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Using 3D Printing to Teach Design and Manufacturing Concepts

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Abstract

Additive manufacturing, also known as 3D printing, is commonly shown to students through low cost 3D printers. Many high school and community college educators have access to 3D printers at their home institutions. In this study, Research Experience for Teachers (RET) participants developed a set of modules which can be integrated with a design project given at both the high school and college curriculum levels to explore the concepts of manufacturing and design (e.g., dimensioning and tolerancing, Design for X, Proof of Concept, etc.). The study identified a product in which these concepts can be integrated, and developed a set of constraints the students need to consider in their design project. It was the goal of the RET participants to identify best practices for teaching 3D printing and develop projects to explain design and manufacturing concepts through 3D printing.

Keywords
3D Printing, Design, Manufacturing, RET

1. Introduction

The use of 3D printing in education has grown rapidly and is used to facilitate improved learning, skills development, and increased student and teacher engagement. As the cost of 3D printers have decreased, the accessibility for educators has risen, and it is important that these tools be used effectively to teach the skills required in science, technology, engineering, and mathematic (STEM) fields. This goal remains consistent regardless of academic level; whether teaching at the high school [1], undergraduate [2], or graduate [3] levels of STEM education.

In a design course, students explore how to follow a process which utilizes problem solving, technical skills, and often teamwork and communication skills. Teaching design thinking is a challenge which many educators face by utilizing project-based learning [4]. Prototyping projects are important in design courses because they allow students to explore the technical elements of their education while giving students the freedom to have ownership over their creations. By working through a hands-on design project, students are able to apply the scientific method to a real-world problem and in doing so increases their aptitude and knowledge of design and experiments [5]. As a result of their effectiveness, hands-on design projects are implemented in numerous design courses [6].

Using 3D printing as an option within a prototyping experience is less cost intensive and less dangerous when compared with bringing students into a machine shop; an option that may also be obstructed by lack of access to a machine shop. By including 3D printing, students feel like they are doing something worthwhile and technically impressive. With 3D printing, students can develop valuable skills beyond that of technical prowess. Moreover, the use of 3D printing is classroom projects will enable students to develop critical thinking, problem solving, creativity, agility and adaptivity, and increased writing and speaking skills [1]. As a result, there are numerous projects that are used within the classroom. Some projects and curriculum include 3D printing object or objects as the only element in the design [7], while others incorporate a 3D printed component as part of a more complex assembly [8-10].

The objectives of this study are to (1) develop methods to allow teachers to explore the fundamentals of 3D printers and the software associated with them integrated with teaching the basics of using the engineering design process as well as tolerances, assembly, disassembly, and designing for a target group, (2) design and create different examples of the 3D printed project that is selected, and (3) prove that the project had an impact on students' understanding of 3D printing, manufacturing, and design concepts.

2. Background

Generally, manufacturing processes are divided and taught in four categories: (1) Removal: carving, milling, drilling, turning, (2) Deformation: molding & casting, forging, extruding, sheet forming, and powder metal processes, (3) Joining: brazing, welding, fastening, and (4) Additive: which includes the seven ASTM-specified 3D printing categories (i.e., binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization).

According to the American Society for Testing and Materials (ASTM), additive manufacturing can be defined as the "Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [11]. Figure 1 shows a brief history of additive manufacturing.

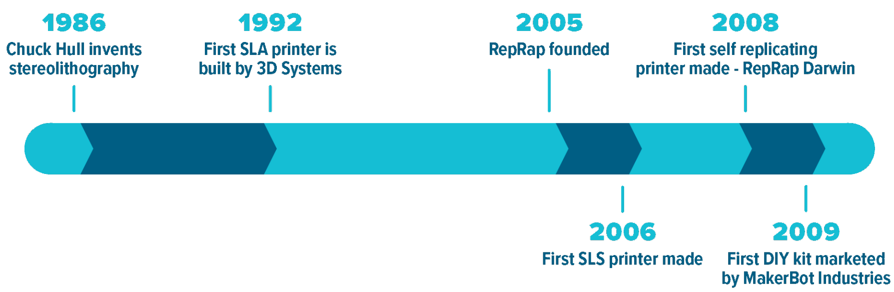


Figure 1: A brief history of additive manufacturing

3D printing is a relatively new class of manufacturing methods which produce physical prototypes from 3D Computer Aided Design (CAD) data. 3D printing is used in a variety of industries, such as government and military, consumer products, motor vehicles, aerospace, industrial and business machines, architecture, medical and dental, and academia. Some examples of what 3D printing is being used for include functional parts, fits and assemblies, education and research, visual aids, presentation models, patterns for metal castings, patterns for prototype tooling, and tooling components. The 3D printing process includes the following steps (1) creating a CAD model of the part, (2) converting the CAD file into stereolithography (STL) file, (3) using 3D printer software to define printing parameters, (4) transferring the file to 3D printer, (4) printing, and (5) removing the printed part. These steps are shown in Figure 2.

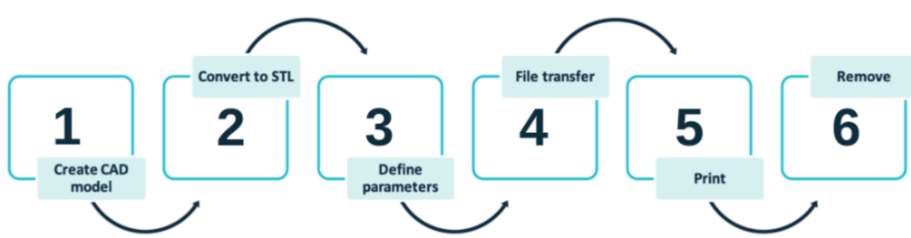


Figure 2: 3D printing process steps

According to Hopkinson and Dickens [12], additive manufacturing can be divided into three different processes: liquid based, powder based, and solid based. Each process consists of different forms including: (1) Liquid Base: Stereolithography, Jetting Systems, Direct Light Processing, (2) Powder Based: Selective Laser Sintering, Three-Dimensional Printing, Fused Metal Deposit Systems, Electron Beam Melting, Selective Laser Melting, Selective Masking Sintering, Selective Inhibition Sintering, Electrophotographic Layered Manufacturing, High-Speed Sintering, and (3) Solid Based: Fused Deposition Modeling, Sheet Stacking Technologies.

The main factors and considerations in 3D printing include: (1) Quality: a measure of how thick the 3D printing layers are (smaller values typically result in stronger parts with finer resolution, but at the cost of longer print times). (2) Shell, or outer wall thickness; larger values result in thicker walls and, as a result, stronger parts. (3) Infill: the percentage of the part interior that is material as opposed to open; larger percentages of infill result in stronger parts (10-25% is the typical range for infill and few cases need more than this). (4) Material: which plastic is used as the feeding material. Some plastics prefer different temperatures to operate correctly. The Poly Lactic Acid (PLA), for instance, can run between 190 and 210 degrees Celsius; running cooler allows for better bridging while running hotter allows for better contouring. (5) Speed: the rate at which the material is extruded onto the part. In general, the slower the speed, the higher quality of the part. Increasing the speed to a high value, dependent on the machine, will result in a print failure. (6) Travel: how fast the printer head moves when not in contact with the part. Faster travel can result in faster printing times but can also cause problems with printer longevity as well as the possibility of becoming snagged on the part which can cause separation or other undesirable results. (7) Print cooling which allows the fans placed near the extruder, if equipped, to regulate the surface area of the print below the nozzle. This can come in handy when a part needs to be cooled down in order to prevent warping. Some materials need to have the fan disabled in order to keep the material above the glass transition temperature. (8) Support: disposable components used to support geometric overhangs over 45 degrees. Th supports have a lower density compared the printed object, causing them to be easier to remove. A support density of 5 – 15% is recommended for typical parts. (9) Build plate adhesion: how the part is assisted to stick to the build plate. The most common way is to use a brim, which is a collection of rows of filament that allows for the perimeter of the part to extend outwards and prevent warping. A raft is another option that provides a stable base to start the print on. Brims are considerably easier to remove and offer a cleaner end result. (10) Optional Settings: different printers offer different additional settings such as dual extrusion. There are also special modes that printers are able to use such as spiralize (vase mode) where there is one single outer wall resulting in hollow parts. This can be beneficial because of the drastically reduced print time.

Additive manufacturing has been around for almost 40 years; it can be nowadays considered a consolidated technology, at least in its technical aspects [13]. This technology is still undergoing a significant innovation process, often through the hybridization of established base-techniques. Many advancements to this technology are expected to be introduced in the near future. Figure 3, adapted from [11], shows an example of how 3D printing may change our future.

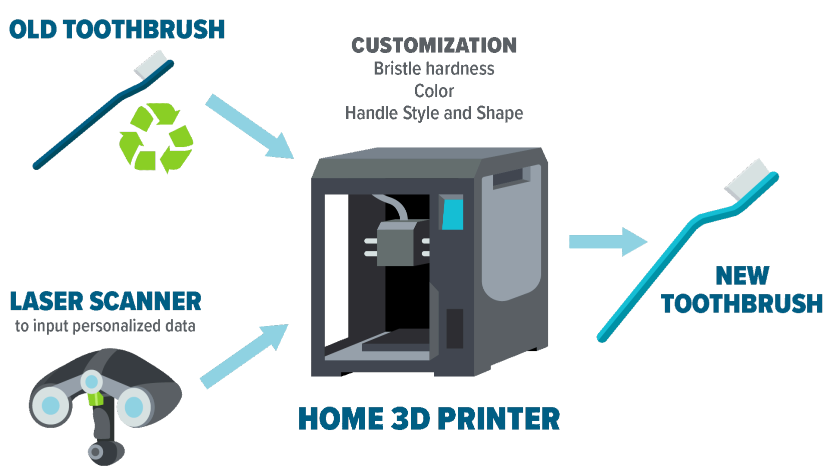


Figure 3: Example of the future of 3D printing in homes

3. Methods

The study framework is shown in Figure 4. First, the learning skills to be developed by the students are identified. These skills include both the design and manufacturing technical skills (CAD modeling, 3D printing, manufacturing processes, manufacturing systems, cost analysis, etc.) and 21st century professional skills (problem solving, teamwork, communication, etc.). Then, the associated national and/or State learning standards are identified. A sample product is selected to illustrate the concepts; in this study we chose a flashlight because it includes both mechanical and electrical components and is relatively easy to model and 3D print. Once the design and manufacturing activities are developed, the students work on a case study or a course project to design and produce the flashlight. Data is collected and analyzed to identify the impact of the project on student learning and skills development. This study develops an instructional unit that is planned for STEM-focused high school or college students. The recommended prerequisite is one semester of CAD experience and the project timeline will span approximately 30 hours. While utilizing engineering modeling software and integrating the provided criterion, this project exposes students to a real-world flashlight design challenge and requires them to consider design and manufacturing concepts.

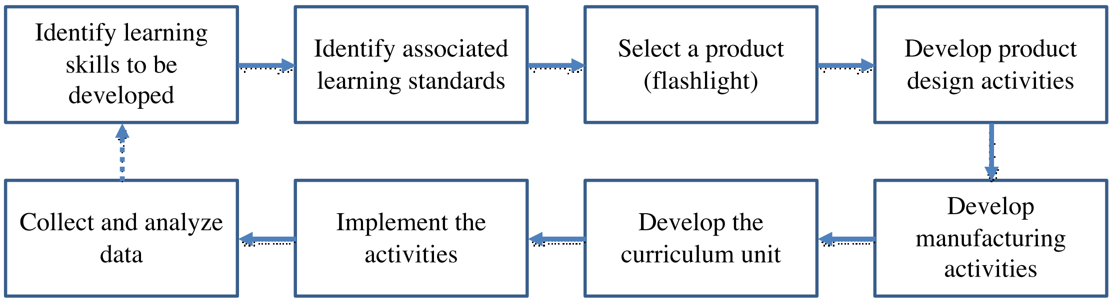


Figure 4: Proposed framework of the study

The instructional lesson plans encompass students designing a flashlight for target customer groups with given constraints using 3D software, understanding basic electronic components, utilizing the design process, prototyping, exploring industrial analysis, and emphasizing professional skills. This project-based learning activity is intended to address several 21st century skills while building on the fundamentals of designing a product for the marketplace. The measurable learning objectives are: (1) By completing the flashlight design and 3D printing activities, the students will produce a working 3D printed flashlight meeting all assignment criterion for their target customer group, (2) By completing the flashlight design and 3D printing activities, the students will identify and present their own engineering design process, step by step, documented in PowerPoint slides, and (3) Given the molding cycle times, associated material, design and labor costs, students will compare production times at incremental quantities and determine at what quantity of finished flashlights it becomes more cost-efficient to replace 3D printing with injection molding in the production of their flashlight. The associated learning standards are shown in Table 1.

Table 1: Summary of learning standards for the Flashlight Design and 3D Printing project

Standards Type	Standards Description
Drafting Standards	○ ASME Y14.100-2017 Engineering Drawing Practices. ○ ANSI-Y14.5 Dimensioning and Tolerancing.
State Career & Work Standards	○ Evaluate conflict resolution skills as they relate to the workplace (Constructive criticism, Group dynamics, Leadership, Mediation, Negotiation, Problem Solving). ○ Evaluate time management strategies and their application to both personal and work situations.
State Core Writing Standards	○ Integrate and evaluate multiple sources of information presented in different media or formats (e.g., visually, qualitatively) as well as in words in order to address a question or solve a problem.
State Standards for Science & Technology	○ Analyze the scale as a way of relating concepts and ideas to one another by some measure.
State Core Math Standards	○ Explain volume formulas and use them to solve problems. ○ Analyze relationships between two-dimensional and three-dimensional objects. ○ Apply geometric concepts to model and solve real world problems.
Next Generation Science Standards	○ Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.
21st Century Skills are addressed	○ Critical thinking and problem solving, collaboration and leading by influence, agility and adaptability, initiative and entrepreneurialism, effective oral and written communication, curiosity and imagination.

4. Results and Discussion

The first iteration of this project occurred in summer 2019 with high school teachers and community college instructors. During this project, the participants focused primarily on highlighting the design process, and industrial analysis of manufacturing methods. In order to teach these concepts, the RET participants developed a project in which students design the prototype of a flashlight as shown in Figure 5. This curriculum is introduced in the high school and community college classes that the teachers run to an expected population of 150-160 students. The activities include developing a flashlight prototype using white papers, bulb, and battery. Then, the students will conduct market analysis, design the flashlight, and then produce it using 3D printing.

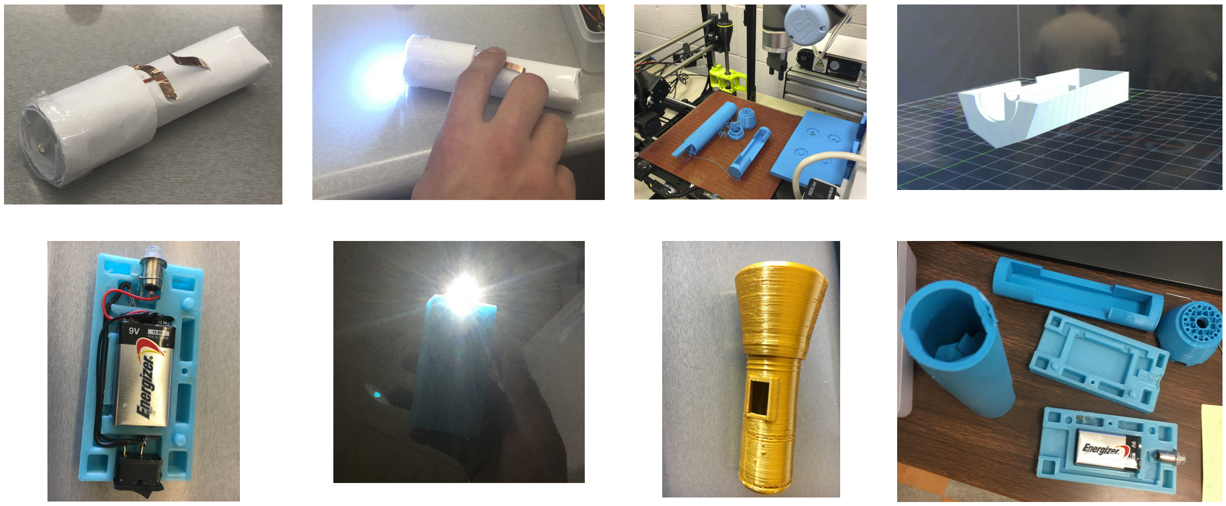


Figure 5: Sample pictures from the research activities

Figure 6 shows sample pictures form three students' projects which include manual sketches for the design, CAD model for the product, and 3D printed functional product. Students' feedback indicated that they learn the concepts of design and manufacturing after completing the 3D printing based project.

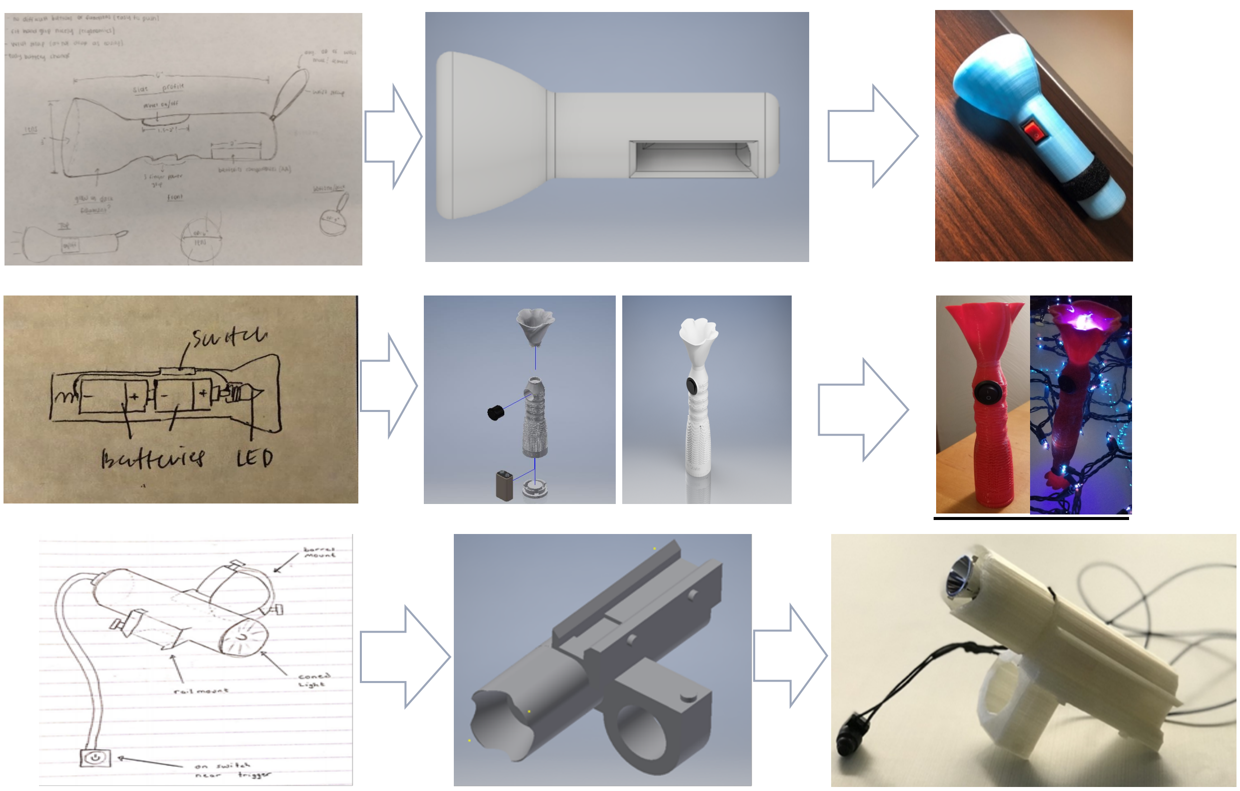
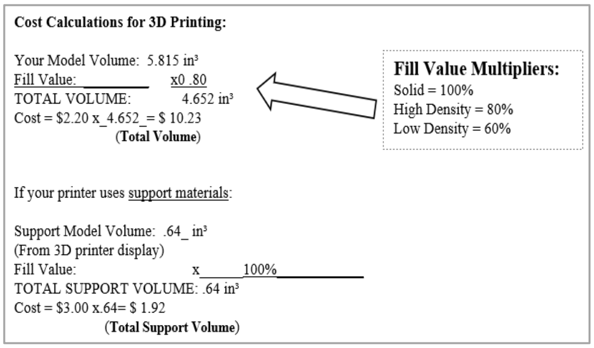
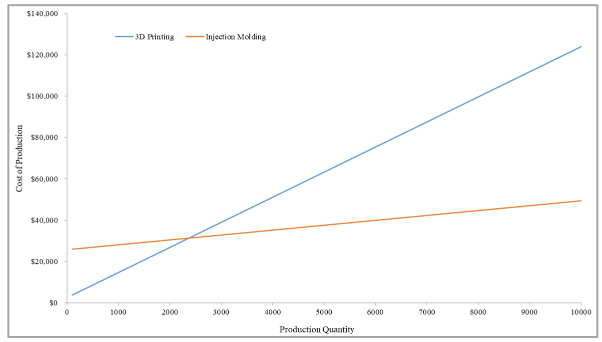


Figure 6: Sample pictures from students' projects

The students also evaluated the cost of producing the flashlights using injection molding. The cost analysis is shown in Figure 7. The breakeven analysis shows that the breakeven quantity is 2,369. Producing more than 2,369 flashlights will make the 3D printing option less viable as compared to injection molding.



Cost analysis of 3D printing vs. injection molding



Breakeven analysis of 3D printing vs. injection molding

Figure 7: Cost and breakeven analysis of 3D printing vs. injection molding

5. Conclusions and Future Work

The RET participants developed a project that highlights the design process and includes an industrial analysis of manufacturing models. The participants identified that a module on 3D printing best practices and orientation would be useful for future projects. 3D printers have a huge variance in quality, so the curriculum is designed to accommodate all printer types. The 3D printed flashlight is a unique way to incorporate manufacturing concepts and 3D printers in problem-based learning projects. The project allows for an interesting approach to provide student exposure to the 21st century skills. By including cost analysis, the project provides higher taxonomy levels than similar design projects. Future work will focus on evaluating the effectiveness of the proposed approach on student learning of design and manufacturing concepts based on data collected from diverse high school and college classrooms.

Acknowledgements

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