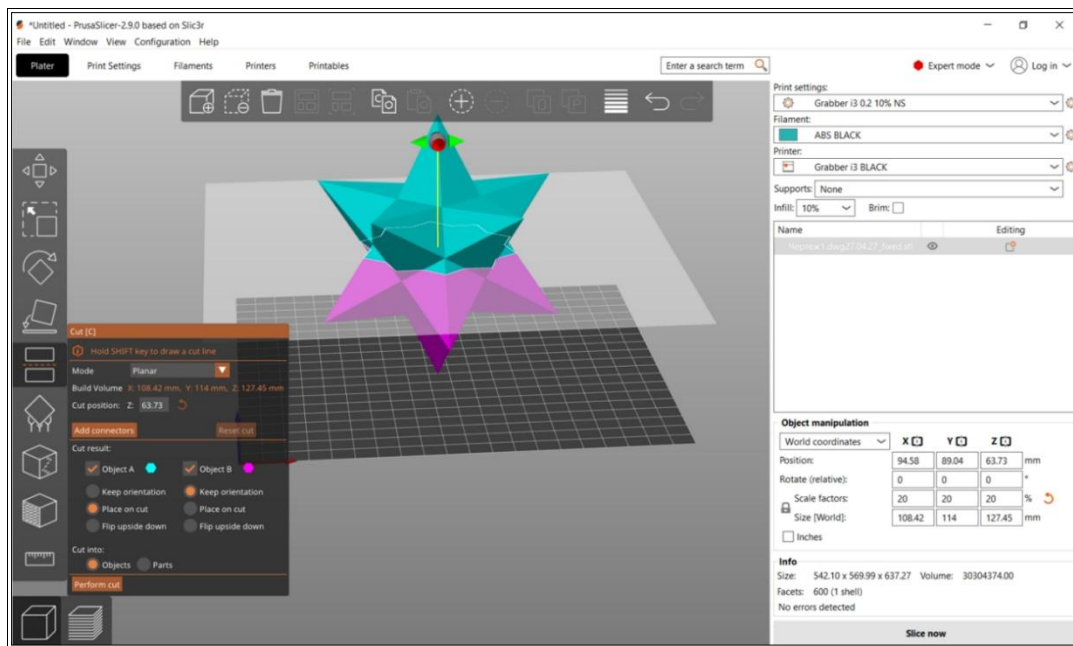


Fig. 6. Process of Cutting the Three-Dimensional Model in Half in PrusaSlicer 2.9.0

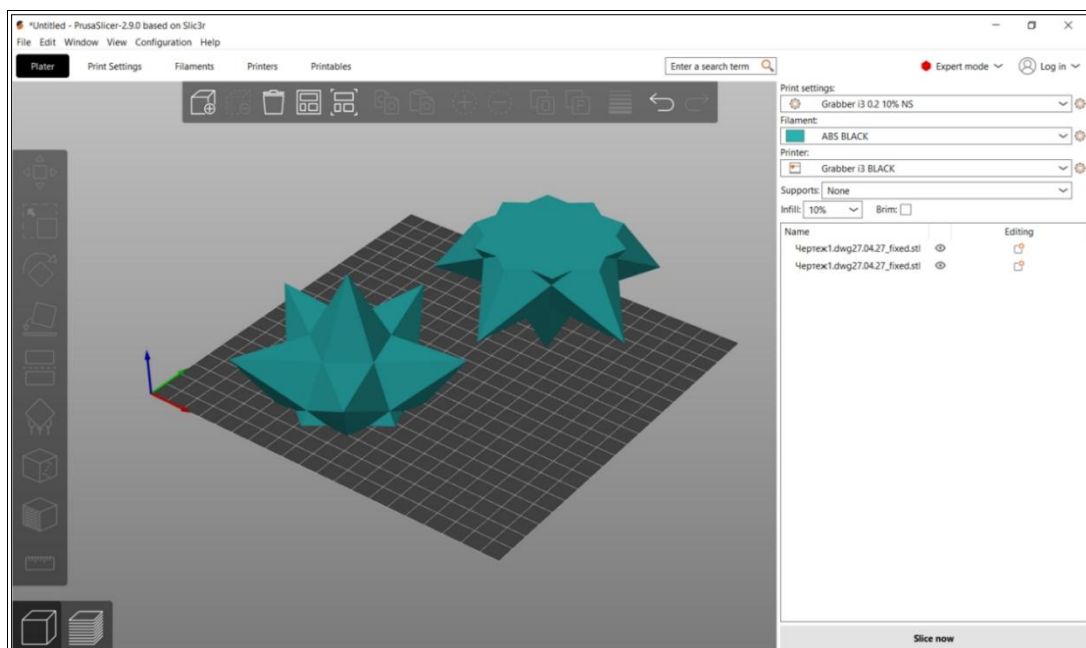


Fig. 7. Model of the Small Stellated Dodecahedron Cut in Half in PrusaSlicer

Step 2. Preparation of the three-dimensional model for printing on a 3D printer consists of dividing the 3D model into layers (slicing into layers), according to which printing is subsequently performed (Fig. 8.). The slicing result is saved as a text task file for 3D printing in g-code format.

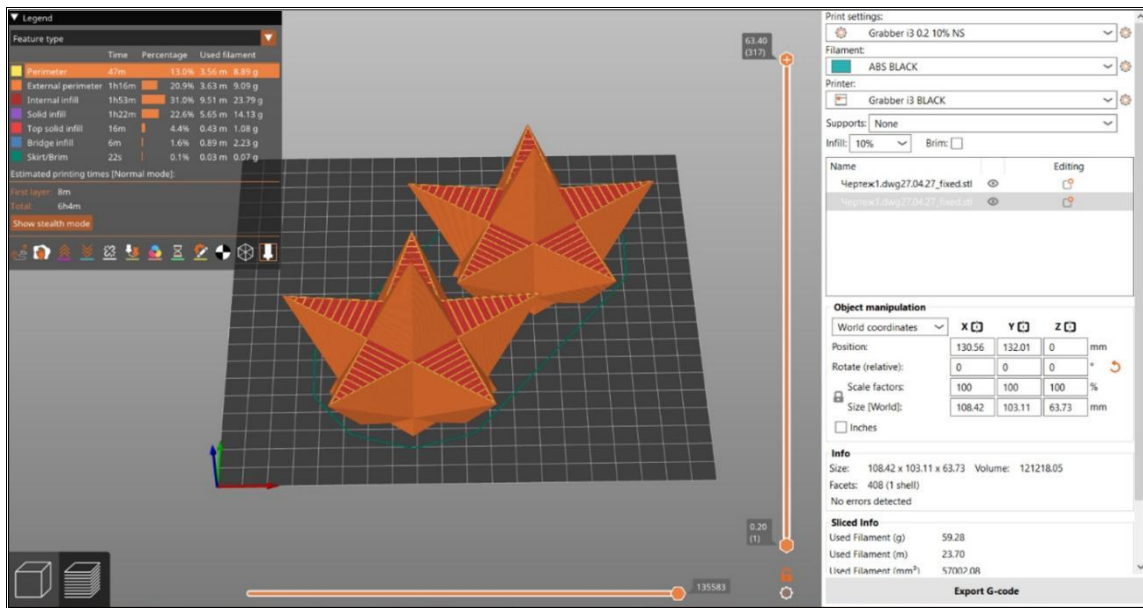


Fig. 8. Model of the Stellated Dodecahedron Sliced for Printing in PrusaSlicer

Step 3. Printing the three-dimensional model on a 3D printer is performed in the Repetier-Host environment. Based on the loaded model in g-code format, a print task is generated and uploaded to the 3D printer print server (Fig. 9.). After that, the model is printed layer by layer (Fig. 10a, b).

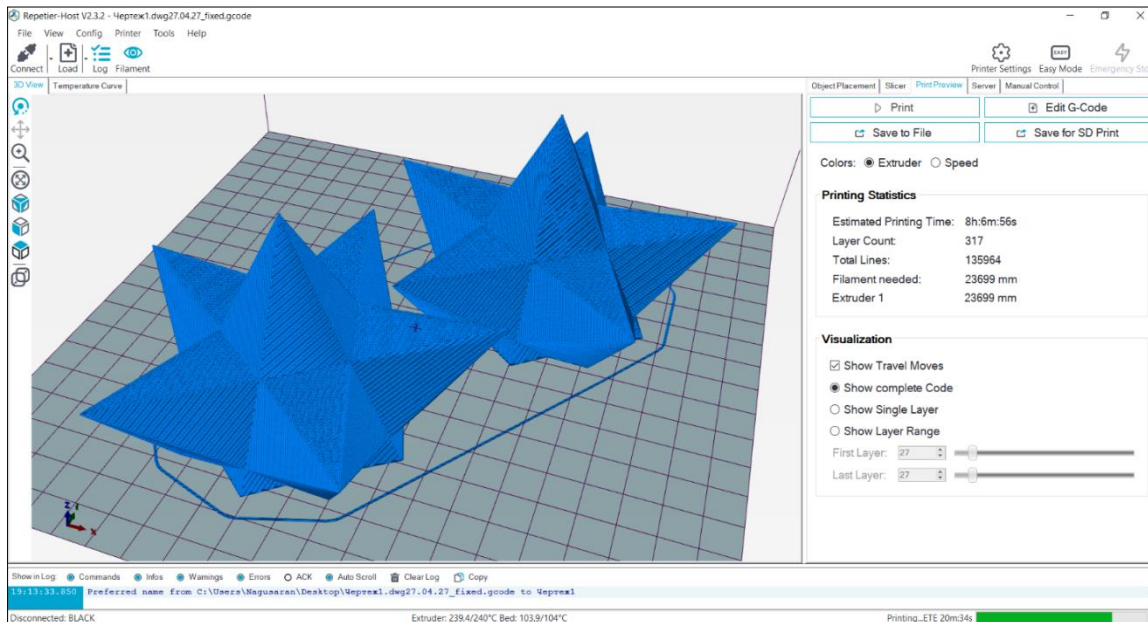


Fig. 9. Repetier-Host V2.3.2 Environment with the Loaded Print Task

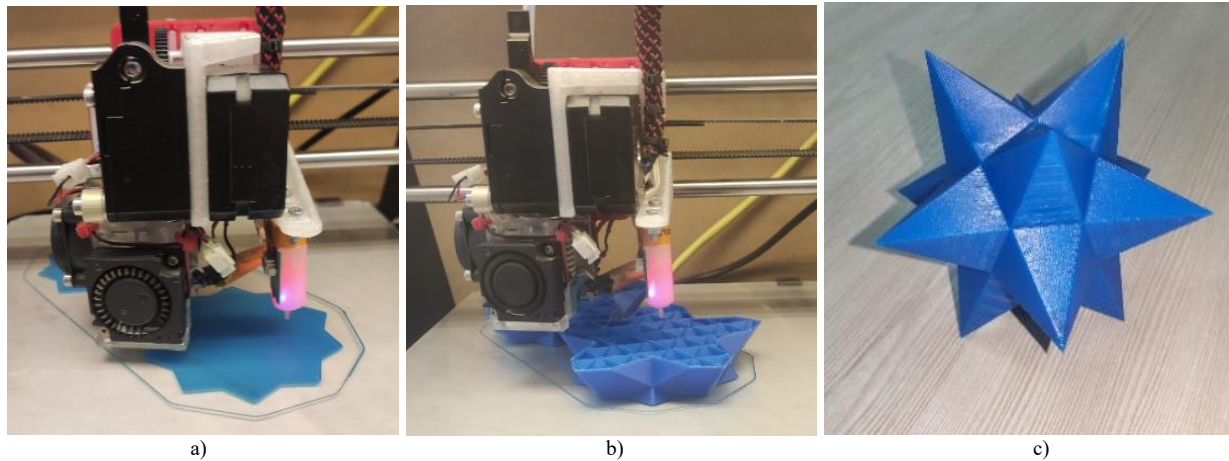


Fig. 10. Beginning of Dodecahedron Printing (a), Printing of a Part of the Dodecahedron (b), and the Completed Model after Gluing (c)

- Step 4. Post-processing of the printed 3D model. Since the model was printed in parts, after printing is completed, these parts are glued together (the gluing method depends on the material of the part). As a result of post-processing, a finished physical model of the small stellated dodecahedron is obtained (Fig. 10c), which corresponds to its mathematical model and can be used, in particular, for educational purposes.

4.5. Stage 4. 3D Model Validation

At this stage, the dimensions of the printed 3D model are compared with the dimensions of the object specified in its digital model. The 3D model is inspected in both manual and automated modes. In manual mode, the STEM project participants directly measure the main dimensions of the physical model using measuring instruments (a vernier caliper).

For the physical model of the small stellated dodecahedron (Fig. 10c), the pentagon edge length (b) and the diameter of the circumscribed sphere D_S (7), which represents its overall dimension, are measured. In the considered case, the digital model has a circumscribed sphere diameter of $D_S = 127.45$ mm (Fig. 6.) and a pentagon edge length of $b = 25.59$ mm. Measurements of the physical model (Fig. 10c) yielded an experimental value of the circumscribed sphere diameter of $D_{SE} = 127.2$ mm and a pentagon edge length of $b_E = 25.3$ mm. Thus, the dimensional deviation of the printed three-dimensional model is approximately 0.3 mm.

In automated mode, the dimensions of the physical 3D model are determined through the computational analysis of its digital images using photogrammetry. For this purpose, the 3D model is placed at a specified distance from a video camera, for example, at the center of a rotary platform. An object with known dimensions, such as a measuring ruler, is placed at the same distance from the camera near the 3D model and is used to determine the scale of the objects in the image. The actual dimensions of the objects are determined based on their dimensions in the image (the dimensions of the investigated object segment in pixels) and the corresponding image scale. After calibration, the dimensions of the objects can be determined automatically with an error comparable to that obtained through manual measurements.

5. Conclusion and Future Research Directions

The study developed a methodology for modeling and manufacturing three-dimensional geometric figures, which can be applied for the STEM training of future specialists in engineering specialties. The theoretical basis of the methodology is the clear structuring and methodological substantiation of the process of implementing STEM projects. The methodology includes a preparatory stage, during which the project task is formulated, and four main Stages 1–4.

Stage 1 consists of designing the object model, and its components include collecting information about the object and creating its mathematical model. The mathematical model is used to calculate the parameters of the investigated object (part).

Stage 2 is intended for the computer-aided construction of a three-dimensional model of the object, the parameters of which are determined during Stage 1. The construction of drawings and the 3D model of the object is performed in the selected environment, for example, in the AutoCAD computer-aided design (CAD) system. Based on the calculated parameters of the object, its 3D models are constructed: wireframe, surface, and solid.

At Stage 3, additive manufacturing is implemented, that is, the manufacture of a prototype of the investigated object by means of 3D printing. For large models or models with shapes that are difficult to print, decomposition (cutting) of the model into parts is performed. After 3D printing, the parts of the model are joined, and post-processing of the physical prototype is carried out.

At Stage 4, control (validation) of the physical 3D model is performed. The conformity of the physical model of the object printed on a 3D printer with its software model is analyzed. The models are compared, in particular, by analyzing

their photographs using digital image processing methods. A visual assessment of the physical model and measurements of its main dimensions are also performed.

The developed methodology was tested in the manufacture of a model of the small stellated dodecahedron; however, it can be applied to the manufacture of physical prototypes with different geometries. A promising direction for further research is the automatic decomposition of 3D models, which is especially important for models with complex shapes. The methodology for modeling and manufacturing was developed for students of engineering specialties. However, this methodology takes into account the main trends in STEM education and therefore can also be adapted for students of pedagogical specialties.

All the Declarations and Statements

Author Contributions Statement

Oleksandr Derevyanchuk – Conceptualization, Methodology, and Supervision: Proposed research ideas, Constructed the overall framework, and supervised project execution.

Serhiy Balovsyak – Data Curation and Software Implementation, and Supervision: Proposed research ideas, Handled data acquisition, dataset preprocessing, and implementing the research model.

Nataliia Ridei – Writing – Review and Editing, and Project Management: Reviewed and edited the manuscript, and supervised project execution.

Mickolay Dominikov – Modeling and Visualization: Developed three-dimensional models of the investigated object and prepared their visual representations.

Hanna Kravchenko – Writing – Review and Editing, and Project Management: Reviewed and edited the manuscript, ensured clarity and coherence.

Oleksii Pshenychnyi – Writing – Original Draft and 3D Printing: Drafted the initial manuscript, contributed to the literature survey, documented the technical background of the study, and performed 3D printing.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Funding Declaration

This research was not supported by a grant.

Data Availability Statement

This study did not use publicly available datasets.

Ethical Declarations

Statements of ethical approval for studies involving human subjects and/or animals.

Acknowledgments

We sincerely thank the experts for their professional evaluation and valuable recommendations, which have contributed to improving the quality of the experiment and the reliability of its results.

Declaration of Generative AI in Scholarly Writing

AI and AI-assisted technologies were not used during the writing process.

Abbreviations

The following abbreviations are used in this manuscript:

3D – 3-dimensional

CAD – computer-aided design

FDM – Fused Deposition Modeling

STEM – Science, Technology, Engineering, Mathematics

Appendix A/B/C..., with appendix title

N/A.

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How to cite this paper

Oleksandr Derevyanchuk, Serhiy Balovsyak, Nataliia Ridei, Mickolay Dominikov, Hanna Kravchenko, Oleksii Pshenychnyi, "Modeling and Manufacturing 3D Geometric Figures for STEM Training of Engineering Students: A Staged Methodology and Case Study", International Journal of Engineering and Manufacturing (IJEM), Vol.16, No.5, pp. 60-74, 2026. DOI:10.5815/ijem.2026.05.03