# DESIGN AND ASSESSMENT OF AN AM VENDING MACHINE FOR STUDENT USE

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## ABSTRACT

Due to prohibitive costs, access to Additive Manufacturing (AM) technologies at academic institutions tends to be limited to upper-level courses that feature significant project-based coursework, such as capstone design. However, with the decreasing cost of desktop-scale AM technology, there is potential to improve student access to such technologies throughout a student's undergraduate career, and thus provide more opportunities for AM education. In this poster, the authors present the design and implementation of an AM "vending machine" that is powered by desktop-scale extrusion-based AM systems. The resulting machine allows for unrestricted student use of AM equipment, and thus provides ample opportunity for informal learning regarding AM. The results of a formal assessment of student use of the machine are presented.

**Keywords:** 3D Printing, Material Extrusion, Vending Machine, Informal Learning

## 1. STUDENT EXPOSURE TO MANUFACTURING

In the "2009 Roadmap for Additive Manufacturing," the workshop participants identified education as a critical area of research and development for the advancement of the Additive Manufacturing (AM) field [1]. Fundamentally, it was thought that current and future engineers' familiarity with AM technologies was lacking, and as a result, was a barrier to AM adoption. As a result, the document urged the development of university "programs for educating the general population to enhance the interest in AM applications and generate some societal 'pull' for the technologies" [1]. AM curricula is emerging in U.S academic institutions (e.g., [2, 3]), but is not yet pervasive.

Providing hands-on learning experiences with AM, and advanced manufacturing technologies in general, has historically been cost prohibitive for most academic institutions. Specifically, costs of purchasing, operating, and maintaining the manufacturing equipment (and costs related to staffing) have often limited the number of institutions with interactive manufacturing curricula. As a result, student access to manufacturing technologies is typically limited to classroom and class laboratory settings. While these contexts provide valuable experiences, they are inherently constrained by the classroom itself. Students have limited hours to access the equipment, have limited amount of working material, and most importantly, are working within the confines and rule sets of an assignment. Unfortunately, these limitations somewhat constrain student learning. Emerging engineering education research suggests that design-based, semi-autonomous experiences in informal learning settings provide important opportunities for self-directed learning.

### 1.1. Manufacturing Informal Learning Environments: Opportunities and Challenges

Most of educational pedagogical practice, development, and research is focused in crafting meaningful experiences in formal learning environments; i.e., learning within the confines of a classroom. However, there is increasing interest in informal learning environments – extracurricular activities such as internships, design competitions, and student engineering professional societies – as they have been shown to positively contribute to students' engineering education [4]. These informal learning environments are characterized as unstructured, socially-based educational environments wherein students collaborate autonomously on a project. A hallmark of these environments is that they are "person centered," meaning that the objectives and goals of the activities are selected by the students, and not imposed by an instructor.

Research of informal learning environments suggests that they can promote and enhance student skills in leadership, collaboration, communication, innovation, and motivation [5]. In addition, informal learning environments have shown to be effective for promoting learning outcomes related to interdisciplinarity [6] and design education [7]. These results are supported by the situated cognition learning theory, which states that knowledge is contextual and is a product of the situations in which it is created, and is thus positively influenced by professionally authentic activities [8].

Manufacturing-related informal learning environments would resemble student machine shops (or equivalent spaces) wherein students are provided autonomous control of the facility to explore manufacturing in a project-based context that is relevant to a personal interest. However, due to the aforementioned resource constraints, few institutions offer such opportunities. Those that exist (e.g., Virginia Tech's Ware Lab [9], Penn State's Learning Factory [10, 11], Georgia Tech's Invention Studio [12] and emerging Makerspaces and Techshop) are often constrained by factors such as:

- *Scale*: The labs are often not large enough to support the entire student body interested in making.
- *Safety and Insurance*: Due to safety concerns of the students (and the equipment), institutions are often relunctant to provide true open access to manufacturing spaces. To overcome this requirement, spaces often require significant training (taking the form of formal classes in some cases), staff oversight, and insurance costs.
- *Institutional barriers to access*: In addition to potential pre-requisite safety classes for shop use, most spaces employ institutional barriers to access such as limits to students of certain departments/colleges and/or of specific design projects (e.g., competition teams). Furthermore, it is rare that shop space is available to students who wish to work on projects that are not directly related to a specific class or research project. This is often justified by the desire to spend a department's resources on only its students.

While these constraints provide a structured way of managing institutional resources, they unfortunately impose inexplicit barriers to student access to informal manufacturing learning opportunities.

## 1.2. Context

Recognizing the importance of exposing future engineers to AM technologies, the authors seek to provide an open-access environment in which students can experience AM (and manufacturing in general). This vision is motivated by the constraints of the existing manufacturing-related learning environments at Virginia Tech and similar large-scale academic institutions. The Virginia Tech College of Engineering offers several AM-related student experiences: the Frith Lab features a Stratasys uPrint system for a few selected design teams; the staff-run machine shops within the departments of Mechanical Engineering and Aerospace Engineering offer AM as an option for realizing students' classroom design projects; the DREAMS Lab, a AM research lab, offers limited support for using AM for specific design and research projects; and there exists a dedicated AM course for senior undergraduate students and graduate students in the College of Engineering. Despite these opportunities, student-access to AM is limited, especially given the scale of the Engineering student body (8,642 students).

In the face of these limitations, the authors desired to develop a mechanism for increasing student access to manufacturing tools and to increase student awareness of modern manufacturing challenges and considerations. Towards this goal, the authors have created an AM "vending machine" for use by all faculty, staff, and students. The purpose of this paper is to document and share the design rationale, the implementation details, and assessment of the system in hopes that these details might aid others' future embodiments. The authors present an overview of the overall system design goals and rationale in Section 2. A discussion of the system embodiment and implementation is offered in Section 3. Preliminary assessmet of the impacts of the system on student learning is provided in Section 4, including both qualitative (Section 4.1) and quantitative (Section 4.2) results. Closure and thoughts on future work are offered in Section 5.

# 2. OVERVIEW OF THE AM VENDING MACHINE SYSTEM

Recognizing the challenges in offering hands-on manufacturing educational experiences at a large-scale institution such as Virginia Tech (Section 1.1), the authors were driven to create a means for students to experience AM technologies with almost no barrier to entry. From this overall goal, the team conceived of an AM "vending machine" system concept. The overall concept of an AM "vending machine" is a system that automatically fabricates and dispenses parts on-demand at the users' request. Instead of providing money in exchange for a fixed piece of inventory, a user provides an AM vending machine a digital part file of his/her own design.

The vending machine interface was identified as a novel means of providing students access to AM, that also circumvented inherent limitations of formal experiences, for the following reasons:

- The system provides means of educating students about AM via hand-on interaction with the technology and via a display of parts fabricated via a wide variety of AM systems. Furthermore, a vending machine interface provides a means of educating students about

AM at a large scale: no registration or formal training is needed to use the system, and it is available at all times.

- The system provides a user interface that is neither intimidating nor imposes perceived barriers to entry. Unlike a dedicated room or laboratory, which might feature locked doors or require user accounts, a vending machine has an interface that is immediately comfortable to the user and imposes no preconceived notion of ownership. Traditional vending machines are operated by everyone and do not require "permission" to use.
- The system can be placed in a public space, such as a hallway, and thus have high visibility and high student interaction.
- The system can be designed and operated economically, and thus can be used by students to create parts for any purpose: design project, classroom assignment, personal projects, etc.
- A vending machine system illustrates the ability of AM to provide just-in-time manufacturing solutions. In effect, the vending machine interface provides a juxtaposition: while traditional vending machines feature a fixed inventory, a vending machine powered by AM systems provides an infinite inventory by delivering user-defined products on demand.

## 3. AM VENDING MACHINE SYSTEM EMBODIMENT

From the overall vision and design goals for an AM vending machine (Section 2), the team created "The DreamVendor," a vending machine system powered by four MakerBot Thing-O-Matic (TOM) desktop-scale extrusion systems [15], as shown in Figure 1. The system case is composed of an extruded aluminum frame, laser-cut acrylic, and custom-made components made via laser sintering (e.g., bin handles, bin hinges, Interface Board mounts).


(a) (b)

**Figure 1.** Images of (a) the DreamVendor system and (b) the Thing-o-Matic extrusion machines in operation.

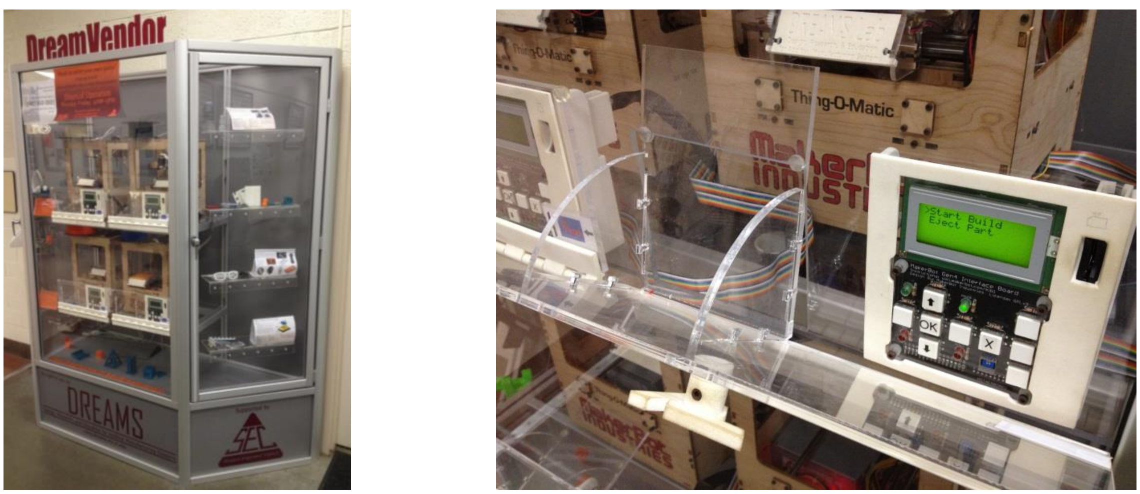
A student begins by loading his/her design (in the form of the MakerBot .s3g toolpath file) onto a SD card. The student loads the SD card into the machine's control panel, and selects the file to print. Once the print is complete, the part is ejected into a bin to be retrieved.

### 3.1. System Implementation Details

At an abstract level, an AM vending machine system must perform four primary functions: (i) receive user input, (ii) fabricate part, (iii) dispense part, and (iv) assess the user experience. In this sub-section, the authors detail the manner in which the DreamVendor accomplishes each of these sub-functions.

<u>*Receive User Input*</u>

The primary “vending machine” user interface is driven by MakerBot Interface Boards [16] that are connected to each of the system’s TOMs (Figure 2a). The interface boards are installed onto the face of the display cabinet using custom designed holders that were manufactured via laser sintering. Using their own personal computers, students generate G-code from their designed .STL file using ReplicatorG software [17]. Students’ file preparation is guided by thorough instructions provided at the DreamVendor website [18]. The resulting G-code is then transferred to a SD card before coming to use the DreamVendor. Once they arrive, the users input their SD card into the appropriate slot on the Interface Board. Using the buttons on the board, they can then view a list of files and select the appropriate file for fabrication (Figure 2b).




(a) (b)

**Figure 2.** (a) The DreamVendor cabinet and (b) user interface board and part ejection bin.

The team considered many other potential solutions for the “receive user input” function. Initial concepts featured users bringing STL files to the vending machine via memory stick; however, it was determined that it was not ideal to have users waiting to slice and generate toolpath while standing at the machine. “Cloud-based” submission solutions (i.e., a cyber-enabled system that allows users to submit files over the internet) were also considered; however, they were not selected for their implementation difficulty.

*Fabricate Part*

Once a part's G-code is selected on the user interface board, the TOM first preheats the build platform and nozzle, and then begins fabricating the part in a layerwise fashion. The modified Interface Board firmware displays the print time and percent completion during a build on the LCD screen.

To ensure that the provided files are compatible with the DreamVendor TOM hardware, the team created a unique "DreamVendor" ReplicatorG profile that students are instructed to use to prepare .STL files. In addition, the Interface Boards' firmware was modified to include a check of the user-provided G-code; if it is detected that the user failed to use the specified profile, the machine will not print the selected part. These precautions are necessary to ensure that users do not accidentally provide G-code that could harm the machines. Finally, the modified firmware provides a secret maintenance menu (accessed by a sequence of buttons on the Interface Boards) that allows users to input basic maintenance commands (e.g., jogging the motors, heating or cooling the printheads, etc.).

*Dispense Part*

Once a user's part has finished printing, a system is necessary to remove the part from the build platform so that other users may use the machine. To this end, the Thing-O-Matic's Automated Build Platform (ABP) was used for ejection. The ABP is composed of a conveyor belt that wraps around a TOM's heated build platform. When driven by its motor at the conclusion of the build, the conveyor belt effectively removes the part from the system as it conveys across the front edge of the build platform. Upon ejection, the part lands in a part collection bin that is mounted into the face of the cabinet. The bin and the interface board are shown in Figure 2b. To ensure that all new builds begin on an empty ABP, the DreamVendor ReplicatorG profile has been modified to include a command in the G-code to turn the conveyor belt before each print.

*Assess the User Experience*

One drawback of using SD cards containing G-code as the primary source of user input is that there does not exist a manner in which to capture data on number and content of printed parts, which would be a valuable resource for evaluating the efficacy of the DreamVendor. Due to this limitation, a secondary assessment instrument was devised to collect information from users.

Specifically, an electronic survey kiosk has been installed onto the side of the vending machine. This system, powered by an Android tablet, allows for real-time assessment and feedback of student use of the DreamVendor. The assessment instrument, an eight-question survey, is driven by a custom-made DreamVendor application. The results from this survey, exported as a .TXT file, are automatically uploaded to a DropBox folder each evening via the tablet's embedded wifi. Results from this assessment are discussed in Section 4.

### 3.2. System Operation Details

The DreamVendor was designed, manufactured and installed by a volunteer team of four graduate students over the course of one year. Initial funding for the system was provided by a student organization; continued financial support, which is used to purchase raw material for the TOMs, is provided by student enrollment fees. Due to these contributions, the system is completely free to use for all faculty, staff, and students of the university, regardless of their year or departmental affiliation.

The DreamVendor was installed in the main lobby of the Randolph Hall at Virginia Tech, which is home to the Aerospace and Mechanical Engineering departments, as well as classrooms for first-year engineering curricula.  This location ensures tremendous foot-traffic by the DreamVendor, and provides a broad exposure.

As the TOMs are of a hobbyist, desktop scale, they are not engineered for around-the-clock fabrication that is required for the "vending machine" context.  As such, system maintenance is often a continuous process.  The DreamVendor's inclusion of four TOMs provides a modular design; if one is under maintenance, it can be either replaced by another system, or repaired without disrupting the other three functional systems. Day-to-day maintenance, which can include unclogging nozzle heads, reloading material, clearing crashed builds, and lubricating machine axes, is conducted by a team of undergraduate student volunteers.

## 4. PRELIMINARY ASSESSMENT OF STUDENT USE

Originally unveiled in March 2012, the DreamVendor system has become a focal point for the Virginia Tech undergraduate engineering curriculum. It has also become a central point of prospective student tours and outreach activities (Figure 3).  This outcome is due to both the DreamVendor's role as a prototyping resource for all students and its nature as a catalyst in creating an informal learning environment.  Preliminary assessment of the system is provided in this section using both qualitative (Section 4.1) and quantitative (Section 4.2) sources.

**Figure 3.** An outreach event targeting under-represented groups visits the DreamVendor

### 4.1. Qualitative Assessment

Since its unveiling, the DreamVendor system has been in almost constant use during its 8 hours of open operation each day. Student use can be classified into three categories:

- *Experiential parts*: Students initial experience with the DreamVendor tends to be focused in participating in the experience. As such, parts are often tokens, statuettes, and other aesthetic tchotchkes that have been downloaded from the internet.
- *Prototype parts*: Providing open access to AM has provided many students the resource needed to create prototypes of their novel designs for personal and classroom projects. One example is a design team, which printed models of fuel-cells for planning the layout of their hybrid-electric competition vehicle. In addition, students conducting analytical research have also used the system to print physical prototypes of the systems they are virtually analyzing.
- *Functional parts*: Students have also used the DreamVendor to create parts that they implement and use. For example, students from Design/Build/Fly competition have used the AM vending machine to fabricate bay doors for their aircraft. In addition, students have created parts for their personal projects, such as the (i) cellphone solar charging device, (ii) monoscopic camera/mirror mount, and (iii) custom toothbrush holder shown in Figure 4.

(a)

(b)


(c)

**Figure 4.** Functional objects created on the DreamVendor: (a) solar-powered cellphone charger, (b) monoscopic camera/mirror mount and (c) custom toothbrush holder.

Beyond its role as a formal student prototyping resource, the DreamVendor system has also exhibited a significant informal learning component. It is not uncommon during the day to see students crowd around the DreamVendor while it is in operation to discuss concepts related to

CAD/CAM, AM, design, and manufacturing. In fact, students have reported learning CAD software just to be able to use the machine. The DreamVendor's undergraduate maintenance team members also have the opportunity to gain hands-on experience in a basic research capacity, coming up with ways to further increase the impact of the DreamVendor. In addition, an extracurricular design competition ("CreatiVT") that awards the "Best Use of the DreamVendor Award" is held each semester to help encourage student design thinking and to help build a community of use.

### 4.2. Quantitative Assessment

As noted in Section 3.1, the team's ability to formally assess student use of the DreamVendor is limited by the fact that the system does not retain copies of users' prints. To provide some means of assessing student impact, the team installed a survey kiosk onto the system. The custom Interface Board firmware asks students to complete the survey before every build. This survey is voluntary and seeks to collect basic information on the demographics of the students using the system as well as on the parts that they are printing. Over the course of 5 months of operation, the survey has had 186 respondents.

For demographic information, students are asked which college they belong to within Virginia Tech, which department they belong to, and what year of study they are currently in. Results for each of these questions are presented in Figures 5, 6, and 7, respectively.

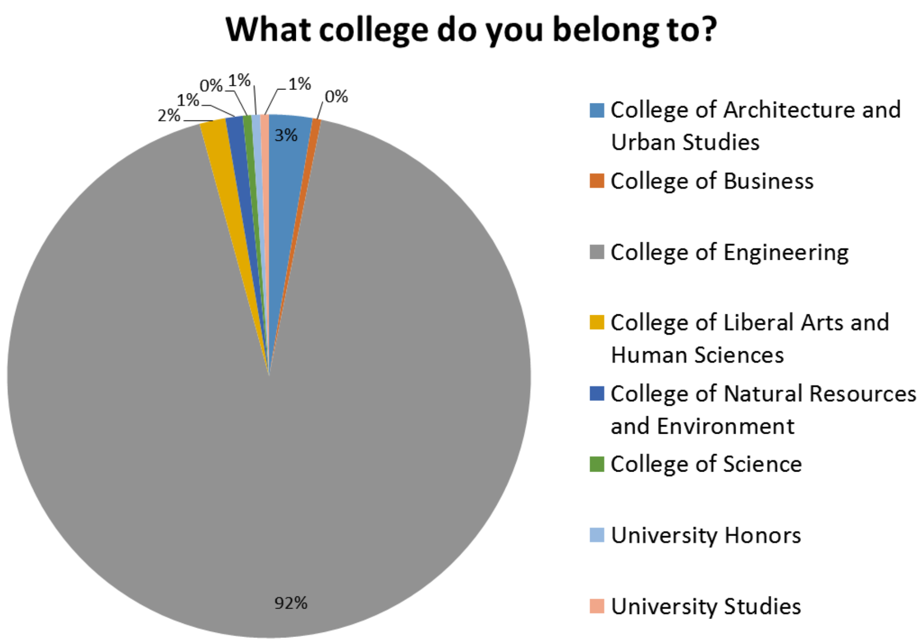



**Figure 5.** College affiliation of DreamVendor users

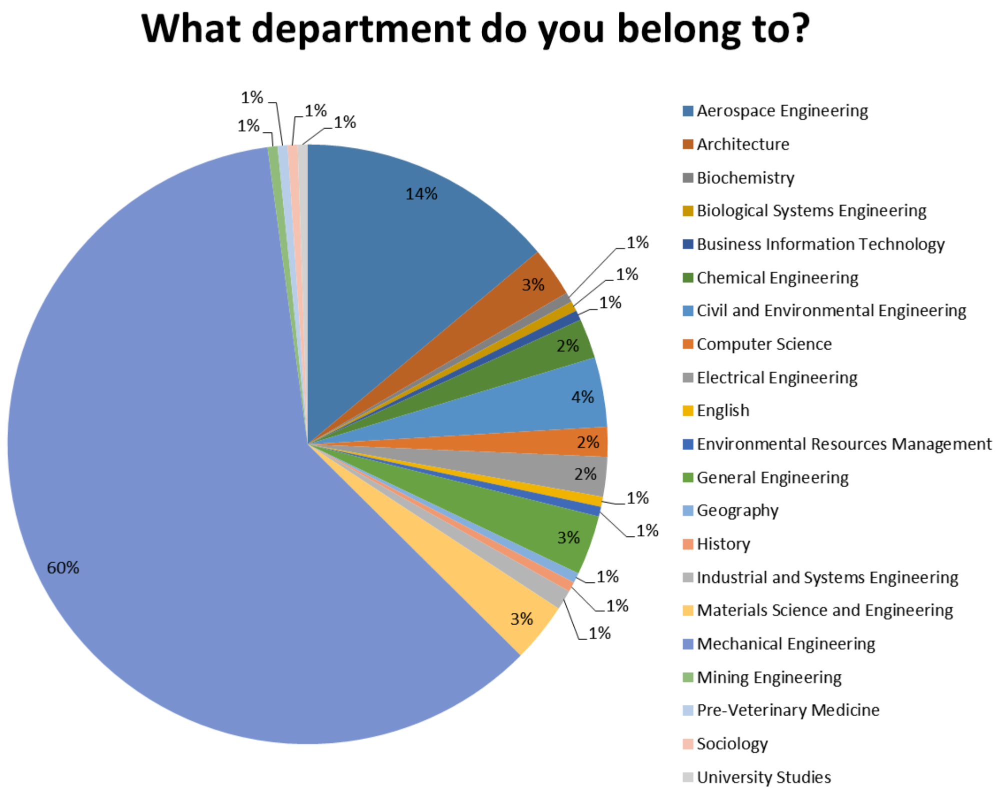



**Figure 6.** Departmental affiliation of DreamVendor users

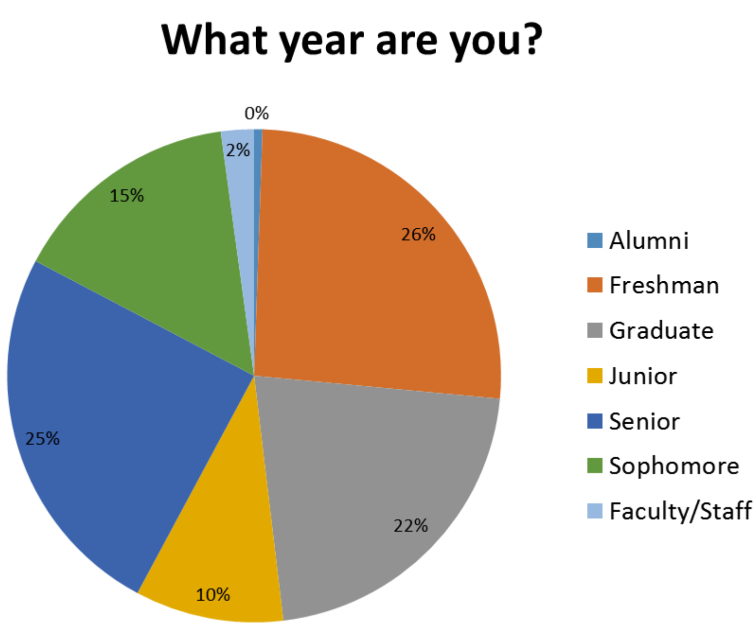



**Figure 7.** Year of study of DreamVendor users

From this data, it is clear that the majority of users are associated with the College of Engineerin. While other university colleges are represented, it is in small proportion to the

College of Engineering. Within the college of Engineering, the majority of users associate with mechanical engineering (60% of sample), with a significant number also associated with Aerospace Engineering (14% of sample). This result aligns well with the field of AM, which is most likely to resonate with Mechanical and Aerospace Engineers at this point in their academic careers. It also aligns well with the DreamVendor's location in the building which houses both departments.

The year of study distribution appears to be more evenly divided among the users, with Freshman students in the majority (26% of sample) and Seniors in second by a small margin (25% of sample). This data suggests that the goal of offering prototyping capabilities to students involved in hands-on design coursework (cornerstone design for freshmen, capstone design for seniors) has been achieved.

Data collected regarding student part creation is similarly illuminating. Students were asked, in general terms, why they were printing the part, whether or not the part was decorative or functional, and how they acquired the part design. Results from the first of these questions (Figure 8) clearly shows that the majority of the students are creating parts for personal use (73% of sample). A sizable portion of students also created parts in fulfillment of their coursework (12% of sample). Student responses to the next question (decorative vs. functional) shows that 50% of users are creating functional parts while 50% are creating decorative parts. This distribution suggests that a sizable portion of student users see the potential in AM processes, even simple desktop-scale extrusion, to create functional, end-use parts. The final question on the survey, asking students how the acquired the part, provided incredibly promising results (Figure 9). 72% of parts made on the DreamVendor system were designed and created by the students themselves. Only 25% of parts were downloaded from online websites such as Thingiverse. This result demonstrates that the majority of students are using the system to create something of their own design, rather than simply acting as consumers of someone else's design. This helps validate the DreamVendor's position as an effective tool to encourage student learning.

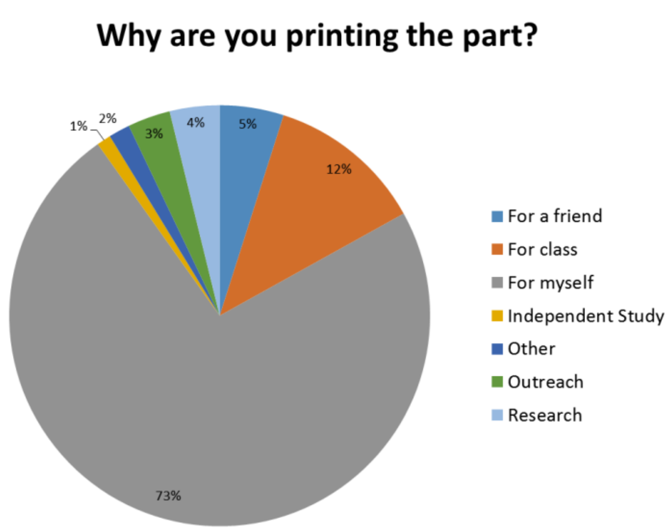



**Figure 8.** The intended use of parts created using the DreamVendor

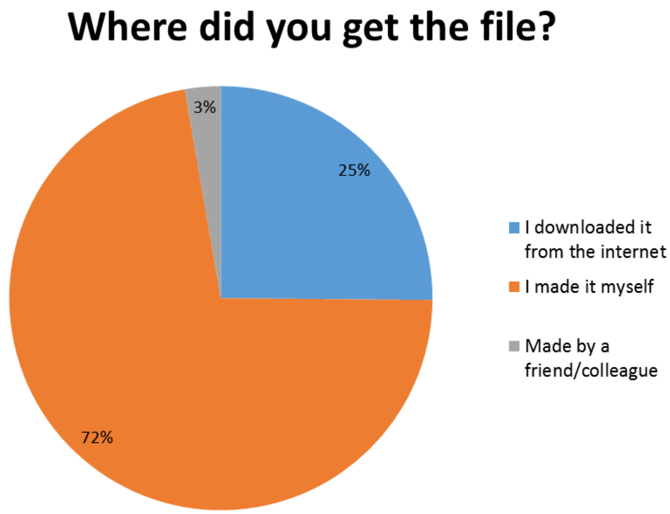



**Figure 9.** Acquisition source of parts created on the DreamVendor

In addition to the quantitative data presented above, students were asked to provide anecdotal evidence of their DreamVendor by providing more specific details about their printed part as well as leave any additional comments about the DreamVendor system. Student comments reveal a wide variety of printed parts for a wide range of uses. Printed parts include a model rocket body, an automatic fish feeder for while a student was away on vacation, various phone stands and cases, as well as a horse massager designed and created by a Pre-Veterinary student. Additional student comments include,

- *"Thank you for having these for free! I love being able to use them and I want to learn CAD more because of this and I have actually started to learn inventor more because of this!";*
- *"This is awesome! Thank you for letting students use this facility.";*
- *"Great opportunity for all students, I am glad it is free."*

While these comments only represent the thoughts of a portion of all users (most users declined to provide additional comments), they clearly demonstrate student appreciation for the manufacturing opportunities afforded to them by the DreamVendor System.

## 5. CLOSURE AND FUTURE WORK

In this paper, the authors have discussed the design and implementation of the DreamVendor public use AM system. The overall design of the system is discussed, as well as specific methods for addressing the user interface, part ejection, assessment, system maintenance. Preliminary assessment has shown that the system meets the goal of encouraging students of all grade levels to learn more about AM and CAD and to create their own parts. Of all the educational benefits offered by the DreamVendor system, the informal learning component is the most surprising.

Future work will focus on improving both the reliability of the system as well as its portability. In addition, assessment will be expanded to gain more detailed quantitative and anecdotal evidence regarding how students are using the DreamVendor to expand their knowledge of manufacturing.

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