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Analysis and proposed improvement of Hamilton County VW eLab equipment

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Analysis and Proposed Improvement of Hamilton County VW eLab Equipment

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Abstract

Digital fabrication laboratories have revolutionized project based learning within K-12 STEAM education curriculum. However, classroom utilization of the labs often requires excessive machine hours to accomplish, and this often leads to rapid machine depreciation and disrepair. Many educators do not have the time to repair their equipment while developing curriculum and engaging with their students. This study focuses on building a repair history for common digital fabrication equipment, which includes Prusa i3 Mk2S FDM 3D printers, laser cutters, and CNC routers. Data were collected over a 6 month period to find which machines encountered the most issues. The 3D printers were the only machines that had consistent issues, with a 15 of the 32 printers failing within their first 2000 print hours. Many printers reached 2000 hours within the 6 months, which is concerning when considering the long-term sustainability of the laboratories. The results yielded a 40% failure rate due to jamming, mostly during large-scale prints. Many of the failures suggest that there is a heating issue due to heat creep from the hotend to the heat sink. A rudimentary heat transfer analysis was run, and the results suggest that it is critical to prevent the temperature from the outside of the teflon tube from reaching 136.77ºC, which would provide enough energy within 15.86 seconds to cause the PLA to reach its glass transition temperature of 65ºC. This issue can be mitigated by installing an additional thermistor into the Prusa's RAMBo 1.3a board and making a modification to the printer's firmware that would allow for a temporary cooling process during a large print, which would increase the number of successful large-scale prints in the Prusa 3D printers. This improvement could also be translated to many small-scale FDM printers. An experimental analysis of heat transfer within the heat sink was planned, but due to equipment malfunctions, this analysis could not be performed.

Contents

Introduction

It was during January, 2017 that the State of Tennessee and Volkswagen of Chattanooga announced a $1 million program to establish digital fabrication "eLabs" in middle and high schools across Hamilton County. This program funded 16 schools to receive roughly $60,000 in equipment which contained several critical components within its template:

- Computer Numerical Control (CNC) router (Shopbot PRS 96x48x6)
- Laser Cutter (Zing Laser, Dremel LC40)
- Fused Deposition Modelling (FDM) 3D printers (Prusa i3 Mk2S, Dremel 3D40)
- Vinyl Cutters (Roland GS-24)

These items, in addition to electronics and wood-shopping equipment, are being integrated into distinct curriculum within each school.[1] This provides students an opportunity to develop skills within the field of design and fabrication[2,3,4,5], when the equipment is functional. However, until this point, there has not been a single publication providing insight on broken and depreciating equipment within a digital fabrication lab. Due to the fact that many labs have only recently been established, there has not been much concern pertaining to the decay of mostly cutting-edge machines. Many newer labs lack onsite repair options in many locations due to the uniqueness of the equipment. There is a lack of concern with this element of sustainability because there is not enough data pertaining to the primary failure points of this equipment. Many of these spaces, especially labs within schools, are utilized heavily, with labs accumulating hundreds of machine hours in a matter of weeks. This can be seen in the VW eLabs, where integration into K-12 curriculum has pushed both the equipment and the specialists to their limit. Over the course of 6 months, a large quantity of the equipment, specifically the 3D printers, had experienced a state of disrepair. The common issues were jamming and poor printing quality. It was noted that 15 out of 32 of the 3D printers needed repair which ranged from calibration errors to LCD Screen replacement. After consulting with several of the schools, all 15 printers had been in a state of disrepair, which included motherboard failure, wiring concerns, and software issues that were beyond the eLab specialist's capacity to repair. After several hours of investigating, there was no research found that directly discussed the process of conducting repairs as machines begin to break down after use. The purpose of this paper is to quantify potential issues within common equipment found within digital fabrication labs, in addition to providing a mechanical improvement to fix the most common issue with the 3D printers, in order to establish a preventative maintenance schedule for the labs.

Goals

The purpose of this research is to utilize 6 months of data that was collected from the machines to yield an empirical failure rate based on machine hours for the 3D printers, CNC routers and laser cutters. A history will be monitored on each machine to isolate root causes of issues that occur due to routine usage. Once a compilation of issues has been acquired, the most common concern will be assessed for potential resolution.

Additional considerations

There will also be a study to isolate different inefficiencies and specific failure points within the Prusa i3 Mk2s FDM printers, which are used across every VW eLab, and to provide suggestions for a mechanical improvement to the FDM process to extend product life, by developing methods to decrease the failure rate, based on the data collected.

Literature Review

Heat Zone

In a study titled, “Numerical and Analytical analysis of 3D printer extruder in Fused Deposition Modeling” by Rajesh Satankar, computational fluid dynamic (CFD) analysis was run over a circular finned heat sink of standard RepRap extruders. They found that the temperature gradient was relatively uniform throughout the sink. When trying to maintain a nozzle temperature of 215ºC, the center of the heat sink reached up to 170ºC, and the uppermost section reached up to 167ºC.[6] This is alarming as PLA enters its glass transition state at around 65ºC and it is printable at temperatures as low as 185ºC. [7] This essentially means that the filament begins the liquification process as it enters the top of the heat sink, rather than at the heat break at the bottom of the heat sink, which dramatically increases the probability of pooling at the nozzle and jamming during the print. Even worse, if it is not cleaned and removed before cooling, the material will solidify and potentially burn within the nozzle, requiring a more intensive cleaning process.

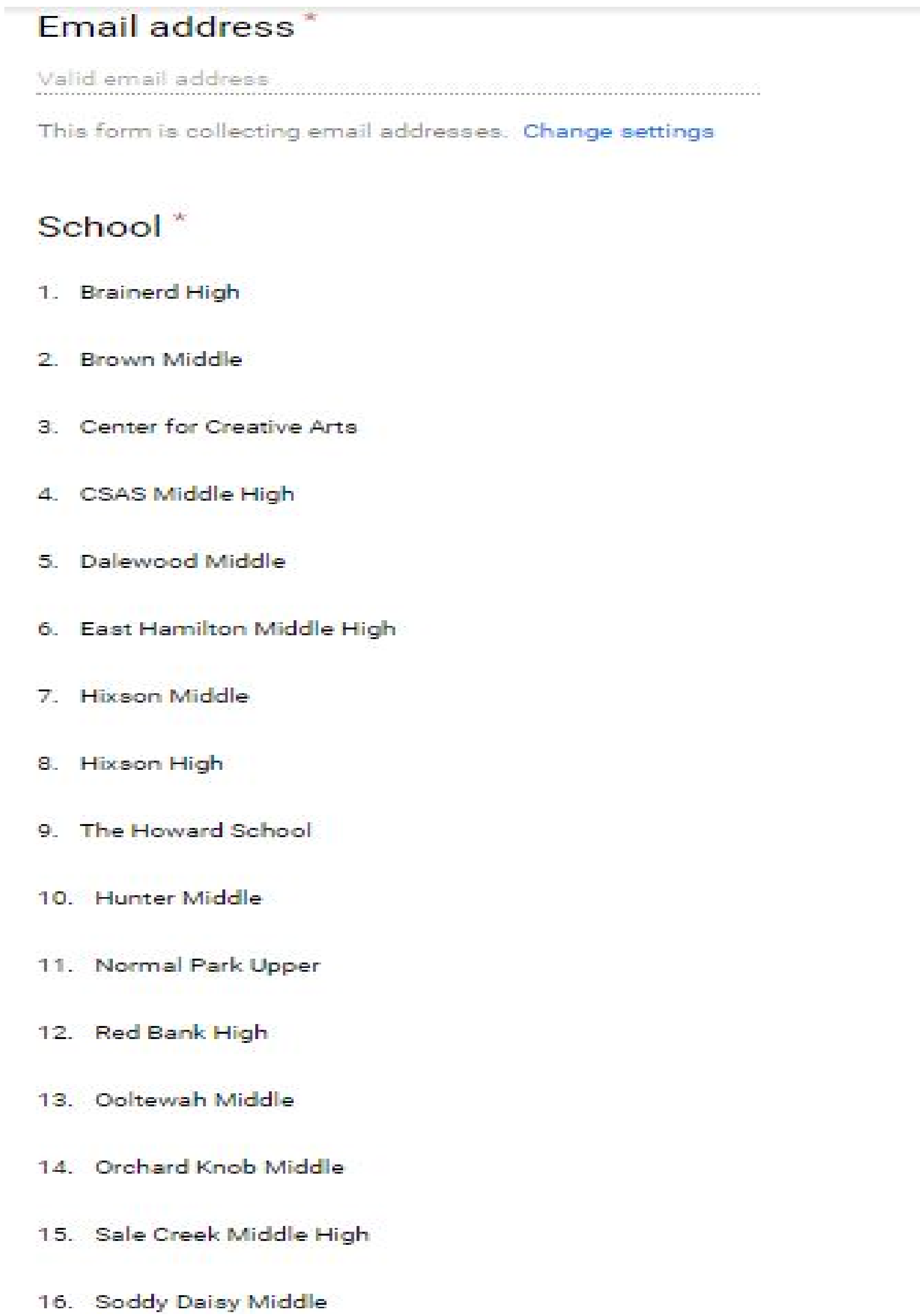
“Finite element analysis of the thermal behavior of a RepRap 3D printer liquefier” by R. Jerez-Mesa, et al, found that using a SanAce40 Sanyo Denki fan, a standard fan in most FDM printers, in an open system helped to reduce the temperature of the top of the heat sink by 130ºC when operating at 30% of the fan’s capacity.[8] The heat sink was in an open area, making heat transfer to the surrounding air easier. The Prusa i3 Mk2S operates using the fan at 65% power, but there still appears to be a liquifying effect that occurs around the datum of the printer nozzle. (Refer to figure 9 in study) It appears that most of the convection heat transfer is mitigated by the fan. However, the conductive heat transfer appears to play a more significant role in the jamming process.

"Investigation of Heat Sink Geometry Effect on Cooling Performance for an FDM 3D Printer Liquefier" by Onur Gunel, et al, compares three unique heat sink designs to gauge any potential variations based strictly around the heatsink geometry. In addition, they utilized a cooling nozzle to dispense a constant 0.25 m/s airflow over the heatsinks. They concluded that the temperature profile of a uniformly finned heat sink was most desirable, because the temperature profile had a more even distribution over the heatsink.[9]

These studies discuss the importance of regulating the temperatures within the heat zone to maintain a consistent liquification of the filament. This reinforces the importance of heat zone monitoring to prevent jamming in the contact area between the heat sink and hotend of the extruder, and it forms a foundation to build upon for this project.

Data Acquisition

Each of the 16 eLabs were visited in order to begin an inventory system in excel for all of their equipment that fell under the category of CNC router, 3D printer, laser cutter, or vinyl cutter. Each piece of equipment is valued at over $100, and this means that they must all be given a unique Hamilton County tag to track ownership over the device. Due to the fact that the lab is quite new, much of the equipment was still in the process of being catalogued. Therefore, all of the equipment without a tag was given a temporary, single digit, sticker ID to allow for a record to be generated for it. As the equipment was listed, a record was gathered of previous issues experienced by the device. Previous issues were categorized into several color-coded states of disrepair. Each issue would be marked “resolved” or “unresolved” with a comment system being in place, with time stamps, to keep track of the repair process for concerning issue.



Email address *

Valid email address

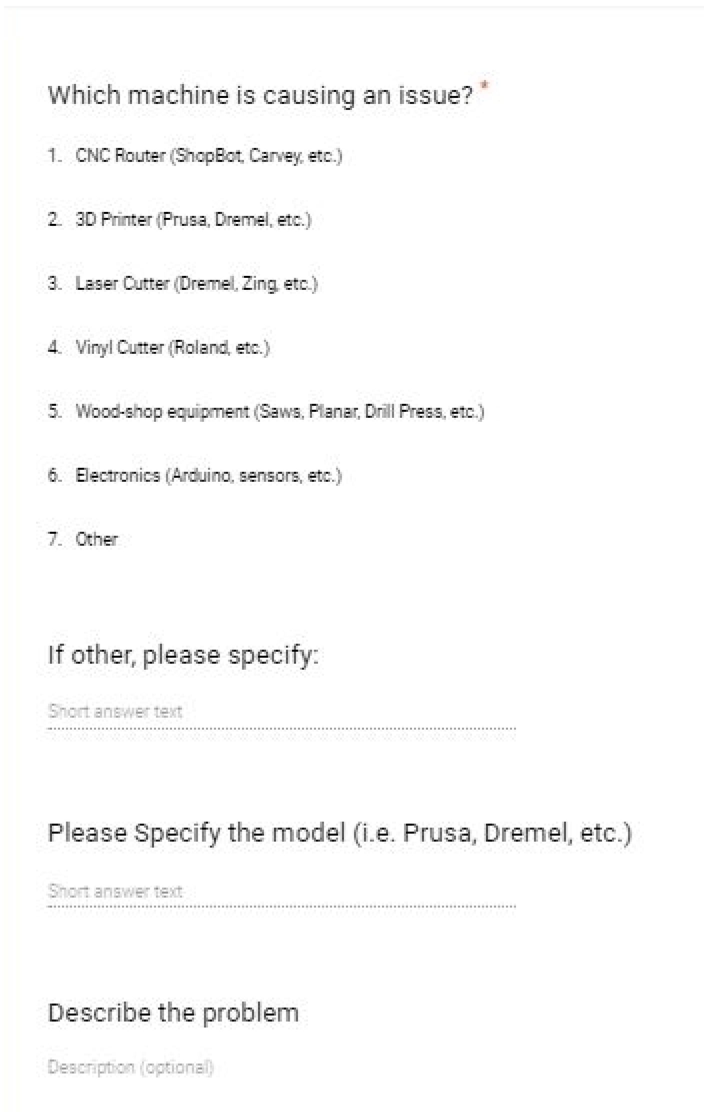
This form is collecting email addresses. Change settings

School *

1. Brainerd High
2. Brown Middle
3. Center for Creative Arts
4. CSAS Middle High
5. Dalewood Middle
6. East Hamilton Middle High
7. Hixson Middle
8. Hixson High
9. The Howard School
10. Hunter Middle
11. Normal Park Upper
12. Red Bank High
13. Ooltewah Middle
14. Orchard Knob Middle
15. Sale Creek Middle High
16. Soddy Daisy Middle

Figure 1: Repair Request - Email and School Selection

The repair request form seen above in Figure 1 begins with the specialist putting their email in the designated area. This was done to make replying easy by having their contact email at the top of the response sheet. This was followed by them selecting the school for which they are requesting the repair.



Which machine is causing an issue? *

1. CNC Router (ShopBot, Carvey, etc.)
2. 3D Printer (Prusa, Dremel, etc.)
3. Laser Cutter (Dremel, Zing, etc.)
4. Vinyl Cutter (Roland, etc.)
5. Wood-shop equipment (Saws, Planar, Drill Press, etc.)
6. Electronics (Arduino, sensors, etc.)
7. Other

If other, please specify:

Short answer text

Please Specify the model (i.e. Prusa, Dremel, etc.)

Short answer text

Describe the problem

Description (optional)

Figure 2: Repair Request - Machine Description

Figure 2 above displays the next stage of the repair form, where the machine category is selected, which includes all of the equipment that can be found within the labs. The other option is added in the event that a lab acquires a unique piece of equipment that needs repairs. There is an option as well to include the model of the device for the labs that have more than one type of a device within a category. Finally, the specialist has an opportunity to describe the nature of the issue, which will give a better idea as to the nature of the repair before a repair-person is dispatched to investigate.

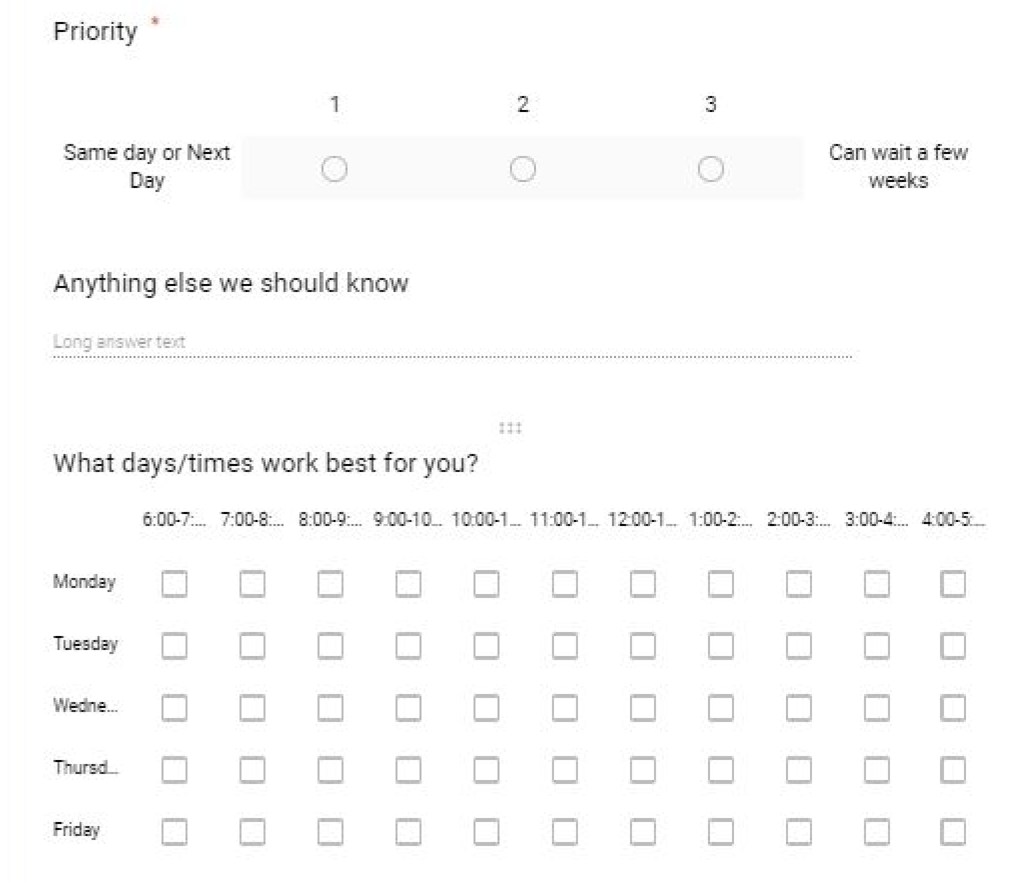


Figure 3: Repair Request - Availability

The final element of the repair form is shown in Figure 3, where the specialist can select a priority for their issue, ranging from same day to several weeks. This is done in anticipation of issues that will occur during a time the machine will be critical for a lesson plan. Many labs have several duplicates of a machine, such as a 3D printer, which would not be as urgent to have fixed as a ShopBot, where there is only one within the lab. There is also an extra response section in case the specialist wishes to disclose any additional details pertaining to the issue. Finally, there is a section that allows for the specialist to put in their hours of availability, which structured around pre, during, and post school hours for convenience to the teacher.

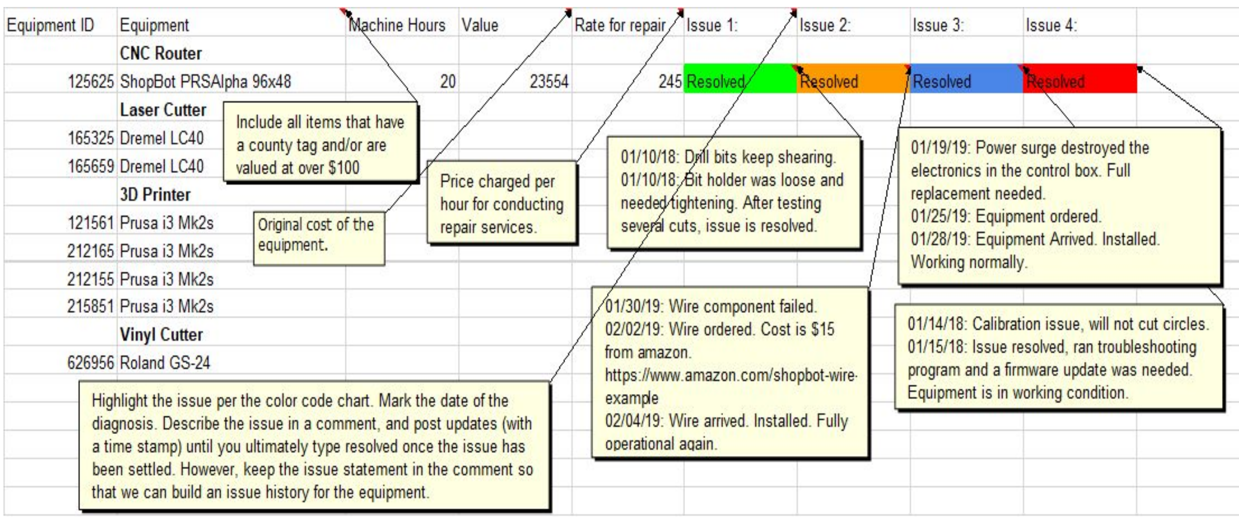


Figure 4: Inventory system template used to catalog equipment within the eLab

It can be seen in Figure 4, where the unique equipment ID, assigned by the county, is listed for each item, the equipment is listed and separated into different fabrication categories, the total machine hours are listed, the original value of the item, the cost rate of repair per hour, and several categories of repair that are to be marked either resolved or unresolved. Green denotes an issue that is fixable without the need for ordering and waiting on a replacement part. Orange denotes a repair need that requires a replacement part to be ordered. Blue denotes a software issue that requires firmware updates and/or modifications to the programming of the machine. Finally, red denotes complete machine failure, where the costs of repair would exceed the cost of purchasing a new machine. Within each issue lies a comment system that allows for further detailing of the repair in addition to a timestamp to build a history with the device.

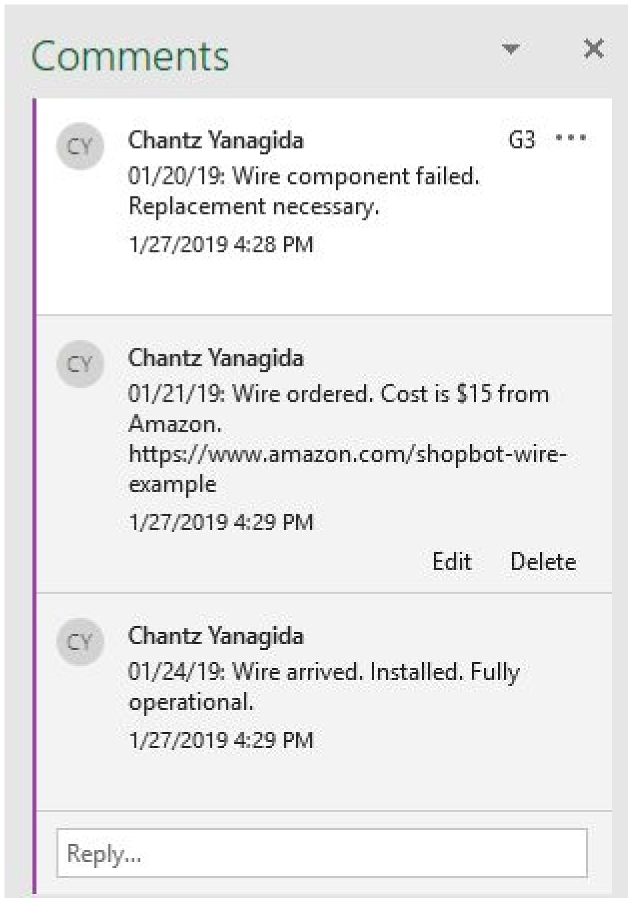


Figure 5: Comment System for Tracking Repair Statuses

The entire repair process is tracked, as seen in Figure 5, starting with a timestamp. This is followed by a brief, sentence-long description of the issue and a sentence regarding the course of action. If it was not fixable on site, details regarding follow-up repairs and diagnostics are to be noted within the comment-chain with a preceding timestamp. Any orders are to be linked within the comment chain and stored in a separate order form.

Results

Data were collected over the course of 6 months pertaining to the history of all of the digital fabrication equipment. It was noted that virtually none of the other equipment experienced significant issues. It appeared that only the 3D printers had issues, which can be attributed to their heavier machine hours over the course of a semester. In total, there were 32 Prusa 3D printers. It was important to see the failure rate of the printers. This was done by seeing the number of printers that had an issue within the first 1000 print hours that was not due to user error, which includes poorly oriented prints, improper temperature settings, etc.

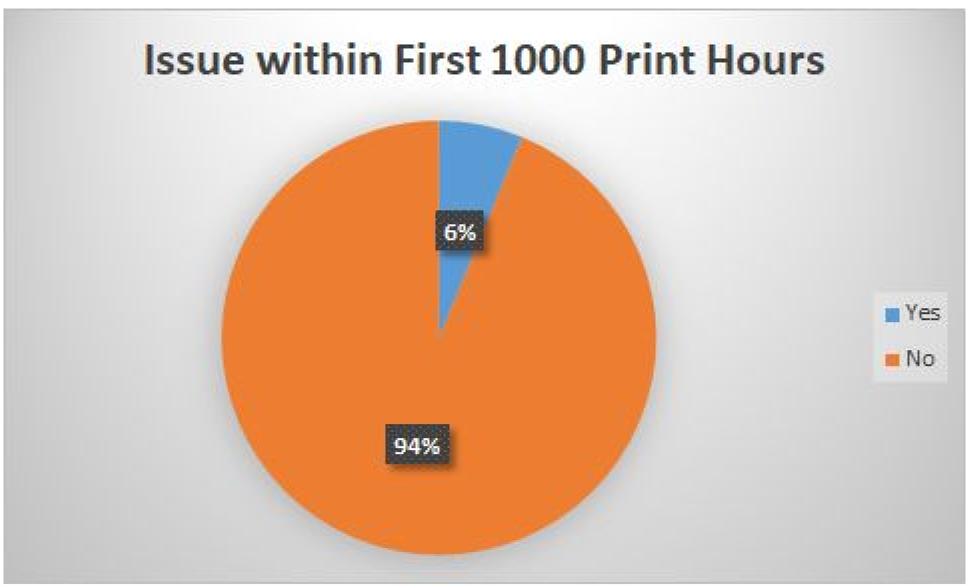


Figure 6: Percentage of printers that failed within their first 1000 hours of printing

It can be seen above in Figure 6 that only 6% (3 of the 32) printers had a non-user based issue over their first 1000 hours of printing. The printers that had issues were essentially dead on arrival due to motherboard failure and heat block issues, which were both a manufacturer related issue.

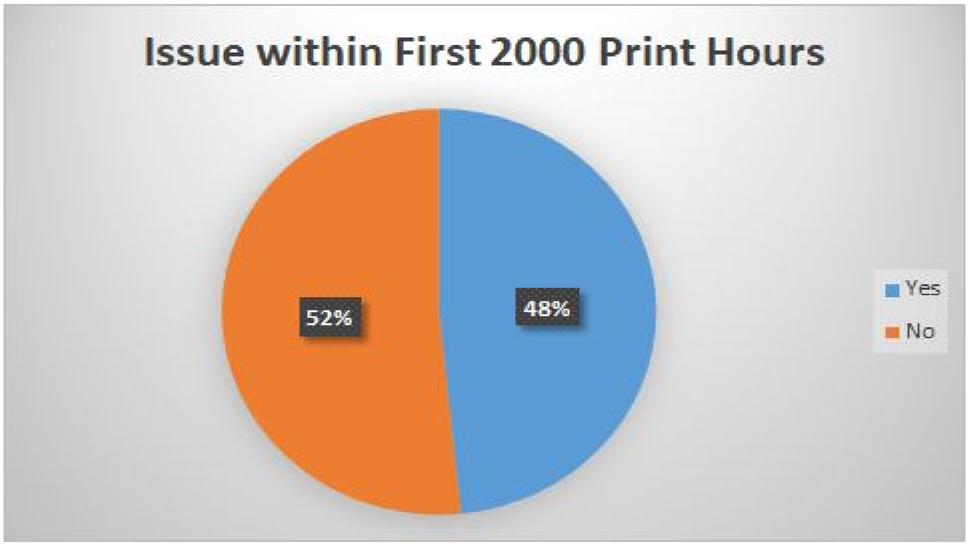


Figure 7: Percentage of printers that failed within their first 1000 hours of printing

As shown in Figure 7, 48% (15 of the 32) printers had an issue within their first 2000 hours of printing. This is where issues with jamming became more apparent. As many of the specialists became more comfortable with the 3D printers, they started printing larger objects. This is when issues arose with the printer reaching its maximum capacity to dissipate heat within the duration of a long-term print. Additionally, degradation of the machine due to heavy usage became apparent with issues such as wearing of the print bed.

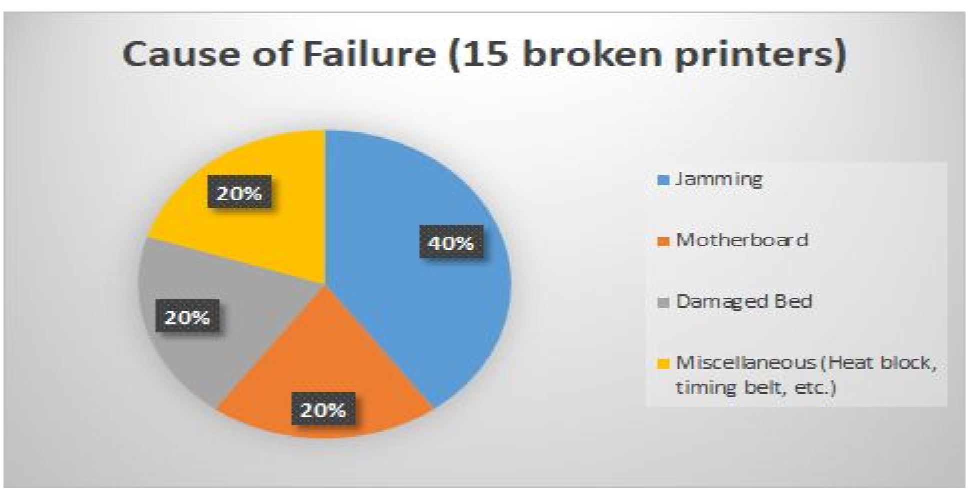


Figure 8: Cause of Failure Chart

Currently, the total print hours of all of the 3D printers range between 23.27 and 6130. The most prevalent issue with each printer was noted, and it can be seen above in Figure 8, out of 15 instances of the printers breaking, 6 of 15 can be attributed to jamming. After consulting with the specialists overseeing the printers in question, every jam was due to a large-scale print taking place over the course of several hours. Furthermore, the jam occurred at a later point in the print, and it would result in the entire hotend being covered in a solid coating of plastic as seen below in Figure 9.

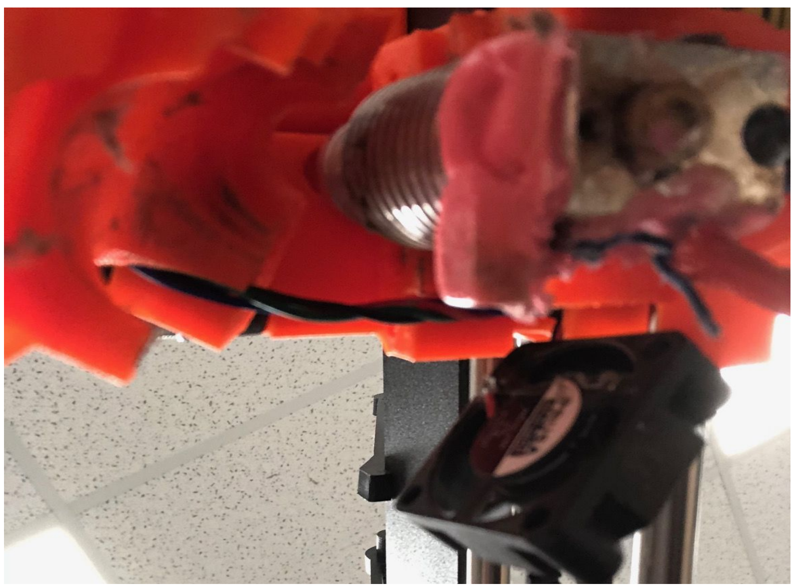


Figure 9: Hotend Covered in Hardened PLA Plastic

It is evident from Figure 9 that at some point the filament became too liquidus, and the print began to fail at the point of extrusion. The molten filament did not have enough time to adhere to the surface and harden, and this produced a liquid surface that made printing another layer impossible for the printer. Over time this produced what is known as a “clown wig” in the 3D printing community, where the printer starts producing loose strands of filament in space, and these strands eventually latched onto the heating element, forming a plastic shell around the entire hotend. As a result, the heating element wire was disconnected, and this forced the servicer to manually chip the filament away since the plastic could not be reheated from the hotend. This led to the conclusion that the issue must be attributed to the regulation of heat over the course of a long term print.

With this knowledge, a solution can be generated around preventing the filament within the heat sink from reaching its glass transition temperature. However, to do this, an analysis will need to be run to find the critical temperature to avoid.

Heat Zone Analysis

A Prusa i3 Mk2s, as seen in Figure 10, was used in testing.

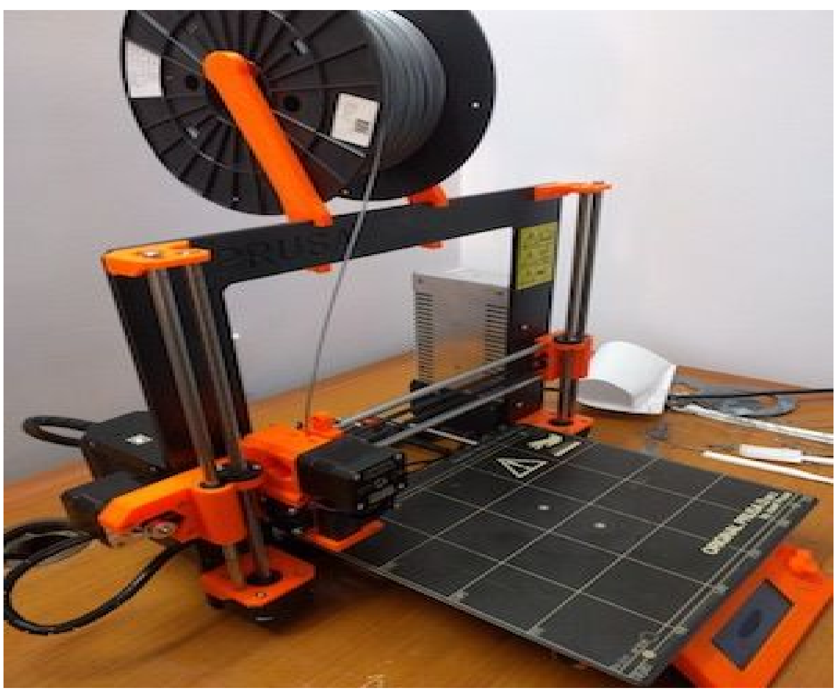


Figure 10: Prusa i3 Mk2S

The Prusa i3 Mk2S utilizes a standard RepRap construction of its extruder. This can be seen in Figure 11.

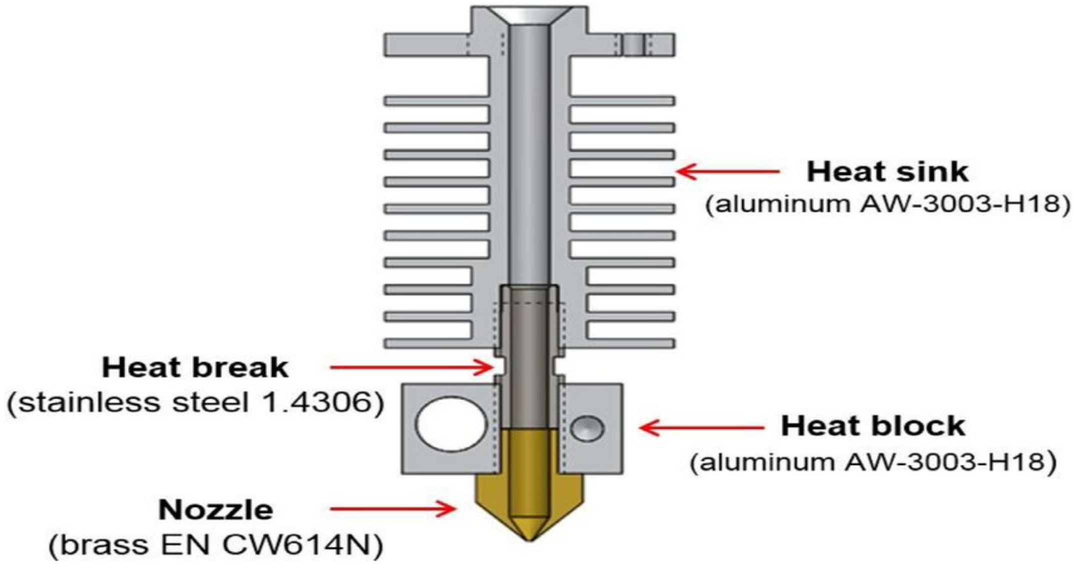


Figure 11: Standard FDM RepRap Heat Zone Components[8]

The heat sink utilizes an annular fin design for more efficient heat dispersion. The M6x1 threaded heat break is screwed into the heat sink. For the Prusa Mk2S, there is a teflon tube that extends from one inch outside the top of the heat sink, down to the entry of the heat break, but it is not fastened to the heat break in any way. The heat break is screwed into the heat block as well, which holds a brass 0.4mm diameter nozzle.

The material properties of each component are listed below:

Table 1: Material Properties of PLA[6]

Thermal Properties of PLA	**Value**
Specific Heat, $c_{p@25C}$[10]	1346.66 J/kg*K
Thermal Conductivity (K)	0.19 W/m*K
Melting Temperature	448 K (175^{o}C)
Density (ρ)	1250 kg/m^3, 1073 kg/m^3@ Melt Temp.
Enthalpy of Melting	45 kJ/kg
Emissivity (ε)[11]	0.92

Table 2: Material Properties of Pure Teflon[12]

Thermal Properties of Pure Teflon	Value
Thermal Conductivity (K)	0.245 W/m*K
Specific Heat (C_p)	970 J/kg*K
Density (ρ)	2160 kg/m^3
Emissivity (ε)[12]	0.850

Table 3: Material Properties of 1.4306 Stainless Steel[8]

Thermal Properties of Stainless Steel	Value
Thermal Conductivity (K)	15 W/m*K
Specific Heat (C_p)	500 J/kg*K
Density (ρ)	7900 kg/m^3
Emissivity (ε)[13]	0.440

Table 4: Material Properties of AW-3003 Aluminum[6]

Thermal Properties of Aluminum	Value
Thermal Conductivity (K)	237 W/m*K
Specific Heat (C_p)	903 J/kg*K
Density (ρ)	2702 kg/m^3
Emissivity (ε)[14]	0.400

Table 5: Material Properties of Brass[8]

Thermal Properties of Brass	**Value**
Thermal Conductivity (K)	109 W/m*K
Specific Heat (C_p)	380 J/kg*K
Density (ρ)	9490 kg/m^3
Emissivity (ε)[13]	0.030

Providing a generalized solution for the heat flow within the heat sink is virtually impossible due to the number of variables present within a single print. The best case scenario for an analytical solution would be derived under the assumption of zero flow rate. This simply means that a solution would not be translatable from a cube to a circular print because the flow rate and print paths would alter the heat introduced to the filament over a period of time.

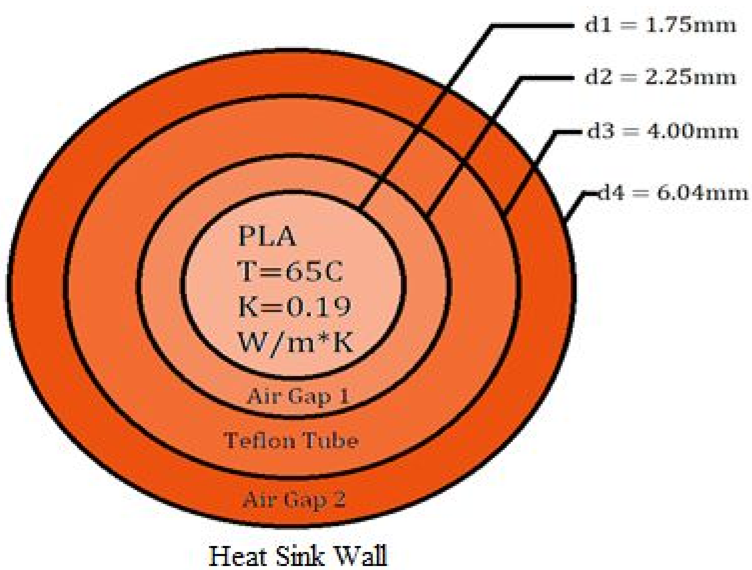


Figure 12: Top View of Heat Transfer Model

Figure 12 is an attempt to visualize the problem by accounting for the number of layers exposed to the heat block. Additionally, since it is symmetric, it has been reduced to a one-dimensional heat path, with the heat flow moving inward from the outermost circle. The vertical flow of heat from the hotend upward was not considered for the purposes of simplification. The purpose of this assumption is to generate a baseline estimate for the energy and time required to heat the surface of the PLA to 65°C, which is the glass-transition temperature of PLA. To solve this, the energy required to heat the PLA from room temperature (assumed to be 25°C) to 65°C will need to be known. It is assumed that this energy transfer is undergoing steady-state conditions with no energy lost in the process. The quantity of energy required can be found using equation (1)[15]:

$$Q = mC\Delta T \tag{1}$$

Where Q is the energy transferred, m is the mass of the filament in the heat sink, and C is specific heat, and ΔT is the change in temperature.

With these variables known at room temperature, equation (1) can be solved:

$$Q = (8.39 * 10^{-5} kg)(1346.67\ J/kg{*}^{o}C)(65^{o}C - 25^{o}C) = 4.51\ J$$

This means that it would require 4.52 J to raise the filament within the sink from 25°C to 65°C. The result of equation (1) will be essential for setting a boundary condition in equation (2)[17] that will determine the minimum required temperature of the surrounding media:

$$Q = hA\Delta T = h(2\pi rL)(T_2 - T_1) \tag{2}$$

Where h is the natural convective heat transfer coefficient. The issue is that h is dependant on ΔT and T_2 is unknown at this time. T_1 is assumed to be room temperature to model the highest heat exchange possible to set an upper-boundary condition for the amount of energy transferred to the filament. This is to provide a conservative estimate for the maximum amount of time that the PLA should be exposed to a specific temperature within the heat sink.

The Nusselt number, as seen below in equation 3[17] is needed to determine the ratio of convective to conductive heat transfer at the boundary of the system. This equation was constructed to model natural convection over a horizontal cylinder. However, the heat sink used is in a vertical orientation, making this an estimate assuming the flow of heat being uniform across the cylinder. It can be used to solve for the h value:

$$Nu = \frac{hD}{k} = \{0.60 + \frac{0.387*Ra^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\}^2 \tag{3}$$

Where D is the characteristic length of the cylinder, Ra is the Rayleigh number, and Pr is the Prandtl number.

The Rayleigh number is necessary for understanding buoyancy driven flow of a fluid media around a solid[18]. Assuming that the value of $Ra \leq 10^{12}$ the value of Ra is directly proportional to the product of the Grashof and Prandtl numbers, as seen in equation (4):

$$Ra = Gr * Pr \tag{4}$$

The Grashof number, which is the ratio of buoyancy to viscous force acting on the fluid[18], can be determined using equation 5[17]:

$$Gr = \frac{D^3 \rho^2 g \Delta T \beta}{\mu^2} \tag{5}$$

Where ρ is the density of the air, g is acceleration due to gravity, and β is the coefficient of volumetric expansion in the air, and μ is the dynamic viscosity of the air.

Finally, the Prandtl number, which is the ratio of momentum diffusivity to thermal diffusivity[18], can be solved using equation (6)[17]:

$$Pr = \frac{\mu C_v}{k} \tag{6}$$

Where C_v is the specific heat, with constant volume, of the air.

All parametric air values were taken from Yunus Cengel's *Heat and Mass Transfer: Fundamentals and Applications, 5th Edition*[18] assuming 1 atm pressure.

Since h is dependant on the temperature assumed for T_2 , an iterative process for equations 2-6 will need to be used to find the critical temperature of the air surrounding the PLA.

Therefore an initial temperature of 125°C for T_2 will be assumed to begin this process.

$$Pr = \frac{\mu C_v}{k} = \frac{(22.79*10^{-6}Pa*s)(727\ J/kg*K)}{0.033W/m*K} = 0.497$$

$$Gr = \frac{D^3\rho^2 g\Delta T\beta}{\mu^2} = \frac{(0.00225m)^3(0.887\ kg/m^3)^2(9.81m/s^2)(125-25)(2.51*10^{-3}K^{-1})}{(22.79*10^{-6}Pa*s)^2} = 42.5$$

$$Ra = Gr * Pr = 0.700 * 42.5 = 21.1$$

$$Nu = \{0.60 + \frac{0.387*Ra^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\}^2 = \{0.60 + \frac{0.387*21.1^{\ 1/6}}{[1+(0.559/0.497)^{9/16}]^{8/27}}\}^2 = 1.252 = \frac{hD}{k} = \frac{h(0.00225m)}{0.033W/m*K}$$

$$h = 18.54\ W/m^2K$$

Now putting this into the equation 2 (with boundary condition)

$$h(2\pi(0.001125m)(0.0279m))(T_2 - 25) = (18.54\ W/m^2K)(2\pi(0.001125m)(0.0279m))(125-25)$$

$$Q = 0.2844\ W$$

This is the rate of energy transferred to the filament with the temperature differential.

Another iteration can be taken:

Assuming a temperature of 100°C:

Gr = 41.25, Pr = 0.508, Ra = 20.94, Nu = 1.252, h= 17.598 W/m^{2}K

These values yield a power input of 0.2024 W,

Assuming a temperature of 150°C:

Gr = 39.94, Pr = 0.498, Ra = 19.84, Nu = 1.24, h= 19.28 W/m^{2}K

This Q value can now be used to find the maximum time allowable for the filament to remain still within the heat sink. Using the power input found for a temperature-allowable of 125ºC, the maximum dwell time allowable can be solved using equation (7):

$$t_{dwell} = \frac{Q}{\dot{Q}} = \frac{4.51\ J}{0.2844\ W} = 15.86\ s \qquad (7)$$

Where t_{dwell} is the maximum dwell time allowable. A trend can be formed using the power input rates of the values between 100ºC-200ºC. This can be seen below in Figure 14:

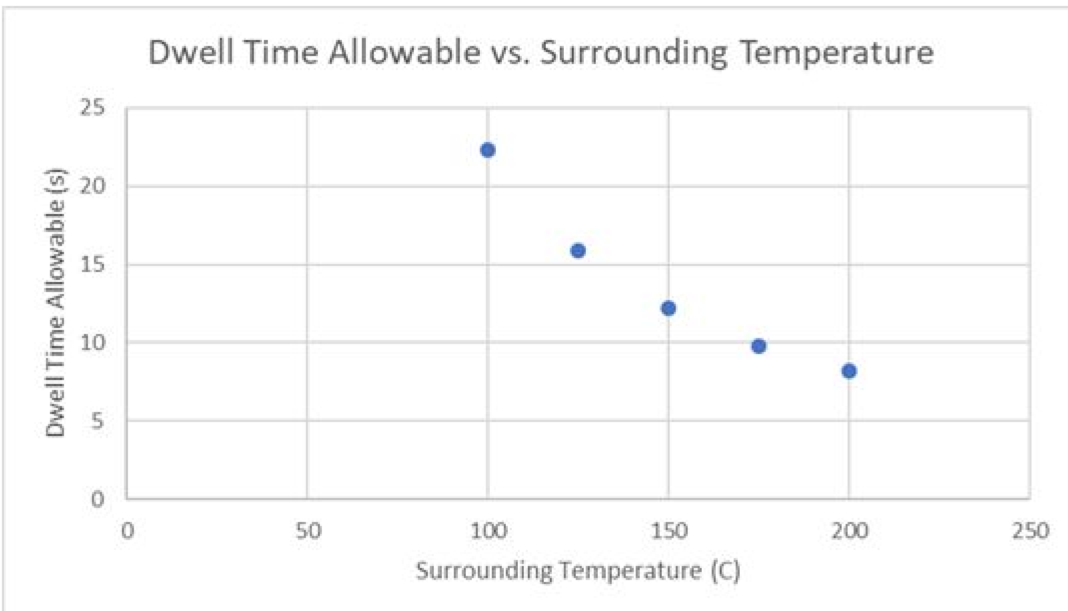


Figure 13: Dwell Time Allowable versus Surrounding Air Temperature

As seen above in Figure 13, the maximum dwell time allowable was plotted in the temperature range of 100ºC-200ºC in 25ºC intervals. These temperature values were chosen because the experimentally determined values for air[18] were known at these temperatures. Each value was calculated using equations 3-7.

Now the critical temperature outside of the teflon tube can be calculated using equation (8)[18]:

$$Q = \frac{2\pi ktL\Delta T}{ln(\frac{r_o}{r_i})} \qquad (8)$$

Where r_o and r_i are the outer and inner radius of the teflon tube, respectively. The only unknown value in this equation is the outer teflon tube temperature:

$$Q = 4.51\ J = \frac{2\pi k t L \Delta T}{ln(\frac{r_o}{r_i})} = \frac{2\pi(0.245\ W/m*K)(15.86s)(0.0279m(T_{out}-125))}{ln(\frac{0.002m}{0.001125m})} \Rightarrow T_{out} = 136.77C$$

With this value it is known that, within 15.86 seconds, there will be enough energy transferred to increase the filament temperature to 65°C. Now, there can be a solution built around preventing this temperature from being reached around the teflon tube.

Experimental Apparatus

List of materials needed:

- 100kΩ Thermistor Cartridge
- Arduino Mini-RAMBo 1.3a

Installing an additional temperature detecting thermistor would allow for the user to monitor the heat zones above the clog point. The 100kΩ thermistor is desirable, because it is inexpensive and operates within the temperature range of most FDM 3D printers, which is usually no higher than 275°C. It can be attached to the motherboard (RepRap Mini-RAMBo 1.3a) and be programmed using Arduino IDE. After drilling a 3mm hole into the side of the heat sink, 27.9mm above the base of the heat sink, the thermistor can be fed through and attached via high temperature epoxy onto the teflon tube. If it reaches a threshold of 136.77°C, the critical temperature at which was calculated during the heat analysis, it can be assumed that the PLA is close to its glass-transition state. In such an event, a procedure would run to temporarily pause the print, turn off the heat, and allow for this region to cool until it reaches a 80°C, and it would ensure that the filament will be cool enough to be forced through the hotend. However, further experimentation and analysis will be needed to establish a more accurate cooling strategy.

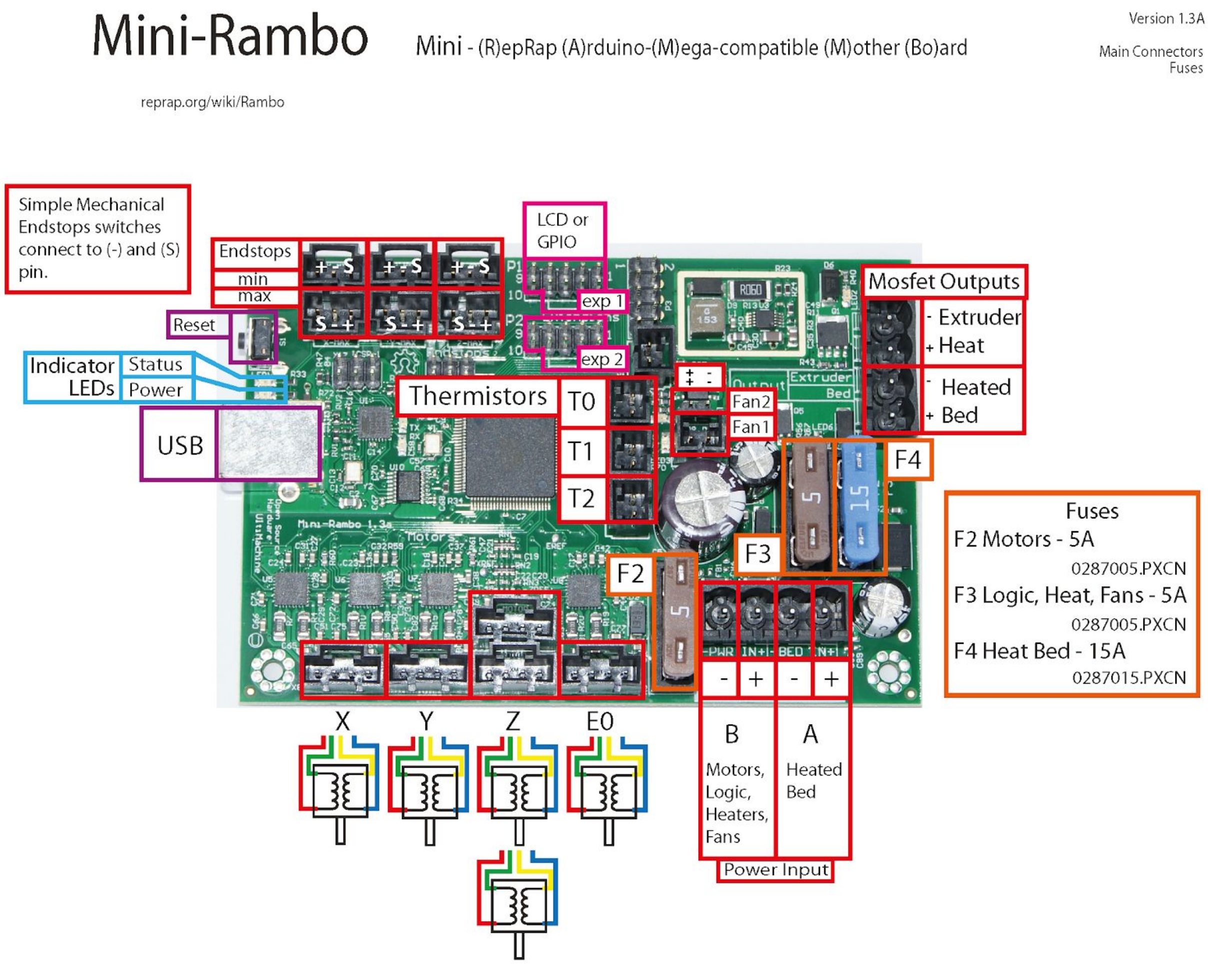


Figure 14: Arduino Mini-RAMBo 1.3a[19]

The 100kΩ thermistor will be inserted into the T1 thermistor port. The majority of Prusa i3 Mk2s models utilize T0 for the hotend and T2 for the bed temperature reading. The temperature reading end of the T1 thermistor will be routed through the heat sink and epoxied to the outside of the teflon tube.

The following adjustments, as seen in Figures 15-18, were made in several different folders to make sure the defined command was recognized across the compiled firmware. All modifications were made to an open source Marlin 1.0.2 version firmware[20] variant.

```
// This makes temp sensor 1 a redundant sensor for sensor 0. If the temperatures difference
between these sensors is too high the print will be aborted.
#define TEMP_SENSOR_1_AS_REDUNDANT
```

Figure 15: Configuration.h Modification

Figure 15 shows the first edit to be made to the firmware. It can be found originally as a comment in lines 116-117. The extra thermistor is defined as redundant due to the fact that the printer being used only has one extruder. It is how the firmware recognizes an additional thermistor at this time. In the event that there are multiple extruders, TEMP_SENSOR_1 would be recognized as the thermistor for the second extruder. However, a second thermistor is left as an option to be an extra protection and prevent a meltdown of the printer in the event that one of the thermistors fails.

```
FORCE_INLINE float degRed() {
  return current_temperature_redundant_temperature;
};
FORCE_INLINE float degTargetRed() {
  return target_temperature_redundant_temperature;
};
FORCE_INLINE void setTargetRed(const float &celsius) {
  target_temperature_redundant temperature = celsius;
};
FORCE_INLINE bool isHeatingRed() {
```

```
  return target_temperature_redundant_temperature > current_temperature_redundant_temperature;
};
FORCE_INLINE bool isCoolingRed() {
  return target_temperature_redundant_temperature < current_temperature_redundant_temperature;
};
```

Figure 16: Temperature.h Modifications

The next firmware edit can be seen above in Figure 16. The modifications made to the temperature.h subprogram are further defining the functions associated with the pin assignment for the redundant temperature sensor. This will allow for the board to recognize the extra thermistor reading, without immediately categorizing it as purely redundant. Each command section was inserted after lines 109, 115, 124, 133,142, and 151 respectively.

```
        #if defined(TEMP_1_PIN) && TEMP_1_PIN > -1
          SERIAL_PROTOCOLPGM(" R:");
          SERIAL_PROTOCOL_F(degRed(),1);
          SERIAL_PROTOCOLPGM(" /");
          SERIAL_PROTOCOL_F(degTargetRed(),1);
If degRed() >= 137
  long_pause()
If long_pause()=True && degRed <=80
  long_pause_resume()
```

Figure 17: Marlin_main.cpp Firmware Modifications

Finally, after defining the thermistor and adjusting the firmware to recognize TEMP_SENSOR_1 outputs as unique, commands could be written based on the outputs of the sensor. As seen above in Figure 17, if the sensor in the heat sink detects a temperature equal to or greater than 137ºC, it will initiate the long_pause command, which will pause the print, save its last location, disable the heater, and turn the fan on to its maximum power. Once the sensor returns a reading of 80ºC, or less, it will run preheat and resume the print from where it was last. 80ºC was arbitrarily chosen to allow for the hotend to be cooled enough to solidify the PLA, but also allow print to be continued within a reasonable amount of time. The defined protocol for the T1 pin was inserted after line 4040 of the firmware package. The long pause command is located between lines 6445-6485. It can be seen below in Figure 18:

```
long_pause() //long pause print
{
        st_synchronize();
        //save currently set parameters to global variables
        saved_feedmultiply = feedmultiply;
        HotendTempBckp = degTargetHotend(active_extruder);
        fanSpeedBckp = fanSpeed;
        start_pause_print = millis();
        //save position
        pause_lastpos[X_AXIS] = current_position[X_AXIS];
        pause_lastpos[Y_AXIS] = current_position[Y_AXIS];
        pause_lastpos[Z_AXIS] = current_position[Z_AXIS];
        pause_lastpos[E_AXIS] = current_position[E_AXIS];

        //retract
        current_position[E_AXIS] -= PAUSE_RETRACT;
        plan_buffer_line(current_position[X_AXIS], current_position[Y_AXIS],
current_position[Z_AXIS], current_position[E_AXIS], 400, active_extruder);

        //lift z
        current_position[Z_AXIS] += Z_PAUSE_LIFT;
        if (current_position[Z_AXIS] > Z_MAX_POS) current_position[Z_AXIS] =
Z_MAX_POS;
```

```
	plan_buffer_line(current_position[X_AXIS], current_position[Y_AXIS],
current_position[Z_AXIS], current_position[E_AXIS], 15, active_extruder);

	//set nozzle target temperature to 0
	setTargetHotend(0, 0);
	setTargetHotend(0, 1);
	setTargetHotend(0, 2);

	//Move XY to side
	current_position[X_AXIS] = X_PAUSE_POS;
	current_position[Y_AXIS] = Y_PAUSE_POS;
	plan_buffer_line(current_position[X_AXIS], current_position[Y_AXIS],
current_position[Z_AXIS], current_position[E_AXIS], 50, active_extruder);

	// Maximize the print fan
	fanSpeed = 255;

	st_synchronize();
}
```

Figure 18: Marlin_main.cpp long_pause() Modification

The only modification made to Figure 19 was the inversion of the fan speed on line 6482. The original script disabled the fan, and this modification simply reversed it to maximum power to quickly remove heat.

Conclusions

The primary goal of this study was to isolate mechanical issues within common digital fabrication lab equipment. Figures 19-34 is a compilation of 6 months of repair history, and it is apparent that 3D printers present a laborious concern for schools that intend on integrating them into their curriculum. A 50% failure rate over the course of 6 months suggests that there must be preventative procedures to mitigate issues that arise from heavy usage. Focus was put on jamming because it had the largest contribution, which was 40%, to the overall cause of failure.

Conducting a rudimentary one-dimensional heat transfer analysis proved helpful towards better understanding the theoretical temperature limits of the PLA within the heated chamber. The critical temperature of 136.77^{o}C for the outside of the teflon tube proved to be well within the temperature capacity of a standard PLA print, which is generally under 210^{o}C. Furthermore, the extra ports on the RAMBo 1.3a board, in addition to the open source firmware, offered the capacity for a wide range of solution approaches, as well as potential for other mechanical upgrades being introduced to the printer.

Developing a better understanding of the utilization and constraints of digital fabrication equipment will be vital to the overall success of their integration into education.

Recommendations

The succeeding phase of this research is to further develop a heat transfer model of the heat sink through experimentation. While the heat transfer model produced from a one-dimensional heat transfer analysis provided an estimate for the temperature failure points within the heat sink, there are a large quantity of parameters that can be integrated into the generation of a more accurate model. Being able to monitor the critical heat zones within the heat sink would allow for a more complete analysis of the cause of jamming within the 3D printer. Additionally, it will allow for a more accurate CFD model to be generated, which would be helpful for testing different heat sink geometries.

Additionally, the thermal properties of PLA are still mostly unknown. The specific heat value of PLA at room temperature had to be extrapolated from a study[10] that used used the specific heat values at 55^{o}C and 100^{o}C.

The results could have been further improved by having a consistent set of objects printed from the 32 printers to better isolate the variables involved with the failure of the print.

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Appendix

Every VW eLab school's inventory:

Equipment ID	Equipment	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router					
	ShopBot PRSAlpah 96x48	23554	250			
	Laser Cutter					
	Dremel LC40	7000	195			
	Dremel LC40	7000	195			
	3D Printer					
	Dremel 3D40	1000	145			
	Dremel 3D40	1000	145			
	Vinyl Cutter					
	Roland GS-24	1855	95			

Figure 19: Brainerd High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
129488	Carvey	N/A	2499	245			
	3D Printer						
129473	Prusa i3 Mk2s	72d6h7m	1000	145			
129474	Prusa i3 Mk2s	70d2h3m	1000	145			
	Vinyl Cutter						
129487	Roland GS-24	N/A	1855	95			

Figure 20: Brown Middle School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:	
	CNC Router							
1	ShopBot PRSAlpha 96x48		23554	195				
	Laser Cutter							
1	Dremel LC40		7000	195				
2	Dremel LC40		7000	195				
	3D Printer							
1	Dremel 3D40		1000	145	Unresolved			
2	Dremel 3D40		1000	145				
3	Da Vinci 3D		159	45				
	Vinyl Cutter							
	Roland GS-24		1855	95	Unresolved			

01/28/18: Filament keeps breaking. External feed system suggested.
-Hiroshi Yanagida

01/28/19: Roll of vinyl keeps coming off of the back.
-Hiroshi Yanagida

Figure 21: Chattanooga High School Center for Creative Arts

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
125625	ShopBot PRSAlpha 96x48	N/A	23554	195			
	Laser Cutter						
1	Zing Laser	N/A	15000	195	Resolved		
	3D Printer						
1	Prusa i3 Mk2s	5109.9	1000	145	Unresolved		
"CSAS eLab" 2	Prusa i3 Mk3	2076.6	1200	145			
3	Prusa i3 Mk3	2039.23	1200	145			
	Vinyl Cutter						
1	Roland GS-24	N/A	1855	95			

12/05/18: Door Magnets failed

12/05/18: door magnets failed.

01/22/18: Damaged bed.

01/22/19: bed is torn up
-Hiroshi Yanagida

Figure 22: Chattanooga School for Arts and Sciences

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
112847	Mill Right CNC Carve King	N/A	699	75			
112848	Carvey	N/A	2499	195			
	Laser Cutter						
112846	Zing Laser	N/A	18000	195			
	3D Printer						
112841	Prusa i3 Mk2s	5878.17	1000	145			
112842	Prusa i3 Mk2s	5966	1000	145	Resolved	Resolved	
112843	Prusa i3 Mk2s	6011	1000	145			
112844	Prusa i3 Mk2s	6038.05	1000	145			
112845	Prusa i3 Mk3	1078.27	1200	145			
	Vinyl Cutter						
112833	Roland GS-24	N/A	1855	95			
112834	Roland GS-24	N/A	1855	95			

09/16/18: X-Axis timing belt issue
-Hiroshi Yanagida
09/16/18: Tightened belt, working fine.
-Hiroshi Yanagida

09/25/18: Runaway build plate error.
-Hiroshi Yanagida
09/25/18: Replaced back wire, Fully functional.
-Hiroshi Yanagida

Figure 23: Dalewood Middle School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
1	ShopBot PRSAlpha 96x48	N/A	23554	195			
	Laser Cutter						
1	Zing Laser	N/A	18000	195			
	3D Printer						
1	Prusa i3 Mk2s	4376.75	1000	145			
2	Prusa i3 Mk2s	4358.02	1000	145	Unresolved		
	Vinyl Cutter						
	Roland GS-24	N/A	1855	95			

01/18/19: Dead heat zone in build plate.
-Hiroshi Yanagida
01/18/19: Replacement build plate needed, will coordinate with Normal Park.
-Hiroshi Yanagida

Figure 24: East Hamilton Middle High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
1	ShopBot PRSAlpha 96x48	N/A	23554	245			
	Laser Cutter						
1	Dremel LC40	N/A		245			
2	Dremel LC40	N/A		245			
	3D Printer						
140397	Lulzbot Taz	N/A	2500	175			
140396	Lulzbot Taz	N/A	2500	175	Unresolved		
1	Dremel 3D40	638.17	1200	145			
2	Dremel 3D40	618.07	1200	145			
	Vinyl Cutter						
1	Roland GS-24	N/A		175			

06/05/18: Dual extrusion head modification has not been added correctly and needs proper installation.
-Hiroshi Yanagida

Figure 25: Hixson High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
1	ShopBot PRSAlpha 96x48	N/A	23554	245			
2	Carvey	N/A	2499	175			
	Laser Cutter						
1	Dremel LC40	N/A					
2	Dremel LC40	N/A					
	3D Printer						
1	Dremel 3D40	1904.47	1200	145			
2	Dremel 3D40	1858.13	1200	145	Unresolved		
3	Dremel 3D40	1852.66	1200	145			
4	Dremel 3D40	1851.5	1200	145			
5	Dremel 3D40	1848.6	1200	145			
6	Dremel 3D40	1841.33	1200	145			
	Vinyl Cutter						
1	Roland GS-24	N/A	1855	175			

01/25/19: Appears to be a Z-axis offset issue
-Hiroshi Yanagida

Figure 26: Hixson Middle School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
1	ShopBot PRSAlpha 96x48	N/A	23554	195			
	Laser Cutter						
1	Zing Laser	N/A	18000	195			
	3D Printer						
1	Prusa i3 Mk2s	4325.23	1000	145			
2	Prusa i3 Mk2s	4311.66	1000	145	Resolved		
	Vinyl Cutter						
	Roland GS-24	N/A	1855	95			

09/12/18: Calibration Error. Resolved.
-Hiroshi Yanagida

Figure 27: Howard High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
1	Carvey	N/A	2499	195			
	Laser Cutter						
151311	Zing Laser	N/A	18000	195			
	3D Printer						
151314	Prusa i3 Mk2s	1480.43	1000	145			
151315	Prusa i3 Mk2s	357.1	1000	145	Resolved		
151316	Prusa i3 Mk2s	1506.95	1000	145			
151317	Prusa i3 Mk2s	1510	1000	145			
151318	Prusa i3 Mk3	2027.43	1200	145			
<099343>	Flashforge CP	N/A	899	95			
	Vinyl Cutter						
151312	Roland GS-24	N/A	1855	95			
151313	Roland GS-24	N/A	1855	95			

10/12/18: Heat block wire broke.
Replacement Hotend Needed
-Hiroshi Yanagida
10/19/18: Part arrived, replaced and calibrated. System working fine.
-Hiroshi Yanagida

Figure 28: Hunter Middle School

Equipment ID	Equipment	Machine hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
<077645>	Carvey	N/A	2499	195			
	Laser Cutter						
<091295>	Boss Laser	N/A	15000	$195	Resolved		
	3D Printer						
<077644>	Prusa i3 Mk2S	6068.23	1000	145	Resolved	Resolved	
<077631>	Prusa i3 Mk2S	6014.66	1000	145	Resolved	Resolved	Unresolved
<091303>	Prusa i3 Mk2S	6130	1000	145	Resolved	Resolved	Unresolved
<077650>	Prusa i3 Mk2S	5931.1	1000	145	Resolved	Unresolved	
<077649>	Prusa i3 Mk2S	328.4	1000	145	Unresolved	Scavenged	
<091304>	Prusa i3 Mk2S	5783.43	1000	145	Resolved		
1	Prusa i3 Mk2S	2153.25	1000	145	Unresolved		
2	Prusa i3 Mk2S	23.27	1000	145	Scrapped for parts		
	Vinyl Cutter						
<077646>	Roland GS-24	N/A	1855	95			

08/18/18: water cooler issue
-Hiroshi Yanagida
08/19/18: just a switch with troubleshooting. Working now

06/04/18: Jammed. fixed

12/03/18: SD card reader failed
12/04/18: Adjusted. Working

01/16/19: Calibration issue.

01/09/19: Jammed

01/09/18: Feed rate issues. Possible jam.

06/06/18: black ring on heat sink broke. Need replacement heat sink

06/05/18: Thermocouple broke, need replacement hotend.
06/06/18: Used scrap hotend piece to replace. Ran calibration test. Working now.

06/05/18: Hot nozzle dug into build surface. Replacement bed needed.

06/06/18: RAMBO unit (motherboard) failed

06/06/18: Motherboard error, scrapped for parts
-Hiroshi Yanagida

06/06/18: RAMBO unit, motherboard

06/05/18: Bed adhesion
-Hiroshi Yanagida

06/05/18: Hot nozzle dug into build surface. Replacement bed needed.
06/06/18: New bed installed from scavenged parts.

06/04/18: Firmware update
06/06/18: Firmware having issues. Reloaded. Fixed

Figure 29: Normal Park Museum Magnet Upper School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
	Laser Cutter						
1	Dremel LC40	N/A	7000	195			
2	Dremel LC40	N/A	7000	195			
	3D Printer						
1	Dremel 3D40	1344.25	1200	145	Resolved		
2	Dremel 3D40	1322.75	1200	145	Resolved		
3	Dremel 3D40	1298.33	1200	145	Resolved		
4	Dremel 3D40	1278.38	1200	145	Resolved		
	Vinyl Cutter						
1	Roland GS-24	N/A	1855	95			
2	Roland GS-24	N/A	1855	95			

08/18/19: USB Port Failed, Sync'd with computer to run prints via WiFi.
08/18/19: USB Port Failed, Sync'd with computer to run prints via WiFi.
08/18/19: USB Port Failed, Sync'd with computer to run prints via WiFi.
08/18/19: USB Port Failed, Sync'd with computer to run prints via WiFi.

Figure 30: Ooltewah Middle School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	Laser Cutter						
165325	Dremel LC40		7000	195			
165659	Dremel LC40		7000	195			
	3D Printer						
1	Dremel 3D40	1598.6	1000	145	Unresolved		
2	Dremel 3D40	1575.8	1000	145	Resolved	Unresolved	
3	Dremel 3D40	1531.23	1000	145			
4	Dremel 3D40	1510.1	1000	145			
	Vinyl Cutter						
626956	Roland GS-24		1855	95	Resolved		

01/22/19: feed rate issues and heating
01/22/19: calibration and bed issues
10/25/18: bed adhesion issues
10/25/18: firmware issues

Figure 31: Orchard Knob Middle School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
129488	ShopBot PRSAlpha 96x48	N/A	23554	195			
	Laser Cutter						
129475	Zing Laser	N/A	15000	195	Resolved	Resolved	Unresolved
	3D Printer						
129473	Prusa i3 Mk2s	1795.5	1000	145	Unresolved		
129474	Prusa i3 Mk2s	1826.43	1000	145	Resolved	Unresolved	
108849	Makerbot	N/A	3000	175			
105915	Makerbot	N/A	3000	175			
108850	Makerbot	N/A	3000	175			
	Vinyl Cutter						
129487	Roland GS-24	N/A	1855	95			

09/13/18: Vent filtration cleaning
10/12/18: Mirror cleaning
10/23/18: Dynamic ip issue
10/25/18: Dead heat zone in bed. Replacement bed recommended.
10/15/18: Bed adhesion issues. Ran first layer calibration to resolve.
11/15/18: Dead heat zone in bed. New Buildplate or heat fan recommended

Figure 32: Red Bank High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	Laser Cutter						
1	Zing Laser	N/A	15000	195			
	3D Printer						
1	Prusa i3 Mk2s	912.47	1000	145			
2	Prusa i3 Mk2s	875.3	1000	145			
3	Prusa i3 Mk2s	849	1000	145			
4	Prusa i3 Mk2s	859.9	1000	145			
	Vinyl Cutter						
1	Roland GS-24		1855	95			

Figure 33: Sale Creek High School

Equipment ID	Equipment	Machine Hours	Value	Rate for repair	Issue 1:	Issue 2:	Issue 3:
	CNC Router						
8	Carvey	N/A	2499	195			
	3 D Printer						
1	Dremel Digilab 3D40	686.08	1000	145	Resolved		
2	Dremel Digilab 3D40	658.3	1000	145	Resolved		
3	Dremel Digilab 3D40	605	1000	145			
4	Dremel Digilab 3D40	660.88	1000	145			
	Vinyl Cutter						
5	Roland Camm-1 GS-24	N/A	1855	95	Resolved		
	Laser Cutter						
6	Dremel Digilab LC40	N/A	7000	195			
7	Dremel Digilab LC40	N/A	7000	195			

01/15/19: Jam over the course of long print

11/18/18: Jam. Fixed.

01/15/19: struggle with depth of cuts, might be problem with blade, ordered new one

Figure 34: Soddy Daisy Middle School