Investigating the Relationship Between Humidity and 3D Printing Failures in a Makerspace

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Abstract

Failures are the largest factor when it comes to waste generated by 3D printing (Toor, 2019; Toor, 2023). Specifically, humidity has been shown to have many adverse effects on polylactic acid (PLA) 3D printing, including lower tensile strength and dimensional accuracy (Faegnell, 2017; Frunzaverde, et al., 2022; Hanon, et al., 2021). As such, the purpose of this study was to create a device to measure humidity and then use it to investigate the relationship between humidity and 3D printing failures in a makerspace. The device was created using a DHT11, and it was coded using Adafruit and smtplib Python libraries to collect humidity data from the makerspace, export it to a comma-separated value (CSV), and email the CSV (Campbell, 2015; Khan, et al., 2021). The device was tested to make sure it could collect humidity data at specified intervals, export data to a CSV, email CSVs at specified intervals, and work autonomously. After 5 iterations, it met all the criteria except being able to work autonomously. Humidity data was collected from the makerspace along with failure data, and a linear regression test indicated that there was a weak correlation ($0 < |r| < 0.4$) between the humidity and failure rate (Zach, 2018). The results indicate that humidity should not be a major consideration for those trying to reduce 3D printing failures. In the future, this study could be used to help design humidity collection devices as well as outline methods for similar studies on humidity and 3D printing.

Keywords: Comma-Separated Values, DHT11, Humidity, Makerspace

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3D printing is an exciting technology that is being rapidly adopted (Shahrubudin et al., 2019), as it provides a host of benefits, from medical to industrial and consumer uses. However, one shortcoming of 3D printing is that it results in a substantial amount of plastic and energy waste. Waste from 3D printing is estimated to be over one million kilograms per year in the United Kingdom alone (Toor, 2023). Although this waste is relatively less than other manufacturing options, finding ways to make 3D printing more sustainable is an important goal given the rising popularity of the technology (Taylor-Smith, 2021).

Notably, up to 80% of waste generated by 3D printing is accounted for by failures, meaning the most effective way to reduce waste is to reduce failure rates (Toor, 2019). Any print that does not meet users' standards is deemed a failure, which in most cases results in the print being discarded. This includes complete failures, where the print is not recognizable in relation to what the user expected, as well as quality failures, where the print could have warping or structural issues. In addition to greater sustainability, lower failure rates would lead to higher satisfaction for users in a variety of settings, including universities where failures are one of the primary problems students experience when printing (Eldebeky, 2021). Thus, the aim of this research is to look into the root of 3D printing failures, and lower the rate at which they occur.

Rationale

In the last decade, the use of 3D printing in university settings has greatly increased, but studies have found that nearly 41% of prints in this environment result in failure (Song & Telenko, 2019; "3D Printing Market," 2023). Conversely, outside of university settings, only 20% of prints fail (Pearce, 2022). Understanding what is behind the higher failure rate in university settings is vital to making 3D printing more effective for students. Additionally, as more 3D prints fail, more plastic waste accumulates, leading to multiple environmental problems (Knoblauch, 2022). In one survey, 3D printer users reported that failed prints accounted for over 80% of 3D printing waste (Toor, 2019). This evidence suggests that reducing 3D printing failures will go a long way toward reducing 3D printing waste. As an intern, I have witnessed firsthand large prints ending up in a sizable tangled ball of filament, resulting in a substantial amount of wasted plastic, which could have been avoided had the print been successful. The goal of this study is to investigate 3D printers at a local university in order to determine ways to improve the successful rate of prints.

Statement of Focus and Sub Problems

Given that 3D printing is becoming increasingly popular in both commercial and industrial settings, it is important to ensure print outcomes are accurate and the process is as user-friendly as possible (Shahrubudin, et al., 2019). This study investigates the relationship between humidity and 3D print outcomes. Literature indicates that humidity can cause PLA filament to become structurally weaker, but research has not been done to evaluate the extent to which humidity affects actual 3D printing failures (Fang, et al., 2020). Research on the effects of humidity on 3D printing failures is important to the Modular Agile Deployment (MAD) Lab to reduce filament waste and costs as well as to understand ways to possibly improve the overall 3D printing experience of students when using the makerspace. By analyzing data gathered from a KSU makerspace, this study further examines the impact of humidity on 3D printing. To this end, the following focus question is generated:

- How does humidity affect 3D printing failure rate?

To address this focus question, this study will answer the following sub problems:

- Basic Sub Problem: What factors are associated with 3D printing failure?
- Basic Sub Problem: How can humidity be measured?
- Applied Sub Problem: How does humidity correlate to the 3D printing failure rate?

  Null Hypothesis: There is a weak correlation between humidity levels and 3D print failure rate ($0 \leq |r| \leq 0.4$).

  Alternative Hypothesis: There is a strong correlation between humidity levels and 3D print failure rate ($0.4 < |r| \leq 1$).

- Design Sub Problem: Create a device that can automatically track humidity and send the data.

  Measure of Success: The device collects humidity data at specified intervals, exports data to a CSV, emails CSV at specified intervals, and works autonomously.

Literature Review

In order to create better printing conditions at makerspaces and reduce environmental waste, this study investigates factors that most affect 3D printing failures in a makerspace, as well as understanding to what extent they do so. The study specifically looks into literature about failure factors and the implications they have on 3D printing in order to inform ideal methods of collecting and analyzing data. Specifically, literature is used to highlight possible ways 3D prints fail as well as how to measure these factors.

Factors that Lead to 3D Printing Failure

3D printing failures can generally be attributed to several factors, including human and environmental influences. In order to investigate which factors are most impactful in a makerspace, the typical factors that lead to 3D printing failure must be understood.

Human Error

In a makerspace, 3D printing is done by uploading a 3D model, usually from computer-aided design (CAD) software, to a 3D printer (Daley, 2022). However, the 3D printers available in a makerspace have certain limitations that can prevent them from being able to successfully print any and all models that are uploaded. For instance, 3D printers struggle to print overhangs more than 45 degrees, so if an overhang is more than 45 degrees, supports need to be added to the 3D model; this is generally done in a 3D printing slicer (Dwamena, n.d.-b). However, this has to be done by a user, and inexperienced users might not know how to add support to a 3D print; as a result, the print could end up failing.

There are other user-related mistakes that can also lead to failed prints. For example, users can create 3D models that have very fine edges, such as a feather, that increase the risk of failure because standard 3D printers used in makerspaces do not have the precision to accurately print very fine edges (Dwamena, n.d.-b). Ultimately, the human side of 3D printing is a crucial part, and inexperienced users could be more prone to mistakes.

Humidity

Humidity is a factor that affects the filament used in 3D printing. The most common filament used in 3D printing is PLA, which is a hygroscopic material; this means that it absorbs moisture from the air, becoming saturated (Faegnell, 2017; Frunzaverde, et al., 2022; Hanon, et al., 2021). Once the filament becomes saturated, it is referred to as wet filament, and wet filament has distinctly different characteristics than dry filament (Toor, 2022; Dwamena, n.d.-a). For example, wet filament has a larger diameter as well as a weaker structure than dry filament, and both of these characteristics can lead to print failure (Faegnell, 2017; “Humidity: The Great Enemy,” 2018). Specifically, the larger diameter has been shown to increase the flow rate of filament when printing (Faegnell, 2017) which leads to over-extrusion and inaccurate or even completely failed prints (Boissonneault, 2022). Additionally, the weaker structure of the filament causes the final printed product to also have a weak structure and thus overall weaker mechanical properties in the print, also leading to failure (Fang, et al., 2020).

Any environment with air inherently has humidity (Water Science School, 2019). However, different levels of humidity can affect filament in different ways. In general, higher levels of humidity cause filament to become wet more quickly than lower levels of humidity (Fang, et al., 2020). Therefore, if the filament is exposed to lower levels of humidity, it can be predicted that it will result in less 3D print failures.

Measuring Humidity

Because humidity can be a factor that contributes to increased failure of 3D prints, this study requires a device that can effectively measure humidity. Literature indicates that a

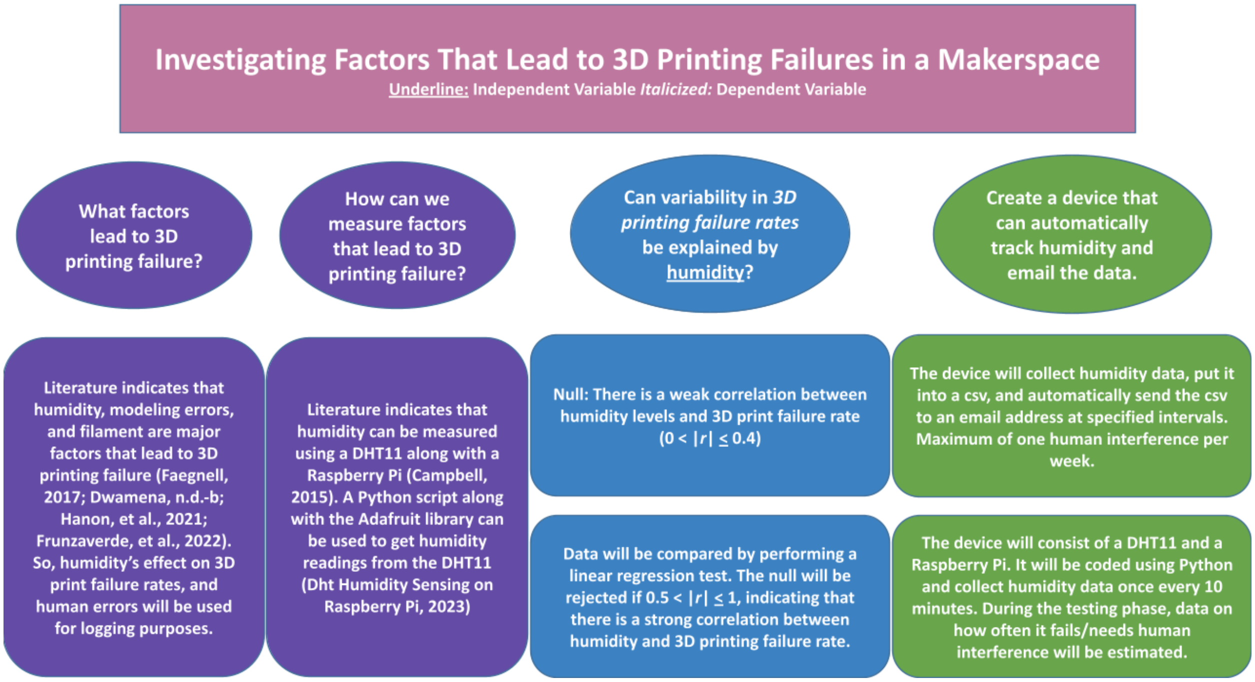
Raspberry Pi with a DHT11 is an effective way to measure the ambient temperature and humidity in an area (Campbell, 2015; Khan, et al., 2021). A Python script along with the Adafruit library can be used to get humidity readings from the DHT11 (*Dht Humidity Sensing on Raspberry Pi*, 2023).

Summary & Implications

By understanding factors that can lead to a failed 3D print, this study can more effectively target and measure those factors in a makerspace. Literature indicates that humidity and human error are common factors for failed 3D prints ("Humidity: The Great Enemy," 2018; Dwamena, n.d.-b; Team Xometry, 2022b). Additionally, each of these factors can be identified as the potential cause of failed 3D prints; for example, humidity can be identified if the print has significant warping, and human error is likely the problem if the print does not have supports where it should (Ultimaker, 2021; Team Xometry, 2022b). By isolating the prints caused by human error from the prints caused by humidity, this study can more effectively measure the true impact of humidity on 3D printing failure rates.

Understanding a trusted method of collecting humidity data means this study can more productively create a humidity data collection device.

Research Map



Scope of Study

Delimitations and Limitations

- This study is limited to data collected in single makerspace.
- This study is limited to data collection over a period of fourteen non-consecutive days.
- This study did not consider factors such as printer calibration, filament color, shape of print, etc. when collecting and analyzing data.
- 3D print fails were categorized based on certain characteristics, which may or may not be indicative of the categories they were put into.

Assumptions

- Failures marked as human error and software error cannot be the result of humidity.
- The mean humidity for a day is representative of the humidity at any given time during said day.
- Factors such as printer calibration, filament color, shape of print, etc. did not affect the outcomes of 3D prints.

Definition of Terms

Terminology	**Definition**
Digital Humidity and Temperature (DHT) Sensor	A low-cost digital sensor used to measure temperature and humidity (Kalaburgi, 2021).
Polylactic Acid (PLA)	A biodegradable material made from vegetable-based plastics; commonly used in 3D printing due to its versatility and affordability (“What is PLA,” n.d.).

Makerspace	A collaborative workspace where university students have access to a variety of tools, including 3D printing (Halbinger, 2020).

Methodology and Design

The focus of this study was to determine whether variability in 3D printing failure rates could be explained by humidity. To accomplish this, humidity and failure rate data were collected from a Kennesaw State University makerspace for fourteen non-consecutive days during the fall 2023 semester. Collecting the humidity readings required designing a device able to autonomously measure humidity and deliver that data via email. Then, data on 3D failure rates was collected and analyzed in relation to the humidity levels. This section describes the methods for the design and applied subproblems as well as the data analysis process.

Creating an Autonomous Humidity Data Collection Device

To address the design sub problem, this study used a DHT11 humidity sensor connected to a Raspberry Pi to secure humidity readings. The device was tested using a checklist as the measure of success. To meet this measure of success, a device would be able to execute four functions: collect humidity data at specified intervals; export data to via a CSV report; email the CSV report at specified intervals; and work autonomously (Baranovsky, 2023; Khan, et al., 2021; *Sending Emails with Csv Attachment Using Python*, n.d.). The checklist measured each function in absolute terms of pass or fail, meaning the device either met the function requirement or it did not.

The device was coded using Python and its libraries, including Adafruit, time, smtplib, datetime, file, and board. To make the device collect humidity data at specified intervals, the Adafruit library was used to get the readings from the DHT11, and the time library was used to set intervals of ten minutes between data collection points (Khan, et al., 2021). Because of the nature of the DHT11, it often returns errors (*Dht Humidity Sensing on Raspberry Pi*, 2023). These errors can cause short delays in the script. Because these delays did not impact the data collection for this study, they were not taken into account. In addition to the humidity data, the date and time of each data point were also collected using the datetime library. The file module was used to open a CSV and export each data point into it, with the humidity in one column, the date in another, and time in the final column.

An app was made using Google Cloud for the purposes of connecting the Python script to the Google Application Programming Interface (API) (de Langen, n.d.); this allowed the use of Gmail from the Python script. The smtplib library was then used in the script to open a Gmail port, log in to a Gmail account, and create and send emails with the CSV attached.

The device was tested and improved upon over the course of five iterations, with each iteration attempting to complete more of the criteria. For each iteration, the device was tested for a minimum of two days to see which of the criteria it met.

Assessing the Relationship Between Humidity and 3D Print Failure Rate

To assess the applied sub problem, 3D print failure rates needed to be collected. This was done by lab assistants in the makerspace who tracked 3D print failures using a physical log. The log asked assistants to record the date of failure, printer number, and the failure reason, with the options being hardware, human error, software error, and an "other" option where they can describe the error (Song & Telenko, 2019). For each option except "other," examples are provided to help assistants understand the type of failures that fall under each category.

Data Analysis

After the data collection period, the print failure log was selectively coded to determine which print failures were most likely related to humidity; for example, failures marked as a result of a software error or human error were not used when calculating the failure rate, and failures described in the "other" option that could also be said with high confidence to not be a result of humidity, such as a modeling error, were not used. Then, data from 3DPrinterOS were used to determine how often and when 3D prints were completed during the study period to give the total number of prints for a day. Next, the failure rate was calculated by dividing the failures (excluding failures determined to be caused by software or human error) by the total number of prints in said day. This daily failure rate was graphed against each day's respective mean humidity, and a linear regression test for correlation was performed (Zach, 2018). If the $0.4 < |r| \leq 1$, the null hypothesis will be rejected, indicating a strong correlation between humidity and 3D print failure rate.

Trustworthiness of Study

Failure data were collected from experienced lab assistants using a log with clear instructions; thus, the data collection method can be considered valid and reliable, as it accurately and consistently measures the amount and type of 3D print failures. Additionally, humidity data were collected using a DHT11, and this can be considered valid and reliable, as it is used within other studies (Khan, et al., 2021).

Results

This section explains the results obtained for each of this study's sub-problems. The success of the design of the autonomous humidity collecting device is discussed first, followed by the results of the correlation analysis between humidity and 3D printer failure rate.

Humidity Collecting Device

Literature indicates that humidity may play a role in the failure rate of 3D prints (Faegnell, 2017; Frunzaverde, et al., 2022; Hanon, et al., 2021), so the first goal of this study was to create a device that could autonomously and remotely collect and send data. For this, a checklist was created to determine if the device was viable for data collection; namely, it had to successfully complete four functions: collect the data at specified intervals, export every piece of data to a running CSV, email the complete CSV at specified intervals, and work autonomously (Khan, et al., 2021; *Sending Emails with Csv*, n.d.; Baranovsky, 2023). The functions were tested in five iterations for at least two days to determine if the checklist criteria were met.

For the first iteration, the Adafruit library was used to get readings from the pin to which the DHT11 was connected, and these readings were refreshed continuously using a while True loop and printed to the console at specific intervals using the time library (i.e. the time.sleep() function). In addition, the date and time were printed for each reading using the datetime library. The first iteration was successful in being able to collect data at specified intervals.

The next iteration used the file module in order to export the readings, date, and time into a CSV. Specifically, the file was opened using the open() function, and then the values were each exported into the CSV using the write() function. As designed, each type of data being collected was given its own column in the CSV. Again, this iteration used the time.sleep function and a while True loop to keep the function running as well as control when the data was collected and exported.

The third iteration was made specifically to email the CSV. Using a Google Cloud app, the Python script was able to connect to the Google API and use Google services, specifically Gmail. Specifically, the smtplib library was used to create a port for Gmail, login to an account, create an email, add the CSV to the email, and send the email. It did not use a loop, nor have the code to collect data, it only emailed the CSV. It was done this way to make sure the code worked before inserting it into the main script.

In the fourth iteration, the email script was successfully added to the main script. The setup of the port, login, and CSV was put outside of any loops while the sendmail function was put inside of a loop. The script used a variable that went up by one for each data collected, and using an if statement, a try-except loop would be used to send an email when the variable hit a certain number. The time spent in between each email could be approximated by multiplying the time specified in between each data collected by the number of the variables needed to satisfy the if statement. This allowed a CSV to be sent after a specified amount of data was collected, as opposed to after every single data was collected. This increased the efficiency of the algorithm.

The fifth and final iteration required emailing the complete CSV at specified intervals. A Google Developer's account was made and connected to Python API. The password was put directly into the Python code, as the data is considered low-risk, and it was the most feasible option (*Risk Classifications*, n.d.). Then, a port was created, and a variable with the CSV was also created. The account was logged into, and once every specified time interval, an email was created with the variable as the body and sent to the email address. One issue was the CSV being sent, but the version was not updated. It seemed as though after a certain amount of time, the "email" CSV and the "saved" CSV diverged, with the code sending the same outdated version of the CSV during the same run of code, despite the actual CSV that was saved to the computer being confirmed to be updating live. Once the code was stopped again, however, the updated CSV was sent. Because of this issue, the device was unable to email the completely updated CSV at the specified time intervals. While this criteria might not be vital to the functionality of the device, because a person could access the device and send an email whenever needed, it is important for the device to be fully autonomous.

Table 1

Humidity device checklist

Iteration	Collects Data at Specified Intervals	Exports Data to CSV	Emails CSV at Specified Intervals	Works autonomously
1	X			X
2	X	X		X
3			X	
4	X	X	X	
5	X	X	X	

Relationship Between Humidity and Failure Rate

Once the device was able to successfully collect humidity data and export it to a CSV, data were collected from the makerspace using the humidity collecting device, a physical log, and 3DPrinterOS to understand the relationship between humidity and 3D printing failure rate

(Table 2). The average humidity over the time span of fourteen non-consecutive days was 35.674%, with a minimum of 19.931% and a maximum of 46.918%. The total number of prints was 113, with 69 being successes, 32 being printing fails, and 11 being non-printing fails. The average daily printing failure rate was 21%, with a minimum of 0% and a maximum of 56%. There was an average daily non-printing failure rate of 8.967%, with a minimum of 0% and a maximum of 33.333%. Then, to better understand if there is a relationship between humidity and printing failure rate, a linear regression test was performed where $0 < |r| \leq 0.4$ indicates weak correlation and $0.4 < |r| \leq 1$ indicates strong correlation. An r of -0.111 was calculated, indicating a weak correlation between humidity and 3D printing failure rate. These findings diverge from the literature, which indicates that increased humidity should have a negative effect on 3D printing, and in turn a higher failure rate (Faegnell, 2017; Frunzaverde, et al., 2022; Hanon, et al., 2021).

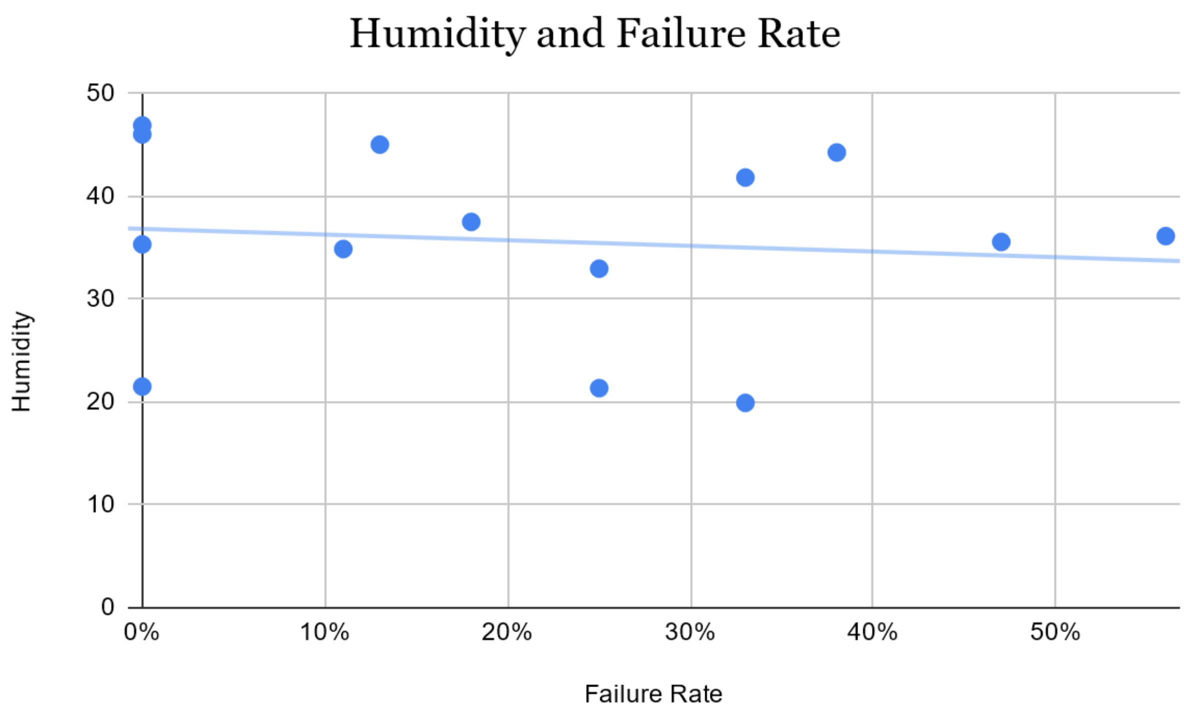
Table 2

Humidity and failure rate

Average Humidity	Average Failure Rate	Max/Min Humidity	Max/Min Failure Rate
35.674	21%	46.918/19.931	56%/0%

Figure 1

Scatter plot of humidity and failure rates


Humidity and Failure Rate
Humidity
50
40
30
20
10
0
0%
10%
20%
30%
40%
50%
Failure Rate

Conclusions

Literature indicates that humidity can affect 3D printing in different ways, but research has not indicated whether humidity correlates with failure rate (Faegnell, 2017; Frunzaverde, et al., 2022; Hanon, et al., 2021). So, this study set out to fill this research gap by exploring whether such a correlation exists in data collected from a makerspace. The first step in the research process was the creation of a device to autonomously collect and send humidity data. Literature indicates that a DHT11 is a practical way of measuring humidity and that emailing a CSV is an effective method to transport data (Khan, et al., 2021; *Sending Emails with Csv*, n.d.). The device created in this study used a Raspberry Pi with a DHT11 with a Python script to email CSVs. The measures of success for the device were that it had to collect humidity data at specified intervals, export data to a CSV, email CSV at specified intervals, and work autonomously. The device was successful in meeting all the requirements of the checklist, except being able to autonomously email the complete CSV. Having this device enabled continuous humidity readings to be collected at set intervals without the presence of a lab assistant, reducing human error in the data gathering as well as the need to staff the makerspace throughout the day. Future studies that involve the collection of humidity readings may benefit from the use of this device.

Failure data were collected from the makerspace alongside the humidity data and a linear regression test was conducted to determine the correlation coefficient (r). Results showed that $r \approx -0.111$, meaning that there was a weak correlation between humidity and 3D printing failure rate. Therefore, the hypothesis that there would be a strong correlation was rejected. In other words, while humidity may have effects on some aspects of 3D printing, this study's results indicate that it does not affect 3D printing failure rate.

Implications

This study provided tools for the makerspace to effectively measure humidity, which can also be used by other makerspaces. Having this device enabled collection of continuous humidity readings at set intervals without the presence of a lab assistant, reducing the need for human intervention when collecting humidity data in the makerspace.

Overall, this study shows that humidity did not have a strong influence on 3D printing failure rates in the makerspace. Makerspaces should take this into account when considering forms of humidity control for PLA filament, such as dry storage cabinets.

Limitations

The device was limited to the hardware readily available in the makerspace. Data were only collected over a period of fourteen non-consecutive days from a single makerspace at Kennesaw State University. Different findings may have resulted from a longer period of data collection as well as greater variation in the humidity levels. Additionally, these data are only generalizable to said makerspace. This study was only able to determine strong or weak correlation, not explain it; research should be done in the future to determine this.

Future Research

Future humidity devices could be made using the methods described, in addition to added features. For example, a device could be made to start the script when the device is powered on, which could be useful in the case of a power outage. Future studies on 3D printing failure rates can be completed with the same methodology in other 3D printing spaces to better assess humidity's effect on 3D printing failure rates in different environments. Studies could also be completed at a larger scale over a longer period of time to further explore how humidity affects 3D printing failure rates. Future studies could also include other factors in the analysis to better understand 3D printing failure rates. While this study attempted to account for influencing factors such as human error, it did not account for factors such as printer calibration, filament color, and shape of print. This study serves as a springboard for future research on the effects of humidity on 3D printing, in addition to providing a framework for studies on 3D printing failures in general.

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