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MATERIAL WASTE OF COMMERCIAL FDM PRINTERS UNDER REALSTIC CONDITIONS

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Abstract

Fused deposition modeling (FDM) is a prominent technology for additive manufacturing. Additive manufacturing is thought to minimize material waste, but the actual material waste could be larger than expected due to human or printer error. In FDM, the quantity of support material is influenced by the part orientation and other settings of the printing. Additionally, failures may result from insufficient preheating time, inappropriate geometry of parts, user error or printer malfunctions. Material waste from commercial FDM printers using ABS material in a heavily utilized open shop was collected in this study. The mass data of both support material and failed prints were recorded over time. In addition, the failed prints were classified into 9 different categories and weighed according to failure reasons. The data were analyzed and indicated that about 34% of the plastic used in the open studio was wasted. Only considering the failed prints as the extra amount of material consumed under realistic conditions, the mass of material lost to failed builds was about 2.22 times what might be estimated in a controlled process study. Suggestions to reduce the material waste for each failure type are given.

Introduction

Additive manufacturing, or 3D printing, enables rapid prototyping and revolutionizes manufacturing. There are lots of different technologies developed for additive manufacturing, such as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and other forms of solid freeform fabrication. Among all the technologies, FDM is a widely used, open-source technology, and is utilized by most consumers since the commercial FDM printers feature compact sizes, affordable prices and low maintenance costs. For FDM, the part is produced by extruding molten material to form layers as the material hardens immediately after extrusion from the nozzle.

Additive manufacturing has the potential to be more environmentally friendly than conventional manufacturing methods (Bourell et al., 2009). Some advantages of additive manufacturing are material efficiency, part flexibility and production flexibility (Huang et al., 2013). Faludi et al. (2015) compared the environmental impacts of two additive manufacturing machines (FDM machines and polyjet machines) to a traditional CNC milling machine using life cycle assessment. Their results show that the FDM machine had the lowest ecological impact per part.

Because additive manufacturing builds parts by layering materials, it does not need to remove large amount of materials as in conventional subtractive manufacturing (Huang et al., 2013). Therefore, it could minimize the material waste. Under ideal conditions, the only material waste for FDM is support material. In practice, however, 3D printers may be used similarly to conventional printers in offices and result in high usage error. Since many users of commercial FDM printers are inexperienced in 3D printing operation, the actual material waste could be larger than that under ideal operating conditions without human or printer error. There are two types of material waste from FDM under realistic conditions: the support material and the failed prints. The quantity of support material could be influenced by the part orientation and other settings of the printing. Failed prints might be due to various reasons such as insufficient preheating time, inappropriate geometry of parts or printer malfunctions (Grieser, 2015).

Material waste of FDM provides both cost and environmental concerns. When evaluating the material waste from FDM, most studies only consider the support material generation, in other words, the production under ideal conditions without failures. However, the failed prints contribute to a large portion of material waste based on preliminary observation in the studied open shop. Therefore, this work reports results of a printing failure study in an open shop with daily users of various expertise. From this study, suggestions to reduce the material waste are given. The uncertainties of potential environmental impacts of commercial FDM printers from material consumption perspective could be reduced in the future by evaluating these material waste data.

Literature Review

Additive manufacturing ideally uses only the amount of materials needed for the product. Hence, it may reduce the material used and energy consumed. Environmental analysis for additive manufacturing processes should include process time, energy utilization, primary flow of work-piece materials, and secondary flows of process catalysts (Huang et al., 2013). When evaluating the environmental impacts of additive manufacturing, most studies focused on energy use (Baumers et al., 2011; Kreiger and Pearce, 2013; Telenko and Seepersad, 2012). Few studies have looked at material waste under consumer operating conditions.

Most studies only consider the material and energy costs of builds under ideal conditions. Xu et al. (1999) considered the building cost of FDM as material consumed and included two quantities: the amount of material used to build the part and the amount of material used to build the support. The amount of material to build the support could be influenced by the part orientation (Alexander et al., 1998; Mohamed et al., 2015). Beside the amount of support material, part orientation can also affect the printing time, part accuracy and surface roughness of the print (Cheng et al., 1995; Snyder et al., 2015).

For the failed prints, Telenko and Seepersad (2012) mentioned failed builds as part of the material waste, but did not measure waste material. Seepersad et al. (2012) created a designer’s guide for dimensioning and tolerancing selective laser sintering (SLS) parts. Several online user guides discuss common problems and solutions for commercial FDM printers. Grieser (2015) detailed 16 most common FDM problems with a series of recommended solutions. Print Quality Troubleshooting Guide (Simplify3D.com) compiled an extensive list of the common 3D printing issues with a large collection of real-world images. RepRap.org (2014) provided a print troubleshooting pictorial guide to identify and resolve issues for RepRap 3D printers. These resources illustrate the numerous and frequent errors that occur in additive manufacturing, but the frequency and severity of such errors and various user and machine interactions leading to such errors have not been studied.

Experiment Methodology

This paper describes the material waste created by FDM machines in a large open shop representative of the numerous maker spaces and shops appearing in businesses, homes, colleges, communities, and schools around the world (Barrett et al., 2015). To measure the material waste, two collecting bins with labels were placed in an open shop at a large university, shown in Figure 1. The shop is used primarily by engineering students for personal projects as well as capstone and design course prototyping. It contains 12 Afinia H480 printers and 20 PP3DP UP mini printers. Around 25 printers are running at any time. The open hour for the open shop is from 10 am to 6 pm weekdays. However, the printers continue to operate after closings to complete unfinished printing jobs. The staff can still use them during after-hours. Staff estimate that the foot-traffic of the open shop is over 300 people every day. Waste material was collected from the bins bi-weekly. To analyze the waste ratio, the inventory of ABS filament was also recorded at each interval. The mass of the collected support material and failed prints were measured using a mass balance with accuracy of 2g.

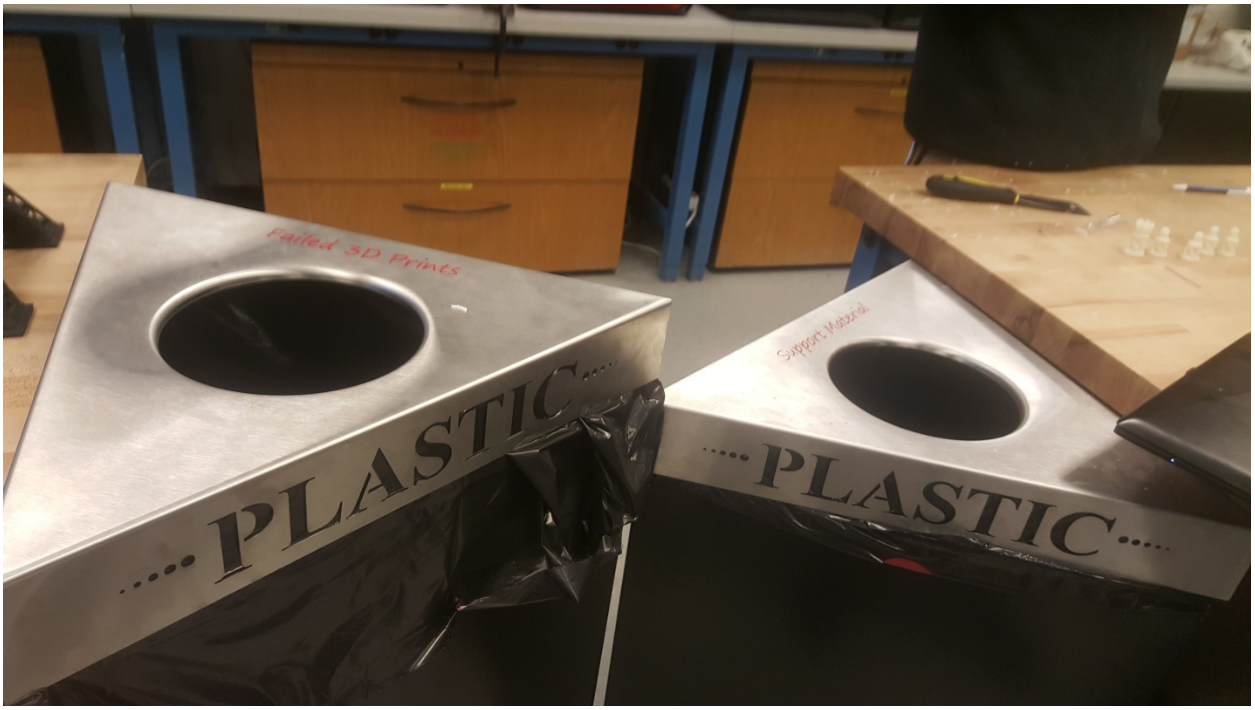


Figure 1. Collecting Bins

After each sample was collected and weighed, the parts were sorted by failure type to determine if failures were caused by human or machine error. Failure types were derived from available FDM printer troubleshooting guides (Grieser, 2015; RepRap.org, 2014; Simplify3D.com), staff expertise, and activities of printer use. Activity diagrams (Galvao and

Sato, 2005; Wood and Otto, 2001) used are shown in Figures 2 and 3. These diagrams aid in determining how failures may be attributed to user or machine errors. The global level activity diagram, shown in figure 4, involves aspects of the printer's useful life such as purchase, installation, maintenance and end-of-life activities. It is independent of single printing jobs. The task level activity diagram, shown in figure 5, describes the activities involved in the unit use of a printer.

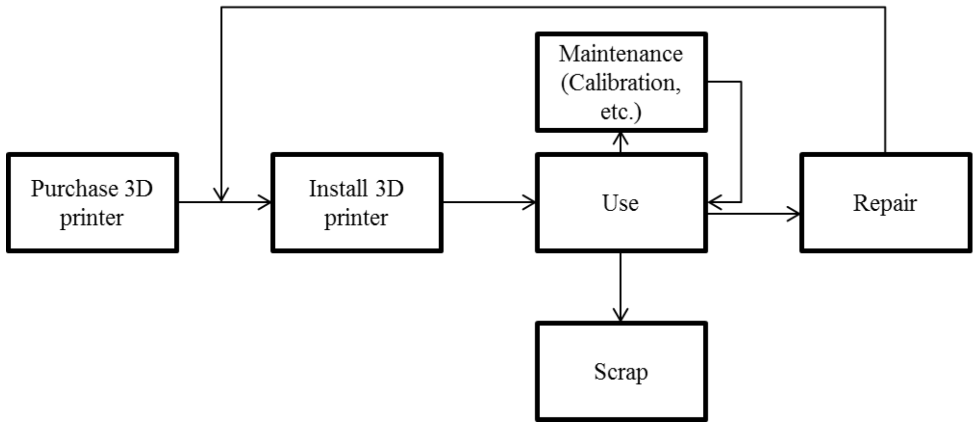


Figure 2. Global Level 3D-Printer Activities

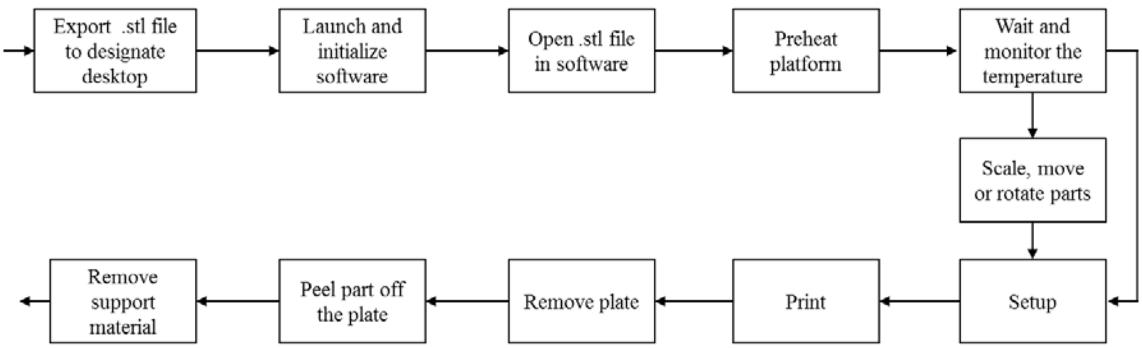
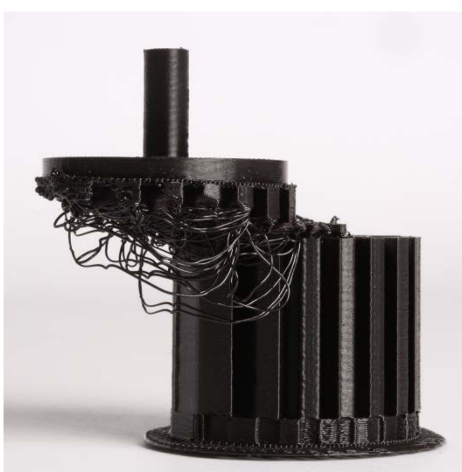


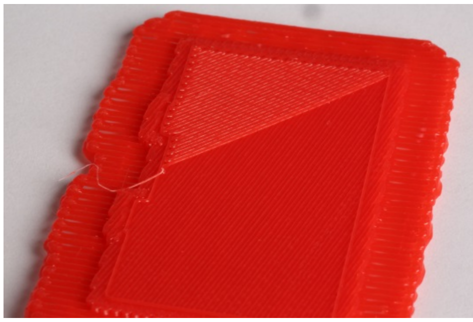
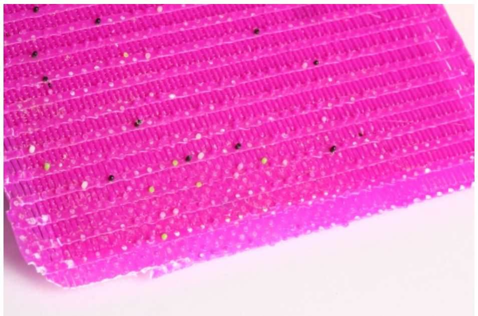
Figure 3. Task Level 3D-Printer Activities

In total 9 types of failed prints were identified. The example images and descriptions for each type of failure are shown in Table 1.

Table 1. Example Images and Descriptions of Each Type of Failure

Type	**Images**	**Descriptions**
Unused Filament		Unused filament could be disposed if part of it distorts or tangles due to printer or user errors. An example is nozzle clogging. Also, if there is not enough material for the next print, the remaining filament could be discarded to ensure seamless operation.

Type	Images	Descriptions
Platform Heating	 	If the platform is not preheated or the temperature is not high enough, warping or cracks could happen. If the first layer of heated plastic is cooling down too fast, it may contract. Then the edges of the print will bend upward until it no longer adheres to the print platform. Cracks in tall objects may also happen due to the platform heating problem. The material cools down faster in higher layers than in lower layers, because the heat from the heated bed cannot reach that high. Therefore, adhesion in the upper layers is lower.
Part Shape		The prints may fail if the specification of the printer cannot support the part shape.
Layer Shift		Layer shift is caused by mechanical malfunctions with the printer: the extruder head does not move smoothly on the x or y axis, or the rods are not aligned correctly.

Type	Images	Descriptions
Support Material Removing Process		After the printer finishes a job, parts may be damaged during manual removal of the support material. Some of the support material may be difficult to remove because of the shape of the part.
Printer Stops		Printer may stop automatically when it or an operator detects any error. Also, the printer may run out of raw material.
Tight Calibration		The nozzle and printing platform are calibrated too close between each other. Therefore, the nozzle cannot extrude material properly. The first several layers may be compressed.
Loose Calibration		The nozzle and printing platform are calibrated too far between each other. Therefore, the first layer cannot adhere to the platform, and the sequential layers cannot adhere to each other properly.

Type	Images	Descriptions
Skip Layers		There are gaps in the model because some layers have been skipped in part or completely due to a printer error. The printer fails to provide the amount of plastic required for printing the skipped layers. There may have been a problem with the filament (e.g. the diameter varies), the filament spool, the feeder wheel or a clogged nozzle.
Non-physical defect	The part has no physical defect, which means it was not disposed because of printing errors but design or other issues.	

These nine types of failure can be caused by user (machine operator) error, machine error, designer error, or any combination of these three types of error. Table 2 summarizes the causes for each failure type.

Table 2. Causes for Failure Types

Type	User Error	Machine Error	Designer Error
Unused Filament	X	X	
Platform Heating	X	X	
Part Shape	X		X
Layer Shift		X	X
Support Material Removing	X		X
Printer Stops	X	X	X
Calibration	X	X	
Skip Layers		X	
Non-Physical Defect			X

Results and Discussion

This section presents the results of the material waste collection and sorting by failure type. Additionally, it proposes solutions to reduce the material waste for each failure type. Limitations and difficulties in collection are also reported.

Although labels were put on the collection bins, some users still deposited the waste into the incorrect bins. Therefore, all the collected waste was evaluated carefully for any cases of sorting error. Specifically, part builds that were put in the support bin were re-sorted into the failed bin. Table 3 shows the mass of re-sorted material waste. The total mass of the failed prints is 20.11 kg, of the support material is 16.51 kg, and the total mass is 36.62 kg for the studied period. Figure 2 shows the trends of mass of ABS over time for the studied period. About 55% of material waste was evaluated as being from failed builds.

Table 3. Mass of Material Waste as Re-sorted by Researchers

Time Period	Failed (kg)	Support (kg)	Total (kg)
Jan. 27 - Feb. 9	3.38	1.85	5.23
Feb. 10 - Feb. 23	2.60	2.21	4.81
Feb. 24 - Mar. 8	3.72	2.69	6.41
Mar. 9 - Mar. 29	2.98	3.51	6.50
Mar. 30 - Apr.12	3.77	3.70	7.47
Apr. 13 - Apr. 26	3.66	2.53	6.20
Total (kg)	20.11	16.51	36.62

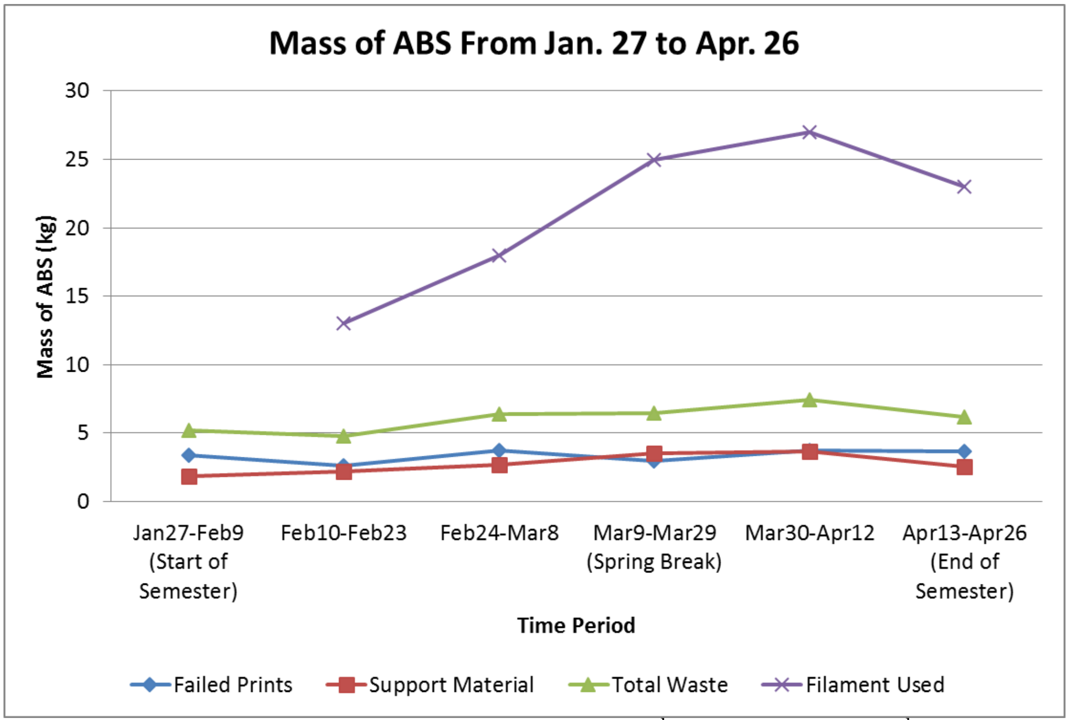


Figure 2. Mass of ABS Data from January 27th, 2016 to April 26th, 2016

To calculate the percentage of material wasted, the total mass of material used for successful and failed builds is calculated by the number of rolls of filament used from inventory over each time frame. Each roll of filament is 1 kg. During the study period, 106 rolls of ABS filaments rolls were used. Therefore, in total 106 kg of ABS material was used for 3D printing in the open shop. Inventory tracking to determine total material use in the shop was delayed by one collection cycle. Over ten weeks of combined inventory and waste tracking, the waste material accounted for 34.6% of the total material used for FDM printing. The detailed ratios for this time period and waste type break-down are shown in Table 4.

Table 4. Material Waste Ratio and Waste Type Break-Down

Time Period	Material Waste (%)	Failed Prints (%)	Support Material (%)
Feb. 10 - Feb. 23	37.0	20.0	17.0
Feb. 24 - Mar. 8	35.6	20.7	15.0
Mar. 9 - Mar. 29	26.0	11.9	14.1
Mar. 30 - Apr.12	27.7	13.9	13.7
Apr. 13 - Apr. 26	26.9	15.9	11.0
Overall	34.6	19.0	15.6
Mean	30.6	16.5	14.2
Standard Deviation	5.2	3.8	2.2

These data show the minimum waste ratio since they assume all the installed filament rolls were empty at the time of collection. The mean of the material waste ratio is 30.6%. The standard deviation is 5.2%. The overall failed prints waste ratio for the studied period is 19.0%. Therefore, only considering the failed prints as the extra amount of material consumed under realistic conditions, the mass of material lost to failed builds was about 2.22 times what might be estimated in a controlled process study. The mass of total material used was about 25% more than under ideal conditions. Figure 3 shows the trend of material waste ratio for the studied period.

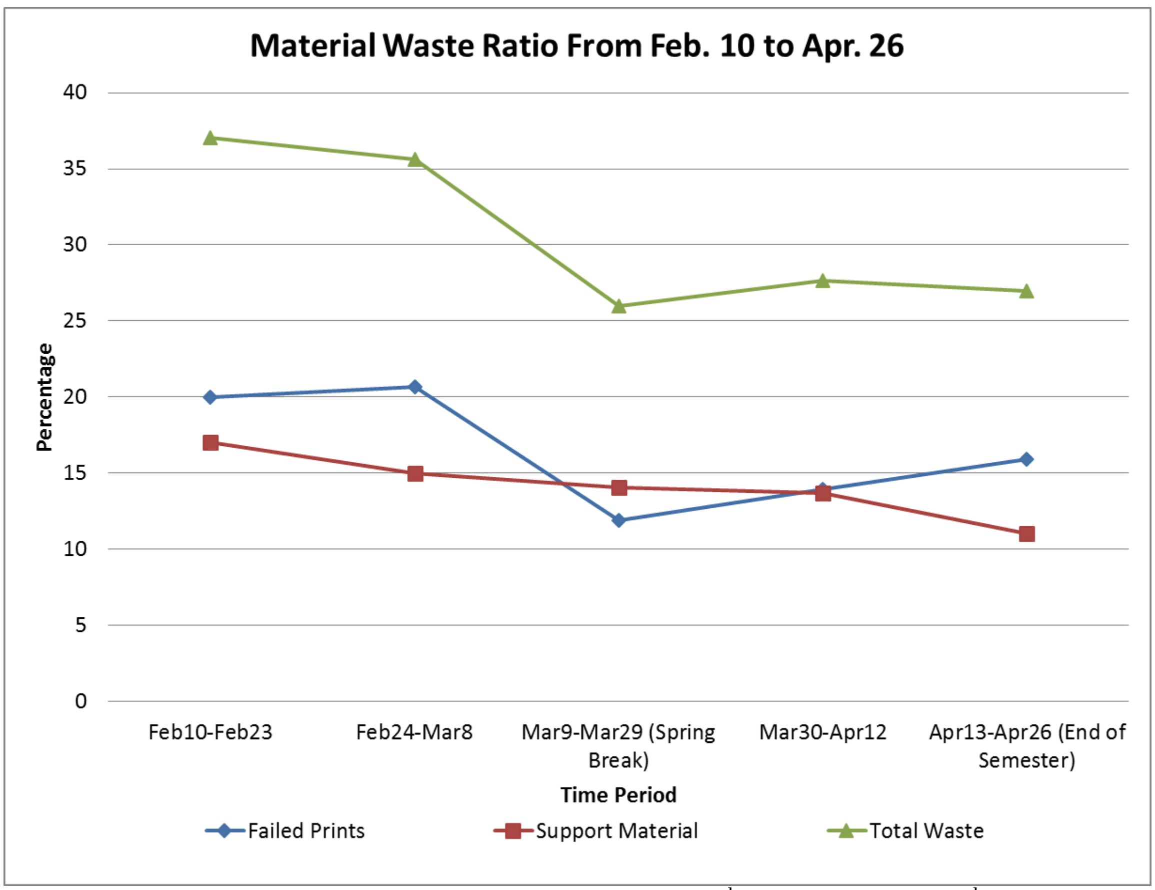


Figure 3. Material Waste Ratio from February 10th, 2016 to April 26th, 2016

From Figure 2 and Figure 3, the material waste ratio decreased over time, though the overall material use increased. The start time of the collection project was the beginning of a semester, and the stop time of the collection was the end of a semester. During the semester, course projects and capstone design projects were gradually introduced. Therefore, the material use was increasing. Users of the FDM printers became more experienced over the semester as well. This increase in experience could explain the reduction in material waste ratio over time. The only time the weight of failed prints was less than the support material was during spring break at the studied university. During the spring break, only trained staff of the open shop could use the 3D printers. The staff are generally more experienced than average users of 3D printers and are responsible for maintenance of the machines. Therefore, the weight and number of failed prints could be reduced during the spring break.

Table 5 shows the mass of failed prints according to failure types for the studied time periods. From the data, calibration problems contributed to the largest portion of the failed prints. If the printer is not calibrated correctly, all parts printed using that printer could fail. Average users usually do not check the printing process. Unlike other failure types which the printer is able to detect automatically such as warping caused by insufficient platform heating, the printers may not be able to detect the calibration problems. In addition, some FDM printers have non-transparent covers, e.g. UP mini 3D printer, which help reduce failure from thermal losses, but hinder the detection of failure occurrence by users. Hence, the printers continue to finish the printing using large amounts of material after the failure occurs. To avoid large quantity of material waste from calibration problems, the consumers should check the printing status of each printer in order to detect the failure timely. If consumers notice any failure, they should inform the staff running the shop. Then, staff could evaluate the cause of the failure. If it is a calibration issue, staff will be able to adjust the calibration to avoid future failures.

Table 5. Mass of Failed Prints According to Failure Types

Time Period	**Mass of Failed Prints According to Failure Types (g)**								
	Unused Filament	**Platform Heating**	**Part shape**	**Layer Shift**	**Removing Process**	**Printer Stops**	**Calibration**	**Skip Layers**	**Non-Physical**
01/27-02/09	162	900	292	214	218	558	1002	0	30
02/10-02/23	148	480	354	136	68	176	996	132	112
02/24-03/08	278	842	308	186	448	486	1114	0	58
03/09-03/29	112	684	420	248	224	322	970	0	2
03/30-04/11	20	994	160	172	134	912	1324	0	49
04/12-04/26	142	430	268	72	592	214	1522	42	382
Total	862	4330	1802	1028	1684	2668	6928	174	633

The second failure type is platform heating. Before the printing starts, the platform should be preheated to avoid part warping and increase the adhesive of part to the platform. The time required for the preheated process varies according to the initial temperature of the platform. If the printer just finished the previous job, the platform would have a high temperature and require a shorter preheating time. If the printer was in idle status for a long time, the preheating time would be longer. There are two different FDM printers in the open shop, Afinia H480 and PP3DP UP mini. Afinia H480 printers have built-in temperature sensors. Therefore, users could check the temperature of the platform easily. However, PP3DP UP mini printers do not have such temperature sensors. Therefore, inexperienced users may not be able to manage the preheating time appropriately. Some users may even neglect the preheating process. Shop staff mentioned that platform heating is thought to be the most frequent failure reason by users. To reduce the material waste caused by platform heating, clear instructions could be posted in the open shop. Moreover, failure by platform heating is not only due to user error, but also can be machine error. Due to the wear of the printer such as the inaccuracy of the temperature sensor, the platform may not be able to reach the required temperature. Therefore, regularly inspection of printers should be conducted.

The material waste caused by layer shift, printer stops, and skip layers could be reduced by regular inspection and maintenance of the printers. The unused filament can be reduced by decreasing occurrence of other types of failures that require re-installing the filament. Also, operators should be careful if removing filament for troubleshooting. The open shop does not have an inspection or maintenance plan currently. Staff repair the broken printers on their own free time.

The material waste caused by damage during removing process could be reduced by user training and education. Improved design for additive manufacture and designs in general could also reduce the material waste from physical and non-physical failures.

Closure

This paper quantifies the FDM material waste produced in a heavily used open shop. In addition, nine failure types were identified and illustrated. The results indicate that about 34% of the plastic used in the open studio is wasted. Failed prints account for about 19% of the materials used in the shop. Only considering the failed prints as the extra amount of material consumed under realistic conditions, the mass of material lost due to failed builds was about 2.22 times what might be estimated in a controlled process study. Calibration problem contributes to the most of the material waste. Suggestions to reduce the material waste for each failure type are given.

The literature has discussed the relationship of part orientation and amount of material used to build support structures. Further work can be done to reveal the relationship between the part orientation and the failure rate. Also, energy consumption of commercial FDM printers under realistic conditions should be investigated. The material waste and energy consumption could be combined to give a more comprehensive life cycle inventory of the commercial FDM printer. In addition, the human behavior and organizational behavior that leads to changes in failure rate will be studied.

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