# Evaluation of RepRap 3D Printer Workshops in K-12 STEM

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## Abstract

As facilitators of 3D printer workshops, the authors developed a survey to gage how the printers are actually being used and whether they support the Next Generation Science Standards (NGSS) requirements, especially in regard to engineering design. The survey response rate was 52% of 68 total participants with the majority conveying that 3D printers do facilitate student understanding of the engineering design process and that the workshops empowered them and their students to tackle projects previously perceived as beyond their skill level. Insufficient preparation for troubleshooting hardware and software issues was listed as the greatest barrier to fully realizing the technology's potential in the classroom. Also highlighted was a lack of resources for development of meaningful lesson plans using this nascent technology.


## Introduction

During the summers of 2013 and 2014 four workshops were held for high school science and technology teachers. The workshop participants built and commissioned their own RepRap 3D printers in order to take them back to their schools to use in classrooms. Workshops were intended to provide the tools and basic knowledge required to initiate creative project/problem based lessons reflecting the modern maker renaissance. Documented use of 3D printing in FabLabs and Makerspaces has provided some insight,[1,2] but these workshops are the first of their kind, so the survey responses provide crucial insight for improving future workshops and informing the maker community on the use of 3D printers in K-12.

## RepRap 3D Printers

RepRap (self-replicating rapid prototyper) 3D printers[3,4] are open-source 3D printer designs available for anyone to build. It is built on structural components that are themselves produced by another RepRap; they are indeed self-replicating.[5,6] Designs are proven and rapidly maturing and given that they are built with readily available parts, they are low cost and exceptionally high value. They consume a polymer filament, typically polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), converting it into a physical object by depositing it in thin, sequential layers. The entire technology, both hardware and software, is open-source and freely available.

University students, faculty and research staff at the Michigan Tech Open Sustainability Technology (MOST) laboratory have been researching, designing, building, testing and documenting versions of RepRap printers since 2010. Nearly everyone taking part in the research became caught up in the process of designing, printing, evaluating and modifying parts that were used for a variety of different purposes. Researchers working with their own children, as young as five years-old, discovered that the children exhibited a similar response. Furthermore, the act of building and commissioning the 3D printer was so empowering that many other complex machines and even scientific apparatus were designed, printed and tested in rapid succession.[7-9]

Researchers concluded that this combination of responses to the technology made it an exceptionally compelling tool for use in primary and secondary education, especially as states begin to adopt the Next Generation Science Standards (NGSS) which have an emphasis on engineering (and engineering design) not seen previously. The very low cost/high value of the technology was also thought to make it more attractive to cash-strapped school districts. It was also thought that since the printers would be built by the end-user, maintenance and upgrading would be easier for them to perform. This level of ownership would free them from fear of violating warrantees or being victims of the "no user-serviceable parts inside" paradigm common with most modern technology.

The RepRap had demonstrated utility in a wide range of educational environments,[10-13] therefore plans were developed for delivering a workshop intended for high school teachers wherein attendees would assemble, commission and learn to operate a RepRap printer and the open-source software tool chain that supported it. The goals of the workshop designers were to 1) share the empowerment that came with building and operating a complex machine with attendees, 2) build basic knowledge necessary for designing and printing parts, 3) build knowledge necessary for maintaining and troubleshooting the printer, 4) plant the seeds for developing lesson plans that tap the technology's potential for supporting  educational outcomes, specifically the engineering aspects of NGSS , and 5) develop a network of teachers using the technology in the classroom who would share their work, solutions to problems, and accomplishments.

**3D Printing & NGSS**

The Next Generation Science Standards (NGSS) have given cause for educators to re-evaluate the methods they use to teach STEM courses. One reason for this is that NGSS is the first set of standards to include engineering and the engineering design process; a topic with which many science teachers are unfamiliar. Studies indicate that high school and college science teachers alike are unprepared to teach the integration of content and practices using the new framework. [14,15] The NGSS guidelines include a framework of K-12 student practices that include design, constructing and/or testing the design of an object, tool, process, or system:

> "The purpose of defining "engineering" more broadly in the *Framework* and NGSS is to emphasize engineering design practices that all citizens should learn. For example, students are expected to be able to define problems—situations that people wish to change—by specifying criteria and constraints for acceptable solutions; generating and evaluating multiple solutions; building and testing prototypes; and optimizing a solution. These practices have not been explicitly included in science standards until now." [16]

One way to help students learn the relationships between engineering and science is to present them with scenarios wherein they define a problem, develop alternative solutions, and then optimize one design solution. Until recently practicing this problem solving sequence with actual custom designed and built components would have been a difficult task because the method used to construct the components has until now required the removal of material with machining equipment like saws, lathes and mills. With the advent of additive manufacturing processes utilized by 3D printing, this hurdle has largely been eliminated. This process, together with computer aided design software such as Google SketchUp and OpenSCAD[17], can be used to construct real objects from virtual 3D models allowing students to experience engineering design in a very hands-on and real way.

**RepRap K-12 Workshops**

The workshops generated STEM subject matter experts from a variety of school districts and grade levels. A total of 68 teachers representing 37 different school districts participated, with the majority (38, 56%) teaching 9-12 grade, (20, 29%) middle school, while the remaining (10, 15%) teaching courses in both middle school and high school. Subject matter expertise from most to least are; science, technology/engineering, science/mathematics, and mathematics with the most of teachers having 15-20 years of experience.

The Square One Education Network and MOST sponsored a 3-½ day workshop for high school teachers during the summer of 2013 wherein 20 teachers working in teams of two built and commissioned a MOST Prusa Mendal RepRap 3D printer. The "Innovative Additive Manufacturing" (IAM) workshop was the first of its kind, producing a dozen working 3D printers built by and for teachers to bring back to their classrooms (see Figure 1).

Figure 1. 2013 IAM workshop

Concurrent with the first IAM workshop in 2013, a University graduate course "The Engineering Process" was delivered as part of professional development training for practicing K-12 teachers funded by a Michigan Department of Education Improving

Teacher Quality grant. During the course two students from the class who are practicing high school biology teachers built and commissioned a MOST Prusa Mendel 3D Printer using the same format as the IAM workshop (see Figure 2).

As an aside, one reason RepRaps (or other 3D printers) are particularly advantageous for science teachers is that the teachers can use them to fabricate high-quality low-cost scientific equipment[18] as seen in mini-centrifuge in Figure 2b. The design built in these first workshops cost approximately $550 for the components, including the 3D parts printed on an existing machine (see Figure 3). It can be assembled in two days, as demonstrated during the workshops.[19,20]

Figure 2. 2013 The Engineering Process 3D printer workshop and a piece of science lab-ware developed from it.

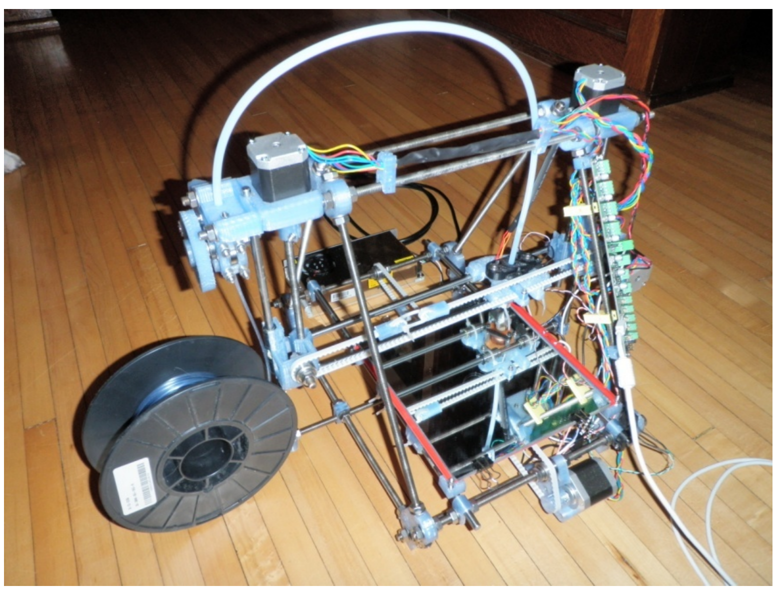

Figure 3. MOST Prusa Mendel RepRap

Following these workshops, the MOST group determined that building and maintaining the MOST Prusa Mendal 3D Printer was more difficult than the newer “Delta” style of RepRap. The Mendel design uses a full Cartesian motion system with the print bed translating in the Y direction. In comparison, the Delta style printer has fewer parts, a stationary print bed and an extruder that moves in all 3 axes.

The MOST group developed instructions and a kit of parts for the MOST Delta RepRap at a reduced cost of $450. The time to assemble the printer by a team of two was reduced to approximately eight hours. In addition, the structure of the frame is made with metal or wood, and for high schools with access to wood shops an additional educational opportunity exists in having students make and customize these parts (see Figure 4).

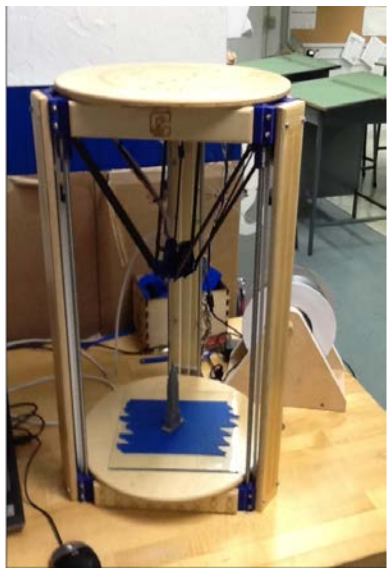

Figure 4. MOST Delta RepRap

With the reduced assembly time, the workshop schedule was redesigned to accommodate every attendee building a 3D printer. In 2014 the Square One Education Network and MOST sponsored the second IAM workshop where twenty-two high school teachers from K-12 schools working in pairs built printers for each of the 22 attendees (Figure 5).

Figure 5. 2014 IAM workshop teachers each building their own Delta RepRap

The final professional development workshop discussed here was conducted in 2014 primarily for science teachers in the Detroit Public School system. The workshop was supported by a grant for improving teacher quality from the Michigan Department of Education. Following the same format as the previous IAM workshop, twenty teachers built twenty MOST Delta 3D printers and learned to use them in their classrooms to help students solve engineering problems (Figure 6).

Figure 6. 2014 MDE grant 3D Printer workshop

Even though the four workshops differed in that the 2013 workshops used Mendel RepRaps and the 2014 workshops used Delta RepRaps, the philosophy providing the teachers a design-build-test experience that they could convey back to their students was maintained. The pedagogy was consistent between workshops in that teachers built the printer, learned to use the software for creating designs and operation of the 3D printer, and discussed ideas for how to integrate the 3D printer into classroom activities.

**K-12 STEM Workshop Content**

Each of the workshops utilized a facilitated, self-paced program with several experienced facilitators available to help participants as they worked through a wiki-based[21], fully illustrated build process. The facilitators consisted of University engineering faculty, a research engineer, high school teacher, an engineering graduate student and a high school student. Additional teacher assistants who had experience building 3D printers volunteered their services to help the process. In addition to building the printers, the teachers are given introductions for the use of the completely free and open-source software tool chain used to design and print models. The basic outline for the MOST Delta RepRap three day workshop is as follows:

Day 1:
0800 - Welcome attendees, make sure they all have laptops and internet access.
0830 - Introduction presentation. – How to utilize 3D printing in high school curriculum.
0900 - Assemble tools, start mechanical assembly of first printer.
1200 - Break for lunch away from assembly.
1230 - Complete assembly of printer one.
Day 2:
0800 - Start assembly of second printer.
1200 - Break for lunch away from assembly.
1230 - Complete assembly printer two.
Day 3:
0800 - Upload firmware.
0900 - Initial power up.
1000 - Calibration.
1200 - Break for lunch away from calibration.
1215 - Presentation: Intro to Thingiverse; downloading; slicing; printing.
1300 - Print a downloaded model.
1430 - Presentation: Intro to OpenSCAD
1500 - Design a simple model; save stl; slice; print

The first two days of the workshop are self-paced while the teams build their 3D printers. The majority of teams were dismissed after an 8 hour day, although teams took advantage of the evening hours preparing parts for day 2 and loading the necessary software onto their laptops. The final day of the workshop generally is 8-10 hours requiring each person to practice using the 3D printer.

At the completion of the workshop the participants were encouraged to join the Google Group comprised of people who have completed workshops or built a MOST Delta printer on their own. This provides an avenue for users to be involved in a forum where questions can be asked and answered and experiences shared after returning to their schools. The Google Group currently consists of 52 members with over 70 threaded discussions with members sharing successes as well as problems encountered. Several members have shared images of parts that their students have created for STEM problem solving projects (see Figures 7-9).

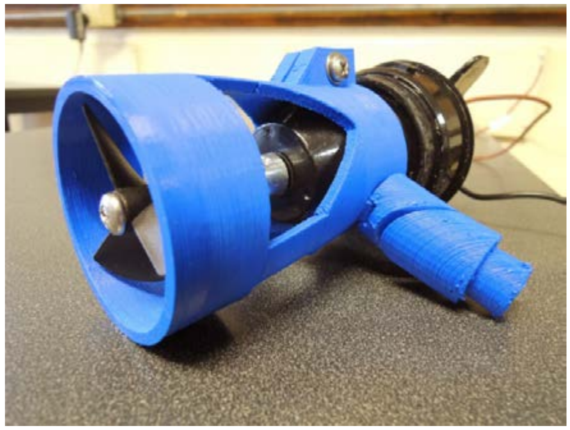

Figure 7. High School Student ROV (Underwater Vehicle) Design Project

Figure 8. High School Student C-clamp Design Project

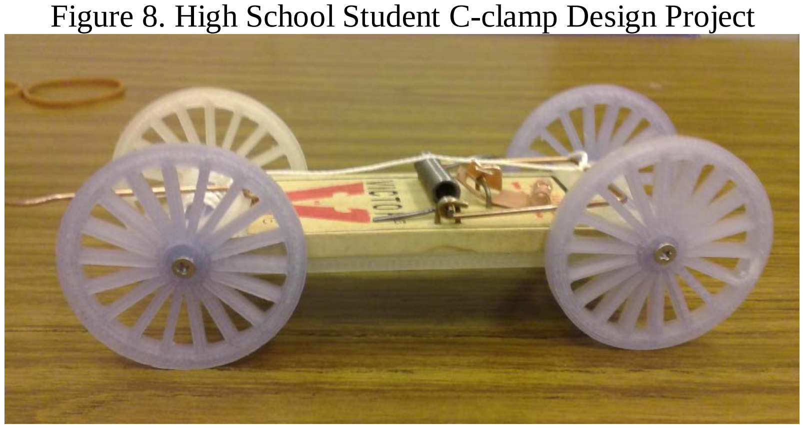

Figure 9. High School Student Mousetrap Car Design Project

## Workshop Evaluation Methodology

At the conclusion of each workshop the participants provided feedback through an online survey, the results of which were resoundingly positive. Participants strongly expressed an empowering “can-do” attitude after building a complex machine from scratch. One 2013 IAM workshop survey respondent commented:

> *“This conference was an amazing revitalization on my own excitement for teaching and working with kids. I couldn't have taken more away in 4 days than I did and I haven't been this excited about getting back to school in decades!!!”*

While this positive feedback is encouraging, it did not reveal whether the workshops made an impact after the teachers returned to their classrooms. To determine this, a follow-up survey was designed and sent to all workshop participants six months after the summer 2014 workshops. This gave participants in the first two workshops a full school-year of implementation, while the second (Delta) workshop participants had one semester’s worth of implementing lessons with the new technology on which to base their responses.

Using insight gained from facilitating the workshops, the authors developed the survey, collected the data, and analyzed results in an effort to determine the effectiveness of the 3D printer workshops. The study results will be used to help understand if and how 3D printers have been influential in student's understanding and practice of Engineering Design as described in the Next Generation Science Standards so as to improve future workshops. The survey consists of 10 short questions taking 10 minutes or less to complete. The questions include one demographic question, seven rating-scale questions and two open ended questions. All 68 participants were sent the survey (using Survey Monkey) allowing approximately four weeks for completion. There were 35 surveys returned, an approximate 52% response.

## Workshop Survey Results/Analysis

The following results are presented first with the survey question (presented in bold) followed by a summary of responses and analysis.

**Question 1: Which of the following describes the 3D Printer Workshop you attended?**
This question established which printer design was built and more importantly, how long the printer was available for student use in the classroom (see Figure 10).

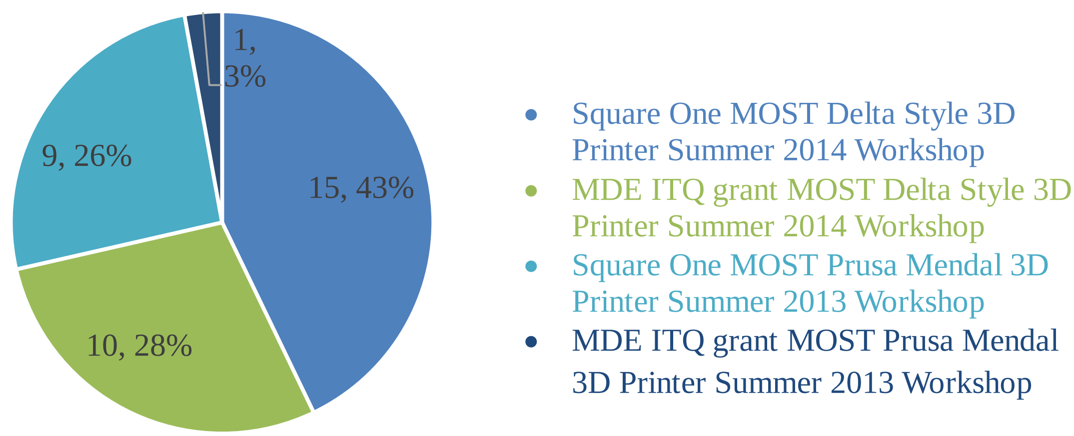


Figure 10. Survey Question 1

**Question 2: What is the frequency (per semester) that you have used the 3D printer for academic projects since the workshop?**

Over half of the respondents use the 3D printers 1-10 times per semester and (7, 20%) have not used the 3D printer at all since the workshop. Comments ranged from "*We use it for projects to enhance our regular curriculum and as a focal point in our after school STEM program*" to "*…and am having difficulty with installing software on laptop and getting it to communicate with printer*" (see Figure 11).

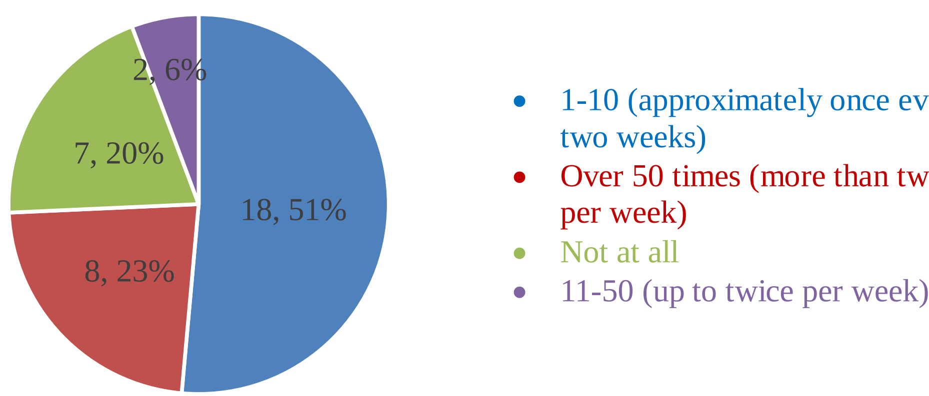


Figure 11. Survey Question 2

**Question 3: Select any obstacle(s) that may exist to integrate the 3D printer into academic lessons (select all that apply).**

For this question respondents were asked to select all that apply and to suggest others that also exist. The top rated obstacle (13, 20%) was insufficient experience/training to troubleshoot issues and the least rated obstacle was insufficient student interest/enthusiasm (0, 0%). The category of "other" obstacles suggested by respondents suggested factors out of control for teachers like "*Limitations due to time (pacing chart)*" and "*Cost of PLA since printer was acquired after budgets were placed for this year*" (see Figure 12).

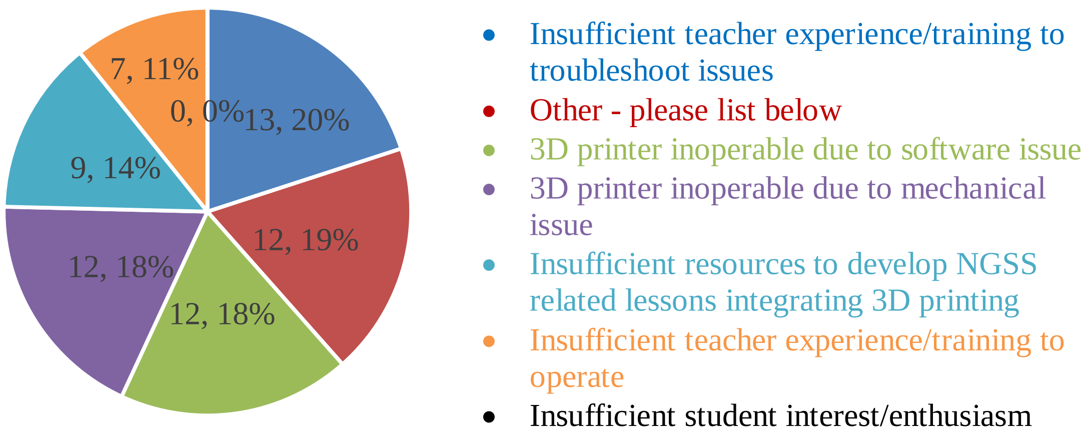


Figure 12. Survey Question 3

**Question 4: Rate the level of support provided from online resources (such as MOST Google Group, RepRap Website, Appropedia wiki, others) for maintaining your 3D printer.**

Because the highest rated obstacle was insufficient experience/training to troubleshoot issues it makes the support resources very critical to the success of implementing 3D printing in classrooms. The majority of respondents (22, 63%) rated the support as excellent or very good and (0, 0%) as poor (see Figure 13).

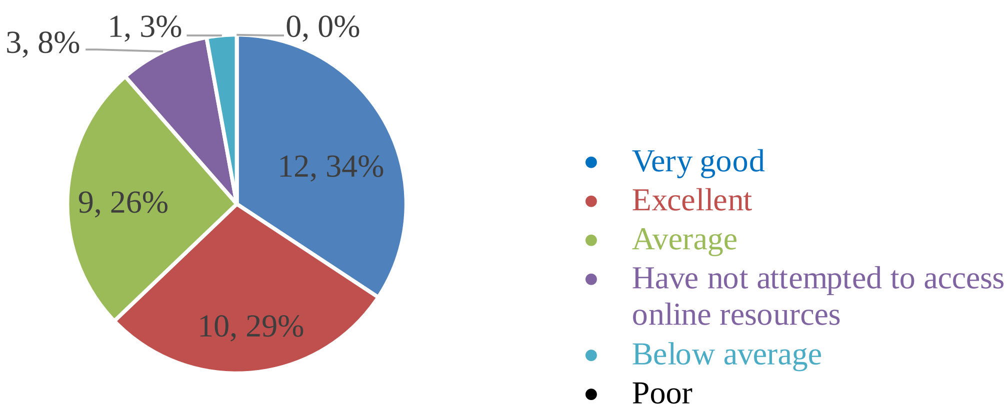


Figure 13. Survey Question 4

The next two questions are specifically aimed at understanding how the 3D printer has impacted student’s understanding of the problem solving process described in the NGSS. This context was established by introducing these questions with the following statement taken directly from NGSS documentation:

> While answering the following questions please refer to the guidelines from "APPENDIX I - Engineering Design in the NGSS" as stated here:

*A. **Defining and delimiting engineering problems** involves stating the problem to be solved as clearly as possible in terms of criteria for success, and constraints or limits.*

*B. **Designing solutions to engineering problems** begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.*

*C. **Optimizing the design solution** involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important.*

**Question 5: When referring to the "Engineering Design in the NGSS" description, does the 3D printer contribute to student understanding of the problem solving process described?**

The majority (25, 71%) of the respondents reported that the 3D printer contributes "very much" to student understanding of the problem solving process described in the NGSS guidelines (see Figure 14).

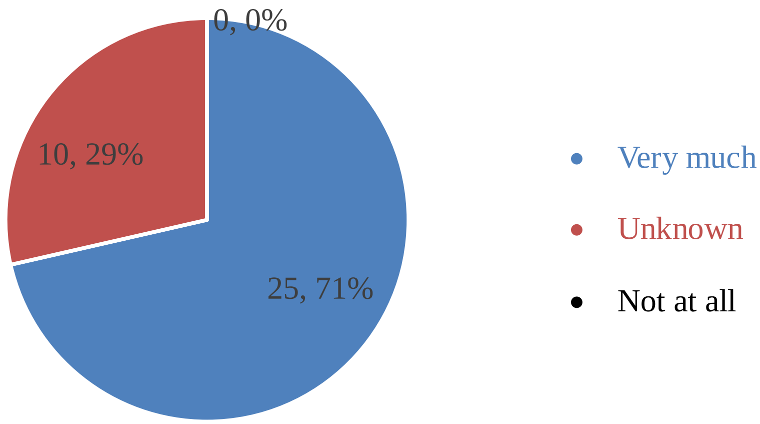


Figure 14. Survey Question 5

**Question 6: Select and rank the items listed below that would be most helpful to integrate your 3D printer for teaching "Engineering Design in the NGSS" in your classroom. (1 = Most Helpful, 4 = Least Helpful.)**

The top ranked item by respondents was "Professional development for "Engineering Design in the NGSS" lesson plan creation integrating 3D printing." Some other suggestions for helpful methods that were suggested by respondents were; "*More professional development in using different design programs*", "*A workshop where we can bring broken printers and repair them with guidance.*", "*Detailed Curriculum materials - step by step. Online resources. Put course on Moodle, make it free*", "*Shared lesson plans would be fantastic- particularly ones that would scaffold from a very simple start that is applicable at the elementary level.*" and "*A booklet with information and specs on my printer.*" The second highest ranked item was "3D printer software hardware troubleshooting support help" which was also addressed in question 3 where teachers expressed that the top obstacle was insufficient troubleshooting experience (see Figure 15).

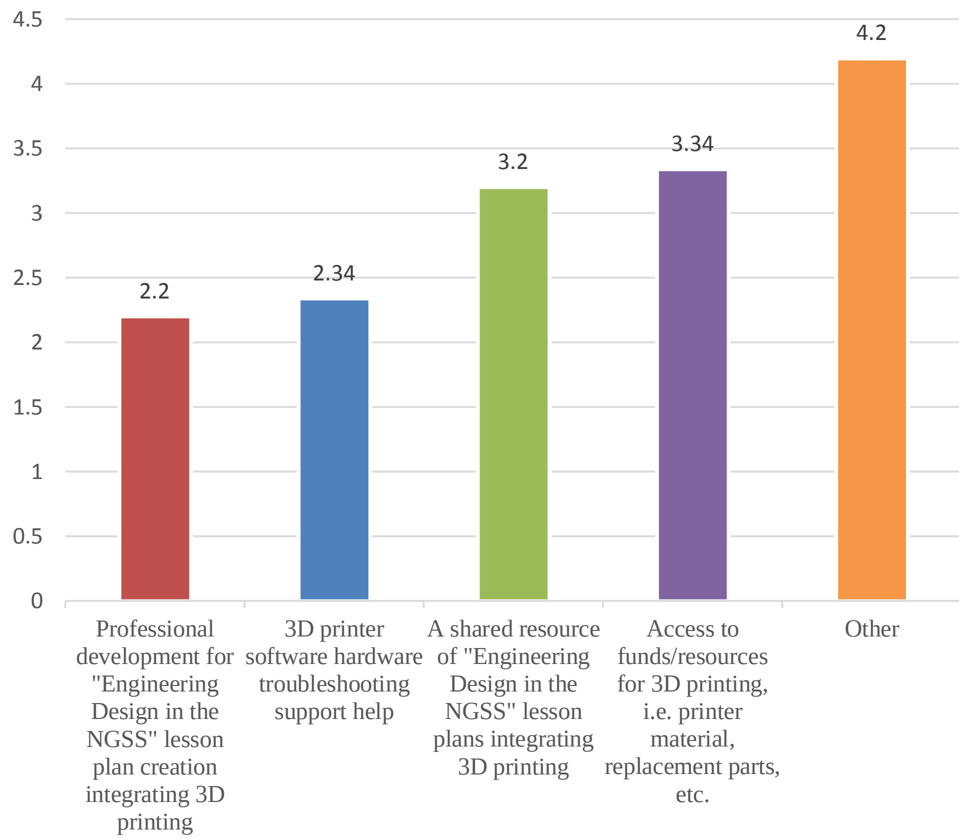


Figure 15. Survey Question 6

**Question 7: After building, commissioning and operating the printer, do you feel empowered to tackle projects that heretofore you would have considered beyond your skill level?**
**Question 8: Do you think this experience can be imparted to your students?** (see Figures 16 &17).

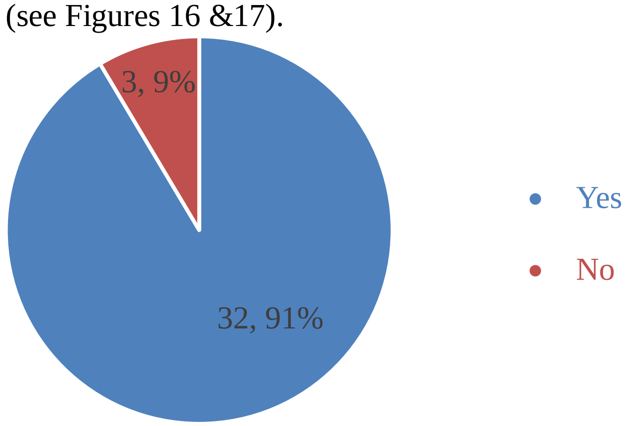


Figure 16. Survey Question 7

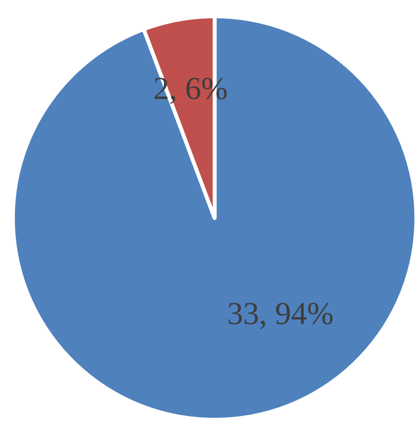


Figure 17. Survey Question 8

**Question 9: What aspect(s) of this technology do you find to be particularly valuable with respect to delivering outcomes specified by the NGSS?**
**Question 10: How do you intend to assess the efficacy of the technology in delivering those outcomes?**
Many of the respondent's answers to these open-ended questions relate to the problem/project based learning approach. For instance, one respondent answered the question 9 stating:

> *"The 3D printer solves the historical problem of not being able to make a prototype. Now the students can imagine a design, create a prototype and evaluate it."*

The same respondent followed with the answer to question 10 by stating:

> *"I will assess the efficacy of the technology by utilizing project based learning with my students. They will be given clear objectives to meet. When they meet these objectives, I will be better able to establish the intrinsic value of their outcome. The students will be required to complete debriefing activities, which will include giving a presentation on how their product met their project's original objectives."*

**Interpreting the Survey Results and Recommendations**

Because of the overwhelming number of positive responses to questions 5, 7 and 8 make clear the potential these workshops possess to provide teachers the means to implement NGSS driven design in their classrooms. The responses to these key questions show that;

1. a 3D printer can contribute to student understanding of the problem solving process,
2. the workshop empowered many of the teachers to tackle projects previously perceived as beyond their skill level, and that
3. this experience, rich in engineering practice, can be imparted to students.

Even though there are many positive aspects to these survey results there is much improvement that can be made concerning future workshops to ensure that the 3D printers will be used more universally and used in ways that enhance student understanding of engineering design.

The workshops offered too-little guidance in troubleshooting software and hardware issues once the 3D printers are deployed in classrooms. Although each workshop attendee actually printed an object with their own printer before leaving the workshops, many participants experienced difficulty when it came time to install the necessary software on computers at their schools. Some of these issues were anticipated given the security structures in use on school computer networks. However, many of these issues result from the relatively immature state of software in use with this nascent technology.

Indeed, the open-source ecosystem in which RepRap 3D printers are entirely steeped is at the same time its most compelling and promising feature and its greatest deterrent to adoption. The open-source rationale has at its foundation the intent of rapidly improving both software and hardware by decentralizing development among a global population of user-developers. Unfortunately, this largely flies in the face of modern business which relies on attracting buyers with a “point-and-click” product that is ultimately disposable and contains no user-serviceable parts. Consumers have been conditioned to expect a product that “just works” without any knowledge or effort on their behalf. Too often, open-source solutions violate this expectation; they require that users have some level of knowledge before they will work at all. Many users have no initial interest in being developers and some never make the transition. However, as the results of this study show, a large majority of teachers were able to make this transition to makers away from being simple consumers. Many provided comments and suggestions to developers thus becoming de facto developers and in one workshop a teacher had even designed and printed a guard for the extruder drive gear before even leaving the workshop.

The initial intellectual investment is clearly the greatest impediment to fully leveraging the potential this technology has for delivering NGSS Engineering Design goals. The software tool chain required just to operate the printer is long and parts of it are complex, well beyond the experience and comfort of an average consumer. The workshop designers are actively engaged in addressing this issue by developing new software and hardware that will eliminate many of these issues (e.g. installation of obscure device drivers and/or installation of non-approved software on locked-down school resources).

There is also a clear need for continued teacher professional development for how to implement problem/project-based learning approaches integrating the engineering design process as illustrated in question 6. The need expressed by the survey respondents for additional professional development could be offered through online video tutorials, a troubleshooting guide for common software and hardware issues, and links to lesson plans offering project/problem based learning approaches used to address the engineering design process as expressed in the NGSS.

As the prohibitive cost of plastic filament was also a concern identified by the respondents, future workshops may be augmented with the inclusion of a recyclebot[22], which is a plastic extruder capable of producing filament from wastes for a small fraction of the cost of commercial filament.[23,24] Versions of these plastic recycling machines are currently being used in a few of the schools we worked with and the preliminary results are promising.

Future workshops should contain at least one fully-tested lesson plan to assist the teachers to get started with the RepRap 3-D printers in their classrooms. The group is now working to adapt lessons and assignments from college level 3D printing courses so they can be effectively used in the K-12 science learning environment. Further direct and indirect measures of student learning of engineering design in the NGSS utilizing 3D printing technology is recommended.

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