FUSED FILAMENT FABRICATION IN CAD EDUCATION: A CLOSED-LOOP APPROACH

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Abstract:

Integrating low-cost Fused Filament Fabrication (FFF) 3D printing as a foundation for learning 3D modeling is explored. This method blends traditional Computer Aided Design (CAD) instruction with additive manufacturing possibilities. Experimental results demonstrate increased comprehension speed and reduced learning time. This hands-on approach empowers students by enabling direct engagement with the modeling process. Analogous to reverse engineering, the strategy instructs engineering students from final product to model creation, closing the gap between theory and practice. Incorporating 3D printing bridges this divide, enhancing understanding, creativity, and problem-solving. The study underscores technology's influence on learning strategies, aligning with the surge of 3D printing in education. Results link advanced design technology usage to improved student performance, with 3D-printed materials yielding 45% higher grades and 30% faster task completion. This study advocates curricular advancement for design-focused careers through enhanced technology integration and favorable 3D printing model reception.

Keywords 3D Printing, 3D Modelling, Computer Aided Design Education, Prototyping, 3D Visualization

Introduction

The development of additive manufacturing, sometimes referred to as 3D printing, has the potential to completely alter how items are created, produced, and distributed. With additive manufacturing, objects are constructed layer by layer using digital 3D models as a blueprint instead of traditional manufacturing procedures, which use subtractive processes, where the material is removed to generate the desired shape. This cutting-edge strategy has several benefits and is changing industries around the world.

Additive manufacturing allows for the creation of complex geometries and intricate designs. In terms of product innovation and customization, this opens up new possibilities. Additive manufacturing reduces material waste because it only uses the necessary amount of material. The technology can work with various materials, including ceramics, metals, and biological materials. Diverse applications can be achieved with this versatility.

Furthermore, additive manufacturing has made significant advancements in the medical field, enabling personalized healthcare solutions and even bio-printing of tissues and organs. Finally, additive manufacturing disrupts traditional supply chains by allowing on-site production and decentralized manufacturing, leading to faster response times and reduced logistics requirements. Additive manufacturing revolutionizes production by offering greater design freedom, waste reduction, versatility, and improved supply chain efficiency.

ASTM (American Society for Testing and Materials) has established a classification system for additive manufacturing methods, as outlined in the ASTM F2792 - 12(2018) standard. This system categorizes additive manufacturing processes into seven groups based on their underlying technology and materials. The classifications are as follows: Vat Photopolymerization (VPP), Material Jetting (MJ), Binder Jetting (BJ), Material Extrusion (ME), Powder Bed Fusion (PBF), Sheet Lamination (SL), and Directed Energy Deposition (DED). VPP involves the selective curing of liquid photopolymer resin, while MJ uses droplets of material to build objects. BJ deposits a binding agent onto powdered material, I extrude semi-liquid or solid material through a nozzle, and PBF selectively melts or sintered. SL bonds sheets of material together, and DED utilizes focused thermal energy to deposit and melt materials. These classifications provide a comprehensive framework for understanding and categorizing different additive manufacturing methods.

Fused Filament Fabrication (FFF), or Fused Deposition Modeling (FDM), is a material extrusion process in additive manufacturing. It involves the deposition of a thermoplastic filament through a heated nozzle, where it is melted and extruded onto a build platform or previous layers. The material quickly solidifies layer by layer to create a three-dimensional object. FFF is known for its simplicity, affordability, and versatility with various thermoplastic materials, making it widely used for prototyping, rapid tooling, and end-use part production. While it may have limitations in achieving high levels of detail and surface finish, FFF remains a popular and accessible method in additive manufacturing.

The Generalized Additive Manufacturing Process Chain (GAMPC) is a comprehensive framework for understanding additive manufacturing workflows. It includes design, pre-processing, printing, post-processing, and quality assurance stages, each playing a crucial role in successful 3D printing. The design stage involves creating 3D models optimized for additive manufacturing. Pre-processing prepares the CAD model for printing by slicing, determining parameters, and generating toolpaths. The object is created using various technologies. Post-processing refines printed parts through support removal, finishing, and additional treatments. Reliability is ensured through inspection and testing. This process flow is depicted in Fig. 1.

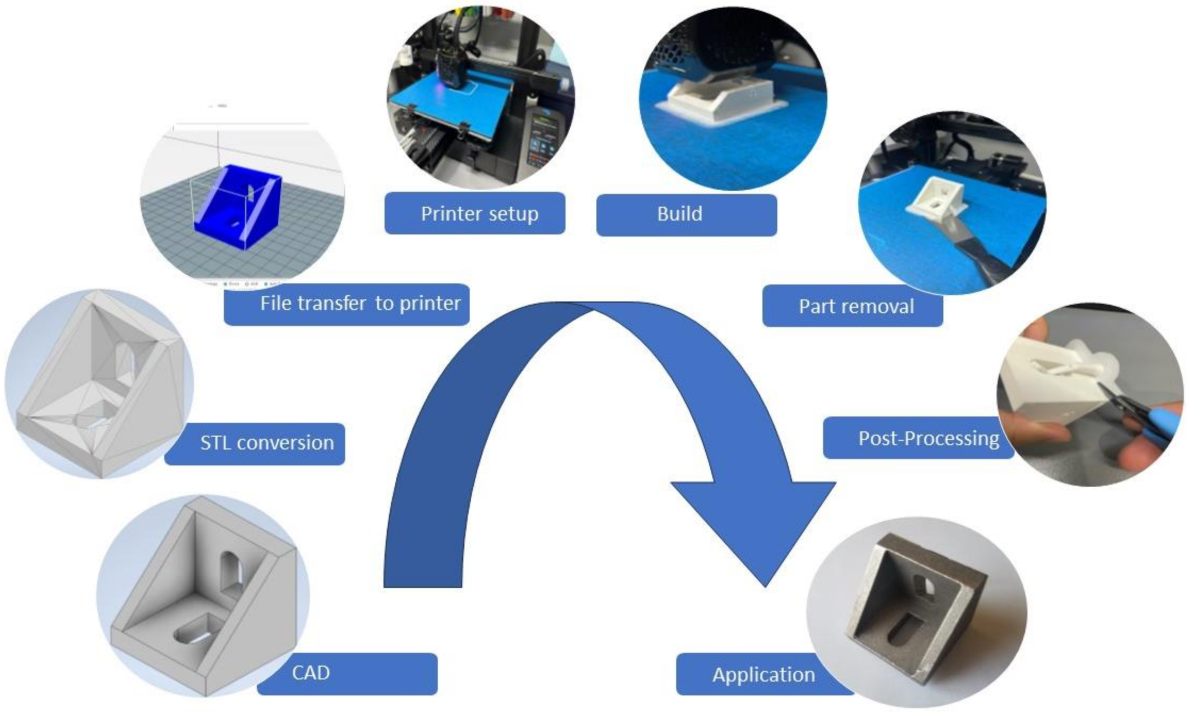


Fig.1. Additive manufacturing process flow

Developing an idea for the product's appearance and functionality is the first step in product development. The process of conceptualization, also known as ideation, can be expressed in various ways, including narrative and textual descriptions, sketches, and models that serve as exemplars. If additive manufacturing is to be used, the product description must be in a digital format that enables the creation of a physical model. Although additive manufacturing (AM) technology may only be used to prototype rather than produce the final product, there are many stages in the product development process where digital models are necessary.

If 3D CAD did not exist, AM technology would not be possible. We couldn't create technology to physically duplicate such objects until we could represent solid objects in computers. This was initially the guiding principle for CNC machining technology in general. Thus, AM can be thought of as a streamlined or direct CAD/Computer Aided Manufacturing (CAM) process. For AM, there is little to no intervention between the design and manufacturing stages, in contrast to the majority of other CAD/CAM technologies.

The first step of the generic AM process is to have 3D CAD information, as shown in Fig.1. There are different methods for creating the 3D source data, such as using a user interface to design it, using software to generate it as part of an optimization algorithm, using 3D scanning to capture it from an existing physical part, or using a combination of any of these. Most 3D CAD systems are based on solid modeling with some surface modeling components; solid models are often made by connecting surfaces or giving thickness to a surface. Thus, to make a 3D printed part, one needs some minimum CAD knowledge and more is beneficial.

Computer Aided Design (CAD) and modeling have revolutionized the field of design and engineering, empowering professionals to create and innovate with unprecedented precision and efficiency. CAD and modeling unleash creativity, providing design freedom and exploring complex geometries. They offer precision and accuracy through measurement tools and parametric modeling. Efficiency and time savings are achieved through quick iterations and collaboration. Simulation tools aid in predicting performance, and integration with manufacturing technologies streamlines the transition from digital to physical.

CAD education plays a critical role in equipping engineering students with the necessary skills and knowledge to excel in their careers. By providing proficiency in CAD software, instilling design principles, fostering interdisciplinary collaboration, and integrating simulation tools, mechanical engineering programs can empower future engineers to embrace the challenges and opportunities in the rapidly evolving world of design and manufacturing.

Traditional CAD teaching methods often face several challenges that the 3D printing in CAD education method aims to overcome. In conventional instruction, the learning curve for CAD software can be steep, potentially leading to student frustration and slower comprehension. Moreover, traditional CAD instruction often relies heavily on theoretical explanations and lacks practical, hands-on engagement, potentially resulting in a disconnect between theoretical knowledge and real-world applications. Additionally, traditional CAD teaching may struggle to cater to diverse learning styles and preferences, as it primarily offers a one-size-fits-all approach. This could hinder some students from fully grasping complex 3D modeling concepts, limiting their creative potential.

The suggested approach, which integrates low-cost 3D printing as a foundation for learning CAD, addresses these limitations. By combining CAD teaching with practical additive manufacturing experiences, it bridges the gap between theory and practice. This hands-on engagement empowers students to learn through direct interaction with the modeling process, enhancing their understanding and fostering creativity. Moreover, the approach leverages the familiarity and tactile nature of 3D printing to make 3D modeling concepts more accessible and engaging, potentially addressing the diverse learning needs of students.

In the realm of CAD (Computer Aided Design), there are two distinct imagination difficulties that individuals may encounter: transitioning from 2D to 3D visualization and, vice versa, from 3D to 2D visualization. When working with 2D representations in CAD, such as sketches or technical drawings, individuals often face challenges in visualizing and conceptualizing the three-dimensional aspects of the design. Converting a flat, two-dimensional image into a fully realized, three-dimensional object requires the ability to extrapolate depth, scale, and spatial relationships mentally. On the other hand, transitioning from a 3D CAD model to a 2D representation, such as a technical drawing or engineering diagram, can also present imagination challenges. Drawing upon the authors' wealth of experience spanning decades in education and industry, a distinct practice emerges: while 3D-to-2D representation finds application in the design phases of parts or products, the transition from 2D to 3D visualization takes precedence within the production environment.

This study introduces the "closed-loop approach" in CAD education to overcome the difficulties listed previously by beginning with 3D printing and moving backward to Computer Aided Modeling. It emphasizes the importance of closing the loop by returning to 3D printing to validate the knowledge gained. By sharing experiences and insights, this study demonstrates the effectiveness of this approach in reinforcing understanding and practical application in CAD education.

Literature Review

As technological advances continue to shape the industry, engineering education, being the foundation of the industry, is significantly influenced by these changes. The study performed by Broo et al. l. explores the impact of technological changes on digital transformation, Industry 4.0, and the emergence of Industry 5.0, highlighting the need for reimagining engineering education by focusing on skills rather than degrees and proposing strategies such as lifelong learning, transdisciplinary teaching, sustainability and human-centric design, hands-on data fluency and management, and human-agent interaction [1]. Technological progress has significantly impacted various sectors, including education, leading to the emergence of Education 4.0, which combines current and emerging technologies with innovative pedagogical practices, proposing four core components (competencies, learning methods, ICT, and infrastructure) and showcasing case studies in Engineering Education to demonstrate their application in program design [2]. Work by Bengu and Keçeci examines the impact of maker spaces on engineering students' learning experiences. It highlights the importance of hands-on experience in addition to theoretical knowledge, emphasizing the development of soft skills and the need for more practical learning opportunities in engineering education [3]. Another study by Catal and Tekinerdoğan explores the challenges and opportunities presented by disruptive technologies, particularly in the agricultural and food sciences. It discusses the need to adapt the current curriculum to reflect these technological innovations and promote the development of both left-brain and right-brain skills, using Wageningen University as a case study and emphasizing the integration of IT and Artificial Intelligence, as well as project-based evaluations and skills such as critical thinking, creativity, and problem-solving [4]. The study by Lantada introduces the concept of "Engineering Education 5.0," a future educational paradigm that goes beyond current trends and industry-driven approaches, emphasizing the importance of ethics, humanism, and sustainability in engineering education [5].

Information Technology (IT) and computers are pivotal in engineering education. They provide essential tools, simulations, and resources that enhance learning, problem-solving skills, and the ability to navigate complex engineering concepts and systems. Modern IT in education primarily serves as a tool for teachers to enhance the teaching process, rather than being a technology that students learn directly, with the teacher's role being to utilize and integrate these technologies effectively to improve the educational content and monitor student knowledge [6]. The article by Sevgi and Uluisik discusses the need to balance virtual and real labs in engineering education due to the increasing complexity and cost associated with high-technology devices. It introduces a virtual instrumentation tool that can be used for numerical Fourier transform calculations and as an educational tool [7]. The research work by Hernandez-de-Menendez and Morales-Menendez provides a review of available information and communication technologies (ICTs) that can enhance the learning experience of millennial students in higher education institutions, specifically in the field of engineering, offering insights into innovative technological tools, trends, and teaching practices employed by selected universities for successful engineering education [8].

The emergence of virtual reality (VR) and augmented reality (AR) has revolutionized engineering education by providing immersive and interactive learning experiences, allowing students to visualize complex concepts, simulate real-world scenarios, and enhance their understanding and problem-solving abilities. The paper by Soliman et al. argues that advancements in virtual reality (VR) technology have led to a shift towards its use in engineering education, providing evidence of positive cognitive and pedagogical benefits, improved understanding, performance, and grades for students, reduced liability and costs for institutions, and equal educational opportunities for special needs and distance learning students, while emphasizing the importance of integrating learning theories in the design of VR applications, particularly constructivist and various learning theories in engineering education [9]. The study by Vergara et al. examines the assessment of engineering professors from different nationalities and universities regarding the use of virtual reality (VR) technologies in the classroom, highlighting gaps in these evaluations based on university ownership and other demographic factors, finding that while professors generally view VR as a valuable didactic tool, there is a lack of knowledge and specific training on its use, and a discrepancy between private and public university professors' evaluations of VR [10]. In addition, the study by Takrouri et al. also reviews the current usage of augmented reality (AR) in engineering education, emphasizing its potential benefits in improving student engagement and visualizing complex engineering concepts while discussing the challenges that hinder its broader integration into engineering curricula [11].

The involvement of 3D printing in education has opened up new possibilities for hands-on learning, fostering creativity, critical thinking, and problem-solving skills as students can transform digital designs into tangible objects, encouraging a deeper understanding of various subjects. The research by Yüksel et al. examines the perspectives of teachers and students regarding the educational benefits of using 3D design programs and 3D printers, finding that these technologies significantly contribute to students' knowledge and skill development, motivating them in the project production process and enabling them to create and print their own course materials [12]. The article by Koliasa highlights the importance of enhancing the formation methods of graphic competence among future engineering teachers using digital technologies, emphasizing the need to improve the teaching methods of disciplines such as "Engineering Computer Graphics" to include two-dimensional graphics, three-dimensional spatial modeling, 3D printing technologies, and the creation of 4D objects in KOMPAS-3D, to better prepare teachers in the field of digital Technologies [13]. Another perspective article describes the development of a 3D Printing Ecosystem (3DPE) designed to facilitate STEAM education by integrating CAD and 3D printing (3DP) across disciplines, offering faculty training and curricular support for project-based learning, and providing examples and guidance for implementing similar models [14]. The review article by Ng et al. examines the existing literature on the application of 3D printing in mathematics education, highlighting its potential to enhance students' mathematical and design thinking skills, as well as digital skills and mindsets, while addressing challenges related to hardware, software, and maintenance issues, and providing recommendations for future research and implementation [15]. A couple of studies about 3D printing gives insights about the current status, methodology applications and future aspects of the FDM or FFF and low cost filament characterization method[16][17].

3D printing has found applications in a wide range of educational subjects, including English teaching. In an exciting study, the application of Internet + 3D printing technology in English teaching by constructing a framework of learning activity design, emphasizing the effectiveness of the Internet + flipped classroom teaching model and the need to adapt teaching methods based on different situations to enhance students' knowledge acquisition and skill utilization [18]. The review by Pearson and Dubé identifies five dominant theoretical approaches and learning outcomes associated with 3D printing in education, including situated learning, experiential learning, critical making, constructionism, and self-directed learning, with learning outcomes such as critical thinking, creativity, design thinking, and collaboration, providing recommendations for educators on implementing 3D printing in the classroom [19]. The paper by Novotný et al. discusses technical project-based learning, explicitly focusing on 3D printing, as an alternative form of schooling for technical experts studying at a university. It presents a case study where students are encouraged to create their 3D printer and use it to recreate a model of a historically significant but destroyed church, highlighting the cross-disciplinary cooperation involved [20].

3D printing is essential in Mechanical Engineering Education, as it enables students to prototype and manufacture complex components, fostering practical skills, design optimization, and innovation in the field. The work by Powar and Patil explores the integration of 3D printing technology and project-based learning in engineering education to enhance students' understanding of internal combustion engines, resulting in improved examination performance and the development of professional skills, fostering multidisciplinary learning opportunities and lifelong learning [21]. The study by Solikin et al. focuses on developing portable and lightweight learning media using 3D printing technology with Polylactic Acid as the base material, specifically targeting Light Vehicle Engineering Vocational School students to support online learning during the Covid-19 pandemic to explain the competency of a 2-stroke engine in a distance learning setting [22]. The work by Sharma et al. focuses on the challenges and approaches involved in teaching machine drawing skills online, highlighting the need for knowledge sharing, adopting a maker education perspective, and drawing conclusions regarding the online pedagogy of spatial visualization-based courses like machine drawing [23]. The paper by Cheng et al. describes the implementation of a Project-based Learning approach in the Engineering

Design Graphics (EDG) course at the Escola Politécnica of the University of São Paulo, including the use of flipped classroom methodology, readiness assessments, and CAD systems for modeling, simulation, and prototyping through laser cutting and 3D printing, while highlighting the course reformulation, content, activities, and addressing the challenges and solutions encountered [24]. Another study have shown that locating the shear or flexural center in non-symmetric cross-sectional beams, essential in structural mechanics education, enables assessing bending and torsion resistance, especially in aerospace, now facilitated by 3D printing for tactile demonstration [25]. An article by R. K. Bradly discusses the creation and use of ease of injection molded parts in education [26].

3D modeling and technical drawing serve as integral components in engineering, providing the means to conceptualize and communicate complex designs and structures visually. The study by Merzdorf et al. introduces the Object Assembly Sketching test, a new assessment tool for evaluating sketching skills in engineering through object assembly tasks, highlighting the importance of sketching for spatial abilities [27]. The paper by Li explores the integration of art education in engineering graphics teaching as a means to cultivate interdisciplinary talents, enhance artistic literacy, promote learning of projection theory and mapping knowledge, and proposes a systematic integration method of visual thinking and creative thinking, contributing to innovative education in engineering graphics [28]. The paper by Bartlett and Camba argues that common spatial skills tests rely on the ability to comprehend two-dimensional representations of three-dimensional objects and highlight the visual problems in the stimuli used in these tests. It also discusses studies demonstrating improved performance by enhancing the clarity and realism of the stimuli, suggesting that the graphical interpretation factor may introduce bias and reduce the validity of spatial skills assessments [29]. The study by Barison examines the experience of teaching Geometric Drawing, Descriptive Geometry, and Technical Drawing courses remotely during the COVID-19 pandemic, focusing on the planning process, challenges faced by teachers and students, and evaluating the effectiveness of the remote teaching methodology through student questionnaires conducted in 2020 and 2021 [30]. The research by Mavromihales et al., evaluates the effectiveness of games-based learning in a computer aided design and manufacture undergraduate module within the context of Mechanical Engineering Education, comparing the outcomes of an experimental group that used a games-based learning approach to a control group using conventional methods, and concludes that games-based learning has the potential to enhance the student experience and learning process in this subject area [31]. The study by Markopoulos et al., explores the incorporation of game mechanics in non-gaming sectors, focusing on its potential benefits in engineering education and professional practice. It evaluates relevant literature, discusses gamification's status, and explores its applications in education and manufacturing[32].

Dynamic models, mental cutting, and spatial thinking are thought to be the basics of engineering drawing and graphics. The paper by Almeida and Castro showcases the use of Geogebra® software to develop 3D dynamic models for online teaching of descriptive geometry, addressing challenging concepts in line-plane inclusion and projection plane changes, and the evaluation through a survey of descriptive geometry professors in Brazilian undergraduate courses, indicating that the 3D models are suitable for online teaching applications and support the development of visual skills in architecture and engineering courses, while also identifying areas for improvement [33]. In this paper by Tóth et al., the authors examine the Mental Cutting Test, a widely used method for assessing spatial skills, and investigate different shapes rendered with Blender for the test, identifying errors and developing a post-processing Python script to detect and correct these issues [34]. In their other work, they introduce a resource browser and a quiz application designed to support researchers, instructors, and students in enhancing their processes related to exercises like the Mental Cutting Test, providing a valuable toolset for developing and measuring spatial skills [35]. The study by Arce et al. demonstrates the successful implementation of the Design Sprint methodology in an Engineering Drawing classroom, promoting collaboration, critical thinking, and the integration of theory and practice, with positive student satisfaction and improved grades achieved through both in-person and remote learning environments. [36]. The work by Sharma and Kumar proposes a structured methodology to train engineering students in drawing and painting skills, specifically focusing on landscapes and nature, as a means to enhance their understanding of engineering concepts and improve performance in STEM courses, highlighting the importance of creativity in the post-digital era [37].

The previous research reveals that the proposed connection between 3D modeling, technical drawing education, and 3D printing has not been sufficiently established, as presented in this work. Nonetheless, introducing 3D printing as an initial step in the transition from 2D to 3D visualization and vice versa offers a fresh perspective on the concept of Model Centered Design (MCD).

Closed Loop Approach in CAD Education

In the realm of CAD, there are two distinct imagination difficulties that individuals may encounter: transitioning from 2D to 3D visualization and, vice versa, from 3D to 2D visualization.

When working with 2D representations in CAD, such as sketches or technical drawings, individuals often face challenges in visualizing and conceptualizing the three-dimensional aspects of the design. Converting a flat, two-dimensional image into a fully realized, three-dimensional object requires the ability to extrapolate depth, scale, and spatial relationships mentally. Some common difficulties include; depth perception, spatial relationships, and assembly and interference. Understanding the depth and perspective of a design can be challenging, mainly when relying solely on 2D representations. Visualizing how different components or features interact in three-dimensional space may require additional effort. Determining the exact positioning and orientation of various elements within a three-dimensional design can be complex. Translating 2D measurements and proportions into an accurate 3D representation requires the ability to visualize the object from different angles and perspectives. Visualizing how individual components fit together and interact within a three-dimensional assembly can be difficult. Understanding potential interference or clearance issues between other parts can be challenging when primarily working with 2D representations.

On the other hand, transitioning from a 3D CAD model to a 2D representation, such as a technical drawing or engineering diagram, can also present imagination challenges. Converting a complex, three-dimensional object into a simplified two-dimensional model involves difficulties like; projection and views, detail representation, and visualization of hidden features. Determining the appropriate projections and views to communicate the design in a 2D format accurately can be demanding. Choosing the right angles and perspectives to capture essential information and features while omitting unnecessary details requires a thorough understanding of the design and its intended purpose. Representing the necessary details and dimensions accurately in a 2D format can be challenging. Conveying the three-dimensional aspects, such as curves, fillets, and complex surfaces, in a clear and concise manner requires careful consideration and skill in drafting techniques. Depicting hidden or obscured features, such as internal components or assemblies, can pose difficulties in 2D representations. Ensuring that critical information is appropriately communicated and understood by the end-users becomes crucial in such cases.

Teaching Methodologies for Dimensional Transition:

Generalized methods of dimensional transitioning education, moving from 2D to 3D imagination and back is combined in the 3D modeling and technical drawing textbook by Bertoline et al. follows [38]:

- Projection Studies
- Physical Model Construction

- Adjacent Areas
- Similar Shapes
- Surface Labeling
- Missing Lines
- Vertex Labeling
- Analysis by Solids
- Analysis by Surfaces

While traditional methods in engineering modeling and technical drawing education heavily rely on 2D representation and drawing, Physical Model Construction emerges as a unique approach that utilizes 3D space and real-life, hands-on application, employing materials like clay, wax, or Styrofoam to create models; this method is recommended in combination with Analysis of Solids to deconstruct objects into basic geometric primitives and subsequently reassemble them. By harnessing the potential of 3D printing, it becomes possible to extend and combine the aforementioned methods, presenting an opportunity for accelerated learning and a comprehensive approach, integrating all aspects into a single holistic method that is both cost-effective and efficient.

Overcoming these imagination difficulties requires practice, experience, and a strong grasp of spatial relationships and visualization techniques. Employing visualization aids, such as 3D rendering or virtual reality, can also help bridge the gap between 2D and 3D representations, allowing for more seamless design interpretation and communication in the field of CAD. Here we are introducing a novel methodology of "closed loop reverse engineering approach" in CAD education.

The reverse engineering analogy draws upon the process inherent to technical disciplines, where engineers break down intricate systems to understand their components, functionalities, and underlying principles. In this context, the application of reverse engineering involves dissecting a complex object, often without access to its original design, to unravel its architecture and functionality[39].

Similarly, within educational methodologies, the concept of reverse engineering finds resonance in the deconstruction of intricate concepts and subjects to facilitate comprehensive learning. By viewing educational content as a multifaceted system, educators can metaphorically disassemble it into smaller, manageable components. This enables students to analyze and grasp individual elements before reconstructing a holistic understanding.

In technical reverse engineering, engineers discern the underlying principles governing the object's functionality. In education, educators can guide students to uncover the fundamental principles that form the bedrock of complex subjects. By isolating these core concepts and presenting them as foundational building blocks, educators help students cultivate a solid understanding that can later support the comprehension of more intricate aspects.

Furthermore, just as reverse engineering can lead to innovations and improvements in technical systems, a similar principle applies to education. By breaking down established teaching methods and curricula, educators can identify areas for enhancement and adaptation. This approach encourages a continuous loop of improvement, where educational methodologies evolve to suit the evolving needs and learning styles of students.

The method begins with owning an inexpensive 3D printer of FFF. A regular FFF 3D printer price for household use would be around 100 – 500 USD depending on the complexity and features that it bears at the time of writing. Making one from scratch might be time-consuming and sometimes cumbersome, but it's worthwhile considering since it is more educational. The second step is the creation of CAD drawings of 3D printed parts specially created for this education. These parts would have a combination of the above features listed as proven teaching methods. To exemplify, a part Shown in Fig. 2 is modeled with additional features on it.

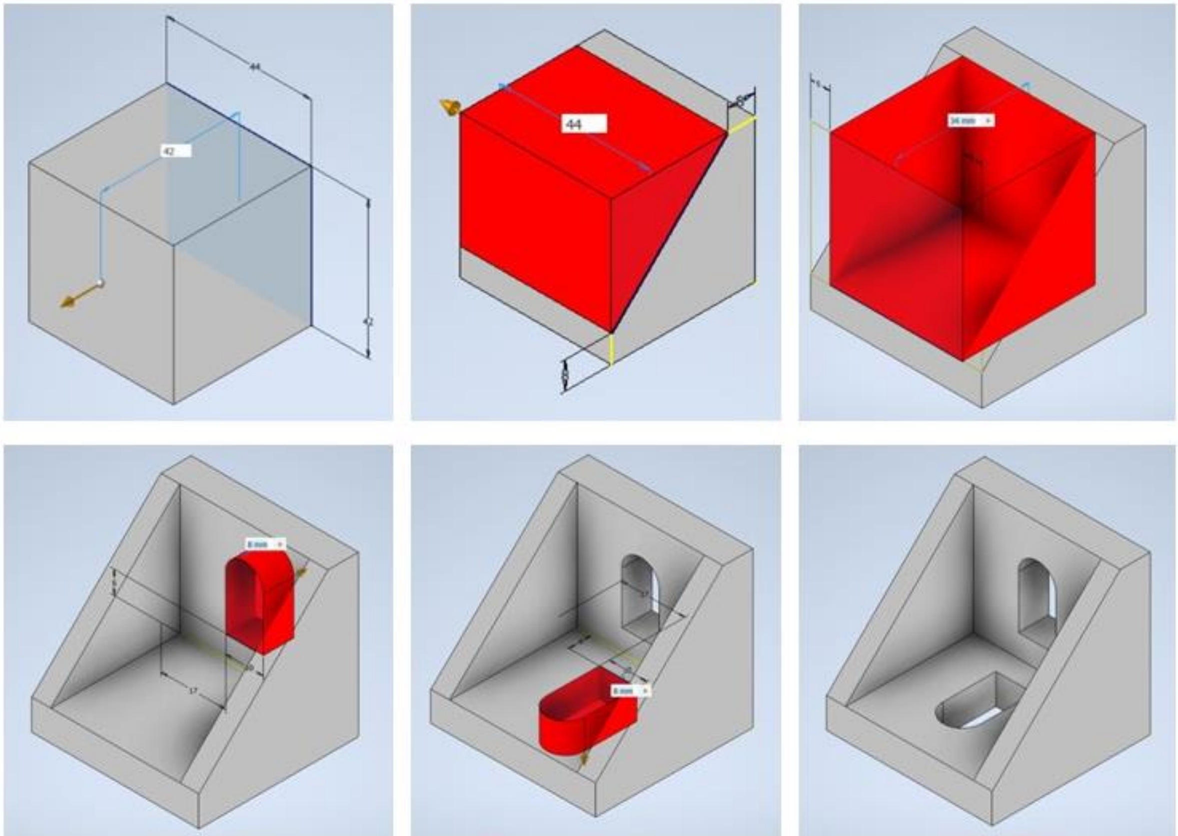


Fig. 2. Steps for creating a solid model using sweeping and Boolean operations

The additional features are based on previously mentioned principles and are shown in Fig. 3. Here, we add, for example, the techniques of Analysis by Solids, Vertex Labeling, Analysis by Surfaces, and Surface Labeling. Later on, the designed part is 3D printed for use, as shown in Fig. 4. Which is a method equivalent to the Physical Model Construction. Out of the nine methods of learning mentioned above, five of them are covered. Missing lines can be paperwork, but the missing line can be interpreted over the physical model. Similar shapes can be constructed with a 3D printer to demonstrate the actual meaning. Projection Studies can easily be exemplified with the layer-by-layer construction of 3D printing from the bottom up. Finally, Adjacent Areas can be demonstrated through faces printed in different colors. In this way, all of the methods of teaching can physically be experienced by the students to create a steeper learning curve.

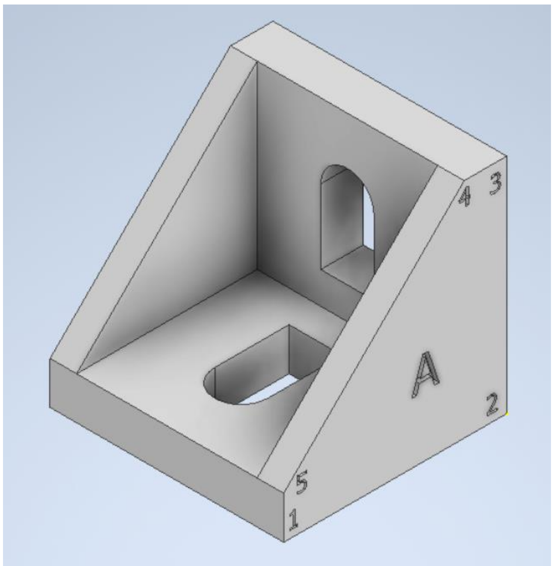


Fig. 3. Part design with additional features.

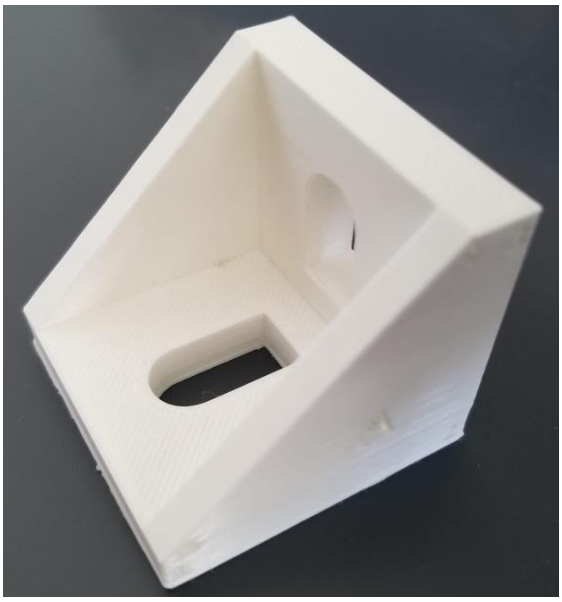


Fig. 4. 3D printed part with additional features.

In the next stage, students have given a chance to play with the parts, as shown in Fig. 5. Explaining different methods over the example print leads to concentration toward better learning. Now it is time to explain 3D modeling and its basic elements as Extrude, Revolve, Sweep, and Loft. These elements are shown in Fig 6. The counterparts of printed elements are also shown in Fig. 7.

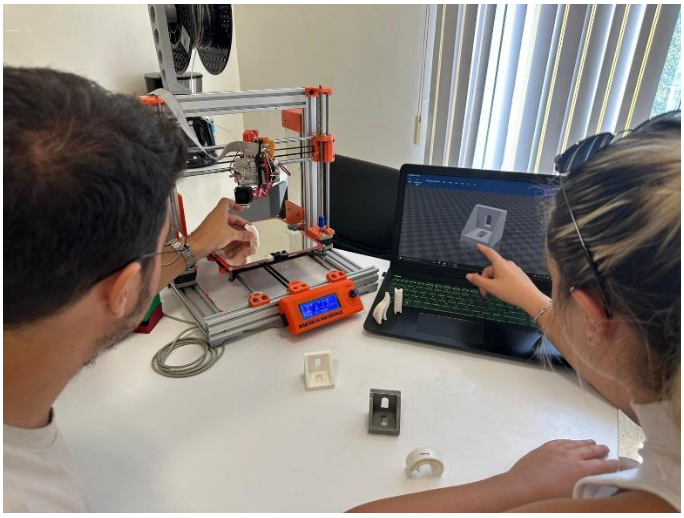
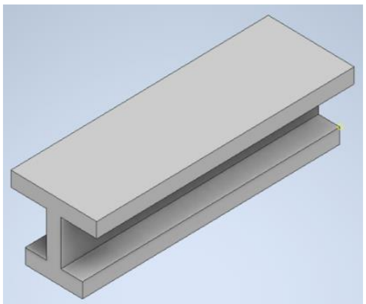
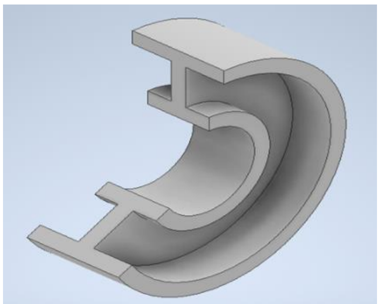


Fig. 5. Students have been given a chance to play with the parts.



a)



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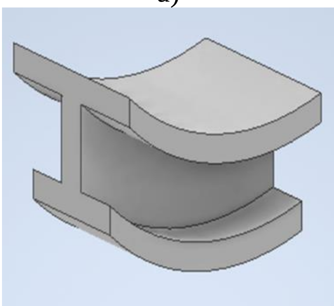

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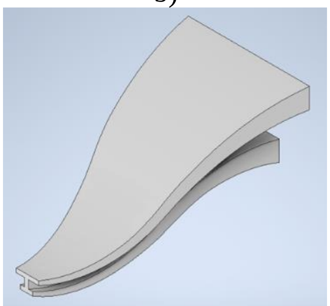

d)

Fig. 6. 3D modeling and its basic elements as a) Extrude, b) Revolve, c) Sweep, d) Loft.

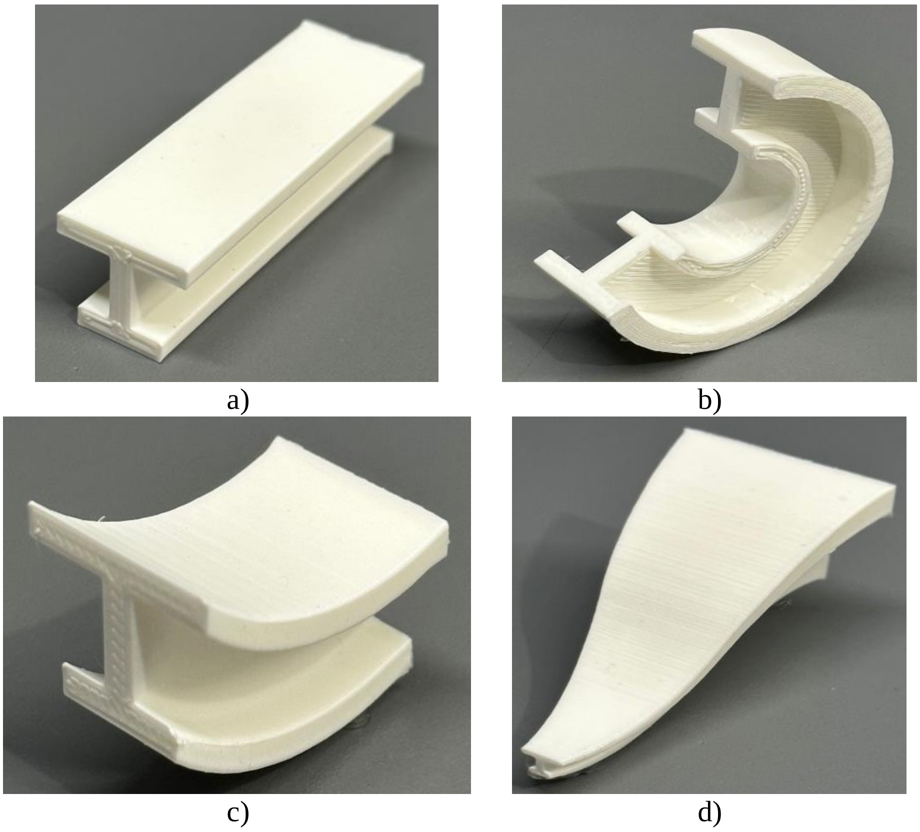

Fig. 7. 3D prints of modeling basic elements: a) Extrude, b) Revolve, c) Sweep, d) Loft.

Once the basics of 3D modeling, starting from sketching and simulating the sketch over the first layer of 3D printing, have been taught, the next step in this learning experience is for students to model example parts using solid modeling software, represented as stage 1 in Fig. 1. Subsequently, the following step involves generating an STL (Standard Tessellation Language) file from the designed model, which corresponds to stage 2 in Fig. 1. Proceeding through stages 3 to 8, as depicted in Fig. 1, completes the study, bringing it to the level of "Closing the Loop." This approach can be described as "Closed Loop Approcah" as the creation process begins from the end and progresses backward towards the beginning as a CAD model. The final product obtained enables students to check the model against physical results, including dimensions and feature evaluation, providing a tangible understanding of the design's characteristics and properties.

The effectiveness of the method required evaluation through experimentation. Two sections of the ME 113 Engineering Drawing I course in the Mechanical Engineering Department at Çankaya University were chosen to implement the same teaching methodology with different approaches in order to assess the outcomes. Each sample group comprised 25 students, ensuring a relatively even distribution of participants. Three key measurements of effectiveness were devised for the experiment:

1. Assessment of grades following the first quiz, which included tasks involving 2D to 3D and 3D to 2D representations, specifically multiview drawing to isometric drawing and isometric drawing to multiview drawing.

2. Measurement of the time taken to complete the modeling period of six parts, once again using the activity timers available in the CAD software for both multiview drawing and isometric drawing.

3. Student surveys focus on the two different learning methods employed.

In the first and second experimental applications, students were given a total of eighteen assignments consisting of six different parts. All of these assignments were graded on a scale of 100, and a reference time of 305 minutes was allowed for completion.

For the third experimental step, student perception is measured. Five questions are asked them to rate from 1 to 5, 1 being "strongly disagree", 2; "disagree", 3; "neither", 4: "agree", and 5; "strongly agree".

Results and Discussion

When both groups were given the same set of assignments, it was evident that the group utilizing 3D-printed training materials and methods performed significantly better, achieving 45% higher grades overall, as indicated by the scoring rubric presented in Table 1. Furthermore, when comparing the time taken to complete the same parts, it was observed that, on average, the group using the learning model required 30% less time.

Table. 1. Assignment rubric for experimental groups

Part	**Assignment**			**Grade Point**	**Reference Time**
Base	Isometric	Multiview	Modeling	5+5+10	15+15+30 min
Body	Isometric	Multiview	Modeling	6+6+13	20+20+40 min
Washer	Isometric	Multiview	Modeling	2+2+6	6+6+18 min
Shaft	Isometric	Multiview	Modeling	4+4+7	12+12+21 min
Holder	Isometric	Multiview	Modeling	4+4+7	12+12+21 min
Handle	Isometric	Multiview	Modeling	4+4+7	12+12+21 min
6 Parts	**18 Assignments**			**100**	**305 min**

Questions and results of the perception rating are given in Table. 2. From the rating, it can be seen that the perceptions of students that apply the proposed learning method are much more satisfactory than the results represented by grades or timings. The perceptions of the students are much more positive than the actual numerical results. Analyzing the statistical results in the table reveals that the satisfaction mean is notably high, with a grand mean of 4.704 out of 5. Moreover, the standard deviation is relatively low. In addition, the reliability statistics indicate a Cronbach's Alpha value of 0.736 and a Cronbach's Alpha based on standardized items of 0.683. These values can be confidently characterized as demonstrating a high level of reliability, especially given the small sample size.

Table. 2. Student perception measurement questions and answers

Question: Compare the before and after the method is applied	**1**	**2**	**3**	**4**	**5**	**Mean**	**Std. Dev.**
I have understood basic 3D modeling concepts much better	%0	%0	%4	%16	%80	4.76	0.52281
I felt I could do isometric drawings more easier	%0	%0	%4	%24	%72	4.68	0.55678
Multiview drawings are easier after my 3D printing experience	%0	%0	%8	%32	%60	4.52	0.65320
I understood the sections much better after the training	%0	%0	%4	%28	%68	4.64	0.56862
Holding the part to model in my hand made me confident	%0	%0	%0	%8	%92	4.92	0.27689

In Table.2. the result of the question "*I understanding the sections much better after the training*" shows that the advantage of 3D printing over modeling is understanding the section view of a part. In 3D printing, objects are built layer by layer, starting from the bottom and gradually building up to form the final part. Each layer is created by depositing or solidifying material, typically in a controlled manner guided by computer instructions. When examining a part created through 3D printing, the section view refers to a cross-sectional perspective that reveals the internal structure and features of the object. By slicing through the 3D printed part, one can visualize the different layers that compose it. This section view provides valuable insights into the internal design, structure, and any internal cavities or voids present within the part. This advantage is seen in Fig.8. where section view is observed while printing.

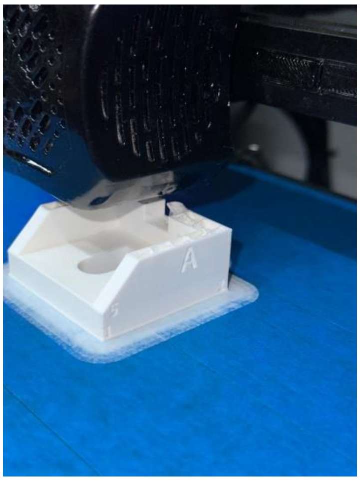

Fig.8. Section view observation while printing

The observations of outcomes show that another advantage of the method is that it helps students comprehend the fundamental creation methods of 3D modeling, such as extrusion, revolve, sweep, and loft. Due to the similarities in the underlying logic of these methods, students can build upon their understanding and apply it to various design scenarios. By engaging with these different creation techniques, students gain a deeper understanding of how to manipulate and transform shapes in the virtual 3D space, enabling them to develop more complex and intricate models. This proficiency in utilizing various creation methods expands their repertoire of design strategies and enhances their ability to conceptualize and bring their ideas to life in the realm of 3D modeling. As demonstrated in the study conducted by Powar et al., the application of a 3D printing-based learning approach led to a significant increase in test performance, ranging from 10% to 16%. These findings align with similar discoveries reported in our study.

An obstacle that individuals might face when considering this method is the availability of a 3D printer, even though these devices are relatively inexpensive and widely used by individuals today. While the cost of acquiring a 3D printer has become more affordable due to its increasing popularity and personal applications, access to one might still pose a hurdle, particularly for those who do not own one or have ready access to such technology. Despite the growing prevalence of 3D printers in various settings, such as homes, schools, and community spaces, there can still be limitations in terms of availability and convenience. Therefore, while the potential for utilizing 3D printing is promising, it's important to recognize that practical access to this technology can vary and impact the feasibility of its implementation for certain individuals or projects.

The integration of 3D printing into Computer-Aided Design (CAD) education holds profound implications that extend far beyond the classroom. This symbiotic relationship between 3D printing and CAD not only enhances learning experiences but also shapes the future of engineering pedagogy and responds to the evolving needs of the industry.

At its core, the fusion of 3D printing and CAD empowers students with a tangible manifestation of their digital designs. This hands-on experience bridges the virtual and physical realms, providing a unique avenue for students to comprehend intricate geometries, tolerances, and material properties. As students convert their digital prototypes into physical objects, they gain a deep understanding of design complexities, fostering a holistic approach to problem-solving that transcends theoretical knowledge.

This integration catalyzes a paradigm shift in engineering pedagogy. It encourages experiential learning, where students transition from mere observers to active creators. By engaging in iterative design processes, troubleshooting, and material selection for 3D printing, students acquire practical skills crucial for real-world engineering challenges. They develop an acute awareness of the interplay between design and manufacturing, enhancing their adaptability and readiness to address dynamic industry demands.

Furthermore, the integration of 3D printing into CAD education aligns seamlessly with the industry's evolving needs. Modern engineering necessitates agility and innovation, where designers must rapidly transform ideas into functional prototypes. By familiarizing students with 3D printing techniques, institutions equip them with skills pertinent to contemporary manufacturing landscapes. Graduates enter the workforce equipped to optimize design for additive manufacturing, demonstrating an understanding of the cost-effectiveness, material efficiency, and design intricacies associated with 3D printing technologies.

Beyond technical skills, the incorporation of 3D printing nurtures creativity and nurtures an entrepreneurial mindset. Students experiment with unconventional geometries, exploring designs that were previously implausible with traditional manufacturing methods. This innovation-driven approach aligns with the industry's shift towards customization and novel product development.

Implementing 3D printing in CAD education, while beneficial, presents challenges including initial costs, the need for technical expertise, maintenance demands, material selection complexities, design optimization considerations, resource availability issues, effective curricular integration, catering to diverse learning styles, sustainability concerns, and potential equipment obsolescence. Educators and institutions can mitigate these challenges by offering comprehensive training, seeking industry partnerships for support, aligning 3D printing with project-based learning, fostering an environment of innovation, and considering sustainable practices. Addressing these challenges proactively ensures that the integration of 3D printing enhances CAD education while navigating potential limitations.

Conclusions and Future Directions

The study's results indicate that the utilization of 3D printing in a design-based course could potentially influence students' experiences and alter their learning of the design process. The combination of empirical data, along with observations from faculty and researchers and student comments, indicates a shift in cognitive strategies due to the implementation of 3D printing technology. This supports the assertion that educational technology can indeed influence student cognition and learning strategies.

With the increasing adoption of 3D printing and rapid prototyping in technology, design, and engineering classrooms, there is a growing curiosity about how students will approach the design process and the outcomes they produce. The findings from this preliminary study provide data suggesting a positive correlation between the utilization of advanced design technology and improved student performance in design. Upon receiving the same assignments, the group utilizing 3D-printed training materials outperformed significantly, attaining 45% higher grades. Moreover, they completed the tasks in 30% less time than the group using traditional learning methods. As a result of the experiment, it became evident that establishing stronger curricular connections between design and production could enhance students' preparedness for careers centered around design. Additionally, it was observed that many students readily embraced the 3D-printed model as an initial step in learning about modeling and technical drawing.

The integration of solid modeling with virtual reality (VR) and 3D printing presents a promising avenue for transforming the design and prototyping process. By combining solid modeling, which enables the creation of complex 3D digital models, with VR technology, designers can immerse themselves in virtual environments and interact with their creations in a more intuitive and immersive manner. This integration allows for enhanced visualization, spatial understanding, and real-time design iteration. Furthermore, by seamlessly connecting virtual reality with 3D printing, designers can seamlessly transition from the digital realm to the physical world. They can use VR to refine their designs, identify potential flaws or improvements, and then directly translate these virtual models into tangible objects through 3D printing. This convergence of solid modeling, virtual reality, and 3D printing holds tremendous potential for revolutionizing design workflows, accelerating innovation, and pushing the boundaries of what is possible in various fields, such as product design, architecture, and engineering.

Study about the proposed approach does not contain any data regarding the variations in student backgrounds, learning styles and the institutional settings. A future research is needed to explore how student diversity, learning preferences, and different institutional contexts might influence the oucomes of the presented approach. Suggestion of the methodlogy of further research might mainlyinclude; related literature review, qualitative data collection, and statistical analysis.

The application of the proposed "closing the loop" method to other 3D visualization required classes, such as the strength of materials, can significantly enhance conceptual explanations and deepen students' understanding of complex concepts. Taking the example of torsion, the use of a TPU (Thermoplastic Polyurethane) printed shaft marked on the outer side can serve as a powerful demonstration tool. As students observe the shaft undergoing torsional forces, they can visually witness the deformation and stress distribution through the marked indicators on the shaft. This tangible representation bridges the gap between theoretical concepts and real-world applications, enabling students to grasp the fundamental principles of torsion in a more engaging and hands-on manner. The integration of 3D printing technology with conceptual explanations in the strength of materials not only facilitates a more comprehensive understanding of the subject but also cultivates critical thinking and problem-solving skills in students as they interact with physical models that vividly depict abstract concepts.

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Replication of Results The paper provides all necessary information for readers to replicate the results and methodology. Data are available on request.

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