

Sustainable Undergraduate Engineering 3-D Printing Lab

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Abstract

Recent proliferation of inexpensive 3D printers allowed most educational institutions to purchase and deploy them. Students at all levels now print plastic objects due to the low cost of plastic materials used. However, failed and/or unwanted prints, as well as support material, are discarded. In this work, a sustainable 3D printing laboratory is described. 3D printed objects and supporting structures are recycled by first shredding the plastic parts using a two-step process, then mixing the resulting material with virgin material, and finally re-extruding the material as filament appropriate for use in 3D printing. Students became aware that the recycling of plastic parts is a large step towards sustainable 3D printing processes.

Introduction

The importance of experiential learning in engineering education is well established through a number of learning theories. For example, in Kolb's experiential learning cycle theory¹⁻³, active experimentation is regarded as an essential part of learning⁴⁻⁷. Experiential education philosophy and practice further reinforce the importance of active learning experiences^{8, 9}. The importance of physical models and working prototypes in engineering education is also well documented in engineering education literature¹⁰⁻¹² and supported in engineering texts^{13, 14}.

3D printing is an additive rapid prototyping (or manufacturing) process based on material addition. A few years ago companies started selling inexpensive 3D printers which in turn enabled their wide acceptance in engineering education¹⁵. Authors of engineering textbooks added chapters on 3D printing and additive manufacturing^{16, 17}. This 3D-printing revolution is enhancing all facets of engineering education due to the low cost of printers and materials. While this technology's great potential for unlocking students' creativity is well recognized, not much is known about what happens with 3D-printed parts after they are made. Students are printing thousands of objects which are slowly taking over university labs and offices. ABS plastic can be recycled. PLA plastic can also be recycled, and is even biodegradable (albeit only in special plants). However, the failed prints and unwanted printed objects often end up as trash in land fields. To minimize waste the number of failed prints could be minimized¹⁸ and the rest of the failed or unwanted plastic objects could be recycled. In this work, a sustainable 3D printing lab consisting of nine inexpensive 3D printers, a desktop plastic shredder, and a desktop filament extruder is presented. Technical project objectives, laboratory development and implementation, engineering/economic analysis, and educational assessments are provided. An integration of plastic object recycling as a part of the life-cycle of 3D printed objects in an undergraduate engineering 3D printing lab is presented. The process and equipment required to accomplish this task are developed and described. Assessment of student perceptions and attitudes towards sustainability due to the implementation and operation of this novel sustainable 3D printing lab is provided. Apart from the reduced cost of operation, this sustainable 3D printing lab has inspired engineering students, university visitors, and K-12 students and teachers.

Curricular Context

The 3D-printing lab addressed in this work is described partially elsewhere^{15, 18}. The lab is used by undergraduate engineering students in most of the engineering courses. Two part-time student technicians help students to minimize the number of failed prints through sharing 3D printing best practices including selection of materials and colors (not all colors print equally), object designs for 3D printing, object placement and orientation, 3D printing process parameters (temperature, speed, fill, rafts, etc.), rework, and post-processing^{19, 20}. Currently, students use nine inexpensive 3D printers based on fused deposition modeling (FDM) technology to print mostly with acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) 1.75 mm diameter filaments. These filaments are widely used in FDM 3D printers and can be obtained from many suppliers. During the last three years, students logged over four thousand 3D-print-time hours and produced over two thousand objects ranging from simple give-away keychains to sophisticated multi-part assemblies of students' own designs. Students and faculty, in special projects, are experimenting with additional materials (nylon, magnetic filaments, metal-like filaments, conductive filaments, etc.) and technologies (3D printing with metallic clay). This paper concentrates on the newest addition to the sustainable 3D printing lab – the system for recycling plastic parts.

The project for recycling 3D printed parts was initiated in January 2015 when the engineering department purchased a desktop extruder that could produce 3D printing filament from plastic granules. Then, a graduate student was tasked to find an acceptable mixture of recycled and virgin material for successful 3D prints. After the proof-of-concept stage was completed successfully, a small manual shredder of plastic parts was purchased, motorized, and modified to accept most of the 3D printed objects. Some objects printed by a large volume Z-18 MakerBot printer still need to be pre-cut before shredding. In the Fall 2015 semester, student technicians were trained to use the recycling equipment, and engineering students were asked to recycle their unwanted objects. These requirements were aligned with the principles of our sustainability minor and with sustainability topics in three engineering courses, Introduction to Engineering, Introduction to Industrial Engineering, and Senior Seminar.

Technical Project Objectives

In this section, project objectives are defined, justified, and analyzed. Also, an implemented solution is presented.

To increase efficiency of the engineering 3D printing lab, the amount of scrap has to be minimized and all scrapped objects have to be recycled. The scrap material originates from failed prints, design iterations, and structural material. To minimize the number of failed prints a few methods are implemented. First, the student technicians working in the lab are well-trained ensuring that they can help students and resolve 3D printing problems as they arise. The technicians are selected from among engineering students. The selection is based on their enthusiasm towards 3D printing and their previous experiences. Usually, technicians are employed until they graduate. Consequently, 3D printers are well maintained, frequently calibrated, and quickly repaired as needed. Before printing, each new design is critiqued and pre-processed with the help of a technician. Here, technicians instruct students about best practices in “printability” and position/orientation of parts to be printed. During printing, students are required to oversee the process for the first few layers to make sure the plastic adheres well to the printing platform. Then, the technicians are required to observe parts for the rest of the time as

they are printed. This allows early detection of failed prints thus minimizing the amount of wasted material and time. In some cases (proven designs) long jobs are allowed to run overnight. Removal of finished objects from 3D printers is mostly left to a technician to protect the 3D printers. With PLA prints, students are allowed to remove the non-heated printing platform and release their own parts. While most post-processing operations such as part cleaning, polishing, assembly, etc. are left to students, some post-processing tasks (minor repairs and small modifications) may require technicians' assistance.

Material recycling in a laboratory setting is at the core of this work. Even though the scrap material due to failed prints is mostly eliminated due to the diligence and expertise of technicians, other scrap sources like support material and scrap due to design errors are still present. In general, the amount of support material used in 3D printing has been decreasing as the printing process has been improving. However, for some object geometries rafts and support structures are still necessary. In addition, due to the lower costs of prints, student designers are more likely to print incomplete or unproven designs and adopt a more-incremental design philosophy. Of course, now designers can try more complicated designs than before. Again, these two design practices create a larger number of discarded objects.

Originally, the engineering 3D printing lab was envisioned to be a lab for all university students. Any student could walk into the lab with an STL file and walk out with a physical object in hand. Most of the equipment was purchased with internal grants. As the number of students using 3D printers grew (creation of objects for most of the engineering courses, senior designs, independent studies, research, etc.) so did the amount of material used, as well as scrap. Since the cost of materials (ABS or PLA) was deemed high (\$40 to \$60 per kg) a solution was sought. Also, since both ABS and PLA plastics are thermoplastic materials, it was reasoned that these materials could be recycled back into filament. Recycling 3D printed materials is well-aligned with sustainability principles, thus, a desktop recycling system was envisioned to meet the recycling needs of the 3D printing lab.

Laboratory Development and Implementation

When a desktop extrusion machine by ExtrusionBot was offered for sale the department purchased one of them. About 5 kg of ABS and 5 kg of PLA were also purchased for testing. Now, the lab technicians could make filament for about \$10 per kg. However, the extrusion machine depicted in Figure 1 was relatively hard to use. While the extruder had a classic PID (Proportional Integral Derivative) temperature controller, the spool motor did not work as intended. It seems that its motor driver would quickly overheat and stop applying power to the spool motor. So, the spool mechanism was bypassed. The extrusion machine was placed near the end of a table and the filament was allowed to simply drop on the floor. This worked, but it required some extra effort to wind filament onto the spool. Also, some experimentation with the extrusion machine was required to achieve the optimal extrusion rate and adequate filament thickness (about 1.75 mm).

As a next step in the 3D printing lab development, the recyclability of the material was addressed. In general, the plastic material which passed through a small 3D printer nozzle does not have the same characteristics as the filament before the nozzle. During 3D printing some of the material's long polymer chains break changing the material's characteristics. Thus, the material becomes harder to extrude and may clog the 3D printer nozzle. For this reason, a number of experiments were performed with different mixtures of recycled and virgin material.

For the experiments the recycled objects were cut manually. The results of this study showed that a mixture containing 20% recycled material extrudes satisfactorily and can be used to create objects of similar physical characteristics as the ones created with 100% virgin filament.



Figure 1. Desktop extrusion machine by ExtrusionBot

From the time the 3D printing lab was established, as shown in Figure 2, scrap was collected in two large boxes for the two plastic materials, ABS and PLA. Some of the material was sorted by color as well. Given that lab uses about 40 kg of filament a year, about 10 kg of scrap per year presents about 25% of the total filament used.



Figure 2. 3D printing scrap material (failed prints, support material, bad designs)

To improve the recycling process, a small manual desktop shredder for plastic was purchased from FilaMaker, a small manufacturer from Germany. This manual shredder, shown in Figure 3 a, is an experimental device. It can shred plastic using a long wrench, but even then it requires an

adequate hopper (otherwise the shredded parts fly everywhere) and a way to collect the recycled material. During the summer of 2015, this shredder was motorized (1/6 HP AC bidirectional motor) and equipped with a 3D printed hopper and a 3D printed drawer. The hopper was designed to be tall enough for safety and to accommodate larger parts. A hopper lid was added since otherwise shredded pieces would often fly out the hopper. While this device (students named it “Crushinator”) has proven useful, it was still underpowered requiring frequent directional changes in motor rotation. Also, the shredded pieces were somewhat large for the desktop extrusion machine. To cut the recycled material into smaller pieces and to mix it well with virgin material, a household blender is used. The results are shown in Figure 4 a. Extruded material filament is shown in Figure 4 b. Color differences correspond to different mixture ratios of virgin to recycled material. Since the virgin material is white, the more color the larger the percentage of recycled material.

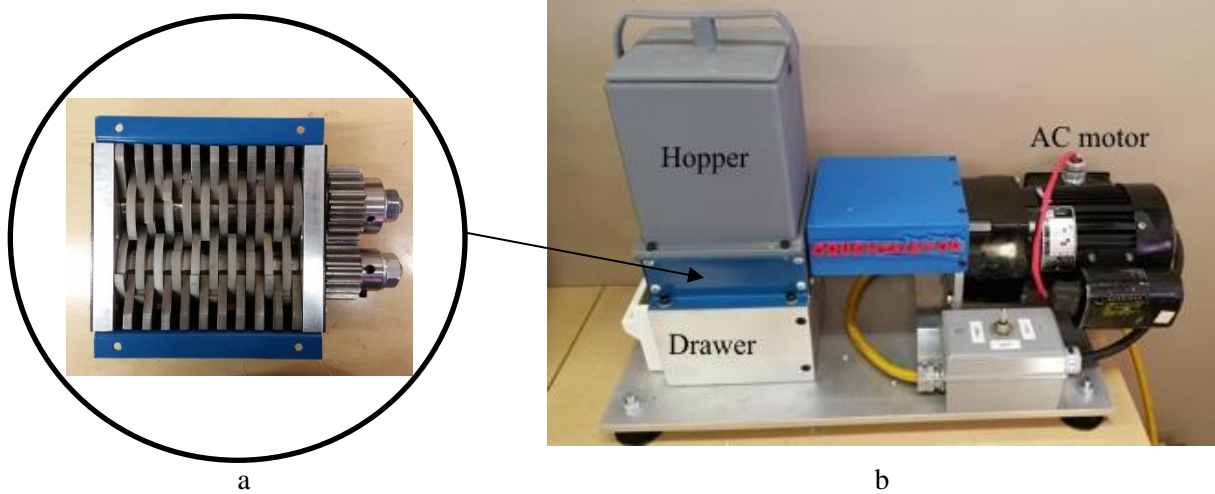


Figure 3. Desktop plastic shredder a) as purchased from FilaMaker b) modified and motorized



Figure 4. Recycled plastic: a) shredded and mixed PLA b) filament of various mixture ratios

With the use of the blender, the range of successful mixture ratios was improved to 70/30. While many 60/40 virgin/recycled filaments were successful, sometimes 3D printing nozzles would clog at this ratio. A possible explanation is that the improvement to 70/30 mixture ratio stems

from better mixing due to the smaller size of recycled particles. In addition, if a 70/30 ratio is used, this would be appropriate for the engineering 3D printing lab since there is about 25% scrap produced by the 3D printing process. A short economic analysis presented in Table 1 shows that the described recycling system is economically feasible even though the analysis presented is only for the first year of operation. However, the prices of the AC motor, switch, and the aluminum plate are not included since these devices and the material were already available.

Table 1. Price comparison: using recycled material vs. purchasing

Item	Price (\$)	Amount	Total (\$)
FilaMaker shredder	720	1	720
ExtrusionBot	772	1	772
Household blender (used)	10	1	10
Virgin material	10/kg	30 kg	300
Recycled material	-	10 kg	0
Subtotal			1802
Filament only	50/kg	40 kg	2000

Recently, a MakerBot Replicator Z18 3D printer was purchased. Unfortunately, large failed parts do not fit in the plastic shredder. For now, they are cut manually to a size adequate for the plastic shredder in the engineering machine shop. An undergraduate engineering student group is designing a pre-shredder cutter to complete the current recycling system.

At this time, most known inexpensive 3D printers based on FDM technology use non-proprietary filament, either 1.7 mm or 3 mm and print in ABS and/or PLA. Even XYZ 3D printers that have proprietary filament cartridges have been successfully re-filled with third-party filament. The recycling system for 3D-printed plastic can work with nylon, HDPE (high density polyethylene used as dissolvable support material), and flexible filament – however, since these materials are not used often they will be addressed in future research.

Further improvements to the described desktop recycling system would be necessary if the system is to be used in commercial applications. The motor currently used in the shredder (1/6 HP) would have to be replaced with a more powerful one. The household blender would also need to be replaced with an industrial-grade blender. Finally, some aspects of the extruder would have to be improved. For example, when the extruder starts the extruded filament often sticks to the nozzle and has to be manually detached from it.

Perceptions and Attitudes

To evaluate the pedagogical success of lab activities utilizing recycled materials for 3D printing, an assessment tool (short questionnaire) measuring students' attitudes is administered and analyzed. Also, student perceptions and attitudes are further explored using informal interviews. Some unsolicited statements from community events participants are recorded to illustrate the impact of the engineering 3D printing laboratory on the local community.

All undergraduate engineering students are required to use 3D printers in many of their courses. All students are asked to recycle their failed prints or unsuccessful designs. Since all engineering students have already been evaluated on sustainability topics in their courses, their sustainability knowledge was not directly assessed here. For the purposes of this study, a basic attitude test was

administered in the lab. Students were asked if they recycle in general and if they employ any other sustainability techniques in their everyday lives. Then, using a Likert 5 point scale, they were asked to provide their opinions about the importance of recycling 3D printed plastic. Finally, they were asked to estimate if the recycling efforts in the 3D printing lab with its 80/20 virgin/recycled material mixture are sufficient to claim the 3D printing plastics as environmentally responsible products.

Responses were mostly positive with only a couple students claiming ignorance. In general, the majority of engineering students recycle paper, plastic, and glass at home, student housing or on campus. They have calculated their carbon footprint and are aware of the importance of recycling with respect to sustainability. Specifically, students are proud that the 3D printing waste problem is addressed and that they are active participants in the solution. They are glad that through recycling, the 3D printing lab became more efficient and cost-effective. They see both ABS and PLA filaments as environmentally responsible products. However, we couldn't measure if these perceptions and attitudes resulted in a change in the number of prints and therefore in the amount of waste produced and recycled. Namely, as our engineering programs grow, more students use 3D printers, and as these students gain experience they print more complex designs resulting in a larger number of failed prints and an increase in material to recycle. Quantitatively characterizing student behavior with respect to 3D printing and sustainability requires further study.

Individual interviews with a number of students addressed questions about the usefulness of 3D printing technology in general, usefulness of sustainability efforts in the 3D printing lab, and coping with failed prints. Students show great enthusiasm for 3D printing technologies and are grateful to be a part of sustainability efforts. They also appreciate that their failed prints are not discarded but recycled. One student stated: "I am glad you recycle – this shows me that you respect my tuition money."

At least once a year, the university organizes an open house where members of the community are invited to visit classrooms and labs. The engineering 3D printing lab is a part of that event. Last year, the sustainable activities of the lab were emphasized. The recycling system was described and demonstrated. One of the local middle-school teachers commented "Wow, this is great. Can we bring our 3D printed plastic so you can recycle it for us?" An engineer stated "I am really impressed that you are not just teaching sustainability, but you have implemented it in practice."

This year, on January 28th 2016, SustaInnovation, a campus wide event on eco-engagement and sustainability networking led by an engineering student featured 3D printed PLA leaves supporting PLA as a sustainable, biodegradable material. During the event, there was a stand in front of the lecture hall with PLA brochures, 3D printed leaves, bracelets, bookmarks, and key chains. This shows community interest and engagement in sustainability efforts including 3D printed materials.

Conclusions and Future Work

This work addressed a sustainable 3D printing lab. A small desktop lab recycling system consisting of a desktop plastic shredder, a household blender, and an extrusion machine was developed, implemented, and justified. Student perceptions and attitudes dealing with 3D printing processes and 3D printing sustainability activities were assessed. The assessment results confirmed that students accepted 3D-printing technology and sustainability activities related to

3D printing as common elements of the engineering design process in general, and rapid prototyping in particular. ABS and PLA 3D-printing materials were regarded as environmentally responsible products. Community involvement and appreciation of the sustainability efforts in the department's 3D-printing lab were unintended positive results.

With further improvements of the desktop recycling system, new opportunities may arise. For example, the sustainable 3D-printing lab may accept 3D-printed recyclable materials from other educational institutions in the area. Also, commercial applications could be developed to help recycling efforts in 3D-printing shops and makerspaces. Further research is planned to include recyclability investigations of other 3D-printing materials like nylon, HDPE, flexible filament, metallic clays, etc. and technologies like inexpensive 3D printers for metallic clays or inexpensive 3D printers based on the SLA DLP (stereolithography digital light projector) technology.

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