Effects of Humidity, Temperature, and Air Conditioning on 3D Printing Failures

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Abstract

Guidelines: Left justified. No paragraph indentations.

No citations (but you aren't really including background literature)

There is a minimum of 200 words and maximum length of 250 words. Write in past tense, but not passive voice, and

- Introduce the study topic briefly
- Clearly articulate the study problem and purpose
- State if the research is quantitative, qualitative, or mixed method and the research design and method
- Identify participants or study population if applicable
- Present key results (include descriptive statistics, and for quantitative studies include relevant test statistics and *p* values)
- Present conclusions and recommendations for future research

Acknowledgements

You may place an optional acknowledgements page here.

Table of Contents

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Chapter 1: Introduction

Fused filament fabrication (FFF) in 3D Printing is an increasingly popular method for researchers, designers, and hobbyists to quickly and affordably create tangible versions of 3D designs (Fang et al., 2020). However, FFF's low costs bring many environmental concerns including excess energy use, plastic emissions, and most pertaining to this study, waste (Liu et al., 2016). Most waste from 3D printing originates from failed prints, which often occur due to the use of weakened filament (Moreno et al., 2020). There have been several studies showing that temperature and humidity have significant effects on 3D-printed objects' structural integrity and tensile strength (Hamid et al., 2023; Karimi et al., 2023; Pang et al., 2022). Degradation of these properties could potentially lead to an increased rate of print failures.

Statement of the Problem

3D printing, although an accessible option for 3D modeling and prototyping, faces challenges with waste, primarily attributed to high print failure rates (Moreno et al., 2020). Several studies have found that temperature and humidity have effects on the properties of 3D printing filament, potentially increasing the rate of print errors (Hamid et al., 2023; Karimi et al., 2023; Pang et al., 2022). These effects could ultimately increase the overall amount of waste produced by 3D printing.

Purpose of the Study

The purpose of this study is to study effects of temperature, humidity, and the air conditioning status on 3D printing error rates in a makerspace at Kennesaw State University. This study seeks to improve on a previous, similar study done by Pieper (2023) by increasing both the amount of data collected and the number of variables studied to form a more informed conclusion. If this study finds that the temperature, humidity, or air conditioning status affect error rates, controlling these conditions effectively could help minimize 3D printing waste.

Research Questions

Q1 To what extent does the temperature, humidity, and air conditioning status affect the frequency of print failures in a makerspace?

Q1.1. To what extent does the temperature affect the frequency of print failures in a makerspace?

Q1.2. To what extent does the humidity affect the frequency of print failures in a makerspace?

Q1.3. To what extent does the air conditioning status affect the frequency of print failures in a makerspace?

Hypotheses

H1 The environmental aspects of the makerspace will have a strong correlation with printing error rates.

H1.1. The humidity of the makerspace will have the strongest correlation with printing error when compared to temperature or air conditioning.

Significance of the Study

The study is important as it could provide a potential solution to excess 3D printing waste. Excess waste from 3D prints not only leads to increased spending, but also has greater environmental impacts regarding energy use. Results from this study will prove useful to operators of makerspaces looking to optimize spending or researchers looking to efficiently expand 3D printing's use to a mass-production scale.

Definition of Key Terms

Fused Filament Fabrication (FFF)

A popular 3D printing method, using melted filament to fabricate an object layer by layer.

Polylactic acid (PLA)

A renewable plastic commonly used for 3D printing filament.

Operational definitions

Makerspace. A laboratory space in a university where students design and print objects using 3D printers. The space is home to over 20 different-sized 3D printers, along with merchandise printing and virtual reality equipment.

Environmental factors. The ambient temperature and humidity of the printing environment.

Summary

3D printing is an accessible and efficient means of producing 3D goods but brings environmental concerns, specifically regarding waste (Moreno et al., 2020; Singh et al., 2020). Printing failures or low-quality prints produce the most waste from 3D printing (Singh et al., 2020). Several studies have confirmed that the temperature and humidity of the printing environment negatively affects the properties of 3D printed objects (Hamid et al., 2023; Karimi et al., 2023; Pang et al., 2022). This study seeks to analyze these variables on the 3D printing process, investigating their effects on 3D printing error rates. The results of this study will inform users of new methods to reduce printing costs.

Chapter 2: Literature Review

3D printing, or additive manufacturing, is one of the most accessible and cost-effective methods of quickly fabricating 3D models (Singh et al., 2020). Consequently, additive manufacturing technology has applications in many fields, from healthcare to food processing (Agunbiade et al., 2022; Aimar et al., 2019; Kirby et al., 2020; Kveller et al., 2024). Despite its many strengths, 3D printing is not a perfect technology. It faces less consistent quality when compared to traditional manufacturing methods, along with environmental and user safety concerns (Moreno et al., 2020; Singh et al., 2020; Stephens et al., 2013).

Fused Filament Fabrication

Fused filament fabrication (FFF) is one of the most popular 3D printing methods, as it is both energy and cost-efficient (Krishnanand et al., 2020). According to Ahmadifar et al. (2021), the FFF process begins with a 3D model generated in computer-aided design (CAD) software, which then converts the model into a stereolithography format (STL). Following this, specialized software divides the model into multiple horizontal layers or cross-sections, generating code with paths for the printer to follow as it prints each layer (Ahmadifar et al., 2021).

Mechanically, Krishnanand et al. (2020) stated that the defining component of FFF-based 3D printers is an extruder, consisting of the nozzle, hot and cold ends, and extruder drive. The nozzle guides the filament melted by the hot end onto the printing bed during fabrication. The cold end limits the heating of the filament before it reaches the hot end. Finally, the extruder drive is responsible for moving the filament across the extruder into the hot end (Krishnanand et al., 2020).

A study by Singh et al. (2020) investigated the current state of FFF along with its issues and future potential. It identified many physical issues in FFF prints, such as poor finish, in-process deformations (also known as printing stresses, causing warping and layering issues), and its speed compared to traditional manufacturing methods. The paper also proposed several solutions for these, along with ideas for future research. The paper emphasized research to be more focused on the broader application of FFF in manufacturing, like researching in settings other than controlled laboratories or exploring new materials to 3D printing (Singh et al., 2020).

Impact and Applications of 3D Printing

Prashar et al. (2022) claimed that 3D printing is one of the most important developments of the modern industry. They attributed this to the technology's low costs, maturity, and many potential applications. The article projected 3D printing to produce two trillion dollars' worth of items, components, and products by 2030. Additionally, the article claimed that developing 3D printing technologies will provide for important needs in manufacturing, such as becoming more affordable and efficient than traditional manufacturing methods for mass production (Prashar et al., 2022).

One of the most significant applications of additive manufacturing is its use in the design process for products and other goods. Ahmadifar et al. (2021) explored the concept of rapid prototyping, where designers fabricate components quickly and numerously to streamline and accelerate development. Currently, FFF is the most affordable option for rapid prototyping, usually using thermoplastic filaments like polylactic acid (PLA) or acrylonitrile butadiene (ABS) (Krishnanand et al., 2020).

One of 3D printing's most extensive applications is in the medical field. Kveller et al. (2024) surveyed clinicians in a hospital about the effects of applied 3D printing in everyday patient care. Most clinicians stated that 3D printing improves their patients' understanding of their condition or procedure, along with the execution of the procedures themselves (Kveller et al., 2024).

The most developed medical applications of 3D printing field today are surgical models and drug development (Aimar et al., 2019). Regarding surgical models, Kirby et al. (2020) discussed the main uses of 3D printing: quick production of anatomical models, implant prototyping, and production of patient-specific implants. Similarly, hospitals have used 3D printing to manufacture personalized drugs for patients in various form-factors like tablets, implants, or microneedles (Wallis et al., 2020). However, Wallis et al. (2020) mentioned that the current costs of producing computer models and 3D printing limit its use across the field, despite general praise of the technology's affordability.

3D Printing Issues and Concerns

Although 3D printing brings many new possibilities to the world of manufacturing, it is not without its own issues and concerns. A significant concern for 3D printing in the modern space is its environmental impact through waste, energy use, and plastic emissions (Liu et al., 2016).

Liu et al. (2016) proposed a framework to investigate the sustainability of 3D printing, addressing many important concerns. The article speculated that 3D printing would have greater environmental impacts than traditional manufacturing at a mass-production scale, which is one of the goals for 3D printing to reach. Additionally, it includes studies suggesting that 3D printing produces significantly more energy than specific traditional manufacturing methods when fabricating similar items. The paper also addressed concerns regarding filament emissions produced during printing, stating that they could negatively impact both the environment and human health (Liu et al., 2016).

Research by Moreno et al. (2020) investigated 3D printing's waste problem more closely, evaluating PLA's capability for mechanical recycling. The study states that most waste from 3D printing results from failed or defective prints and that users only recycle a small amount of material. The study ran several types of PLA filament through a mechanical recycling process, including washing and drying the material, processing it through a micro-compounder, and turning it into film for analysis. The study's results showed that the printing process itself does not degrade the filament significantly, but the washing and reprocessing processes do. Despite this, the study concluded that mechanical recycling is a viable method for filament recycling if users give proper attention to the waste's origins and composition (Moreno et al., 2020).

Regarding the concern of plastic emissions, Stephens et al. (2013) studied the concentration of ultrafine particles produced by desktop 3D printers in a commercial setting. The study found that 3D printing using both ABS and PLA produces a significant amount of ultrafine particulate matter; however, ABS produced much more than PLA by an order of magnitude. The article includes resources stating that fumes from certain thermoplastics have toxic effects on both animals and humans. Finding methods to reduce plastic emissions from 3D printing would help to ensure user safety during prolonged operation (Stephens et al., 2013).

Environmental Effects on 3D Printing Filament

There have been several studies on how characteristics of the environment (temperature and humidity) affect the physical properties of 3D printing filaments such as PLA. Farah et al. (2016) stated that the properties of PLA are largely dependent on its processing temperature and that humidity impacts its biodegradation. Ahmadifar et al. (2021) also considered environmental temperature and humidity as important parameters that influence FFF printing.

Research by Hamid et al. (2023) investigated the effects of humidity on 3D printed PLA's porosity and chemical structure. The study found that humidity affects 3D printed PLA's chemical bonds and increases its porosity, decreasing the object's density. This increased porosity due to exposure to humidity negatively affected the object's structural integrity, decreasing its tensile strength. The study concluded that correct storage of 3D printing filament in a low-humidity environment is essential for maximizing the strength of 3D-printed parts (Hamid et al., 2023).

A study by Pang et al. (2022) also investigates humidity's effects on PLA, supporting the latter study. The research investigated PLA stored in environments with both ambient and controlled humidity. The study found that objects stored in higher humidity had lower tensile strength than those stored in lower humidity. Finally, the study recommended to store PLA filament in environments with minimal humidity to avoid degradation over time (Pang et al., 2022).

Regarding temperature, Karimi et al. (2023) studied the effects of ambient temperature on 3D-printed PLA parts. The study examined the tensile, flexural, and fracture characteristics of 3D-printed objects at four different ambient temperatures: -20, 0, 20, and 40 degrees Celsius. The study found that the ambient temperature significantly affected the tensile strength of the objects, finding a significant decrease from -20 °C to 40 °C. However, the ambient temperature did not significantly affect the objects' morphology or microstructure (Karimi et al., 2023).

Research by Pieper (2023) investigated the effects of humidity on 3D printing failures in a makerspace at Kennesaw State University. This study used Raspberry Pi humidity sensors to collect humidity data, looking for a correlation between it and print errors in the makerspace. The study concluded that humidity has no effect on error rates. However, the study concluded this from a small amount of data, as it only took place over 14 non-consecutive days. This study has clear room for improvement, especially regarding data collection (Pieper, 2023).

Summary

3D printing is an important technology in the modern industrial landscape, with exciting capabilities if implemented at mass-production scale (Prashar et al., 2022). It has uses in fields like product design with rapid prototyping and the medical field with drug development and the creation of surgical models (Ahmadifar et al., 2021; Aimar et al., 2019; Wallis et al., 2020). Despite its strengths in accessibility, cost, and efficiency, 3D printing still has major concerns to address in the future, including energy use, plastic emissions, and waste (Liu et al., 2016). 3D printing's waste issue mainly originates from failed prints (Moreno et al., 2020). Many studies conclude that temperature and humidity significantly influence 3D-printed PLA's structural integrity and tensile strength, potentially leading to increased print failures (Hamid et al., 2023; Karimi et al., 2023; Pang et al., 2022). There have not been many studies directly investigating ambient temperature and humidity on printing failures directly, but those that did drew conclusions from insufficient amounts of data (Pieper, 2023). This study hopefully will fill this gap in literature, providing insight on the causes of print failures and providing solutions to minimize waste from 3D printing.

Chapter 3: Research Method

Copy and paste the problem and purpose (one-sentence statements—not paragraphs) from Chapter 1 verbatim. You can rewrite/rephrase them if you choose, but you do not have to change them. Restate the research question(s)/hypotheses verbatim from Chapter 1. Do not include any passive voice. This chapter of the final paper should be in 1st person, past tense. Conclude the introduction with a brief overview of the chapter without giving a turn-by-turn road map. Writing that you will include methods, then population, then sample, then materials, etc. is unnecessary.

Research Design(s) and Method(s)

Accurately describe the research design(s) and method(s). Change the L2 heading to reflect a singular or plural design and method. Substantiate the appropriateness of the design(s) and method(s); include a statement about why the method/design(s) was/were chosen or was/were the appropriate way to address the goals of the study. So, this means including quantitative/qualitative, type of study with data collected by observation/ survey/ experimentation/ etc., and a general plan of the method. In this section you should not give a reproducible procedure, only the overview.

Remember that design alone does not dictate data and data alone does not dictate design. Just because you collect quantitative data (numerical values), you may still utilize a quantitative or qualitative design. Sometimes you have a variable that you collect as numbers, but it is actual ordinal data and cannot be treated the same as a count (Likert scale).

Discuss the assumptions and limitations imposed by the type of design and method you have chosen as well as how those assumptions and limitations impact the various types of validity of your study. These assumptions and limitations need not include those that arise from the selection of your population and sample as those will be covered in that section. Validity and reliability may be high or low because of design and/or methodology – describe what types and how so?

Population and Sample

Provide a description of the population (as appropriate), estimated size and relevant characteristics. Depending on the study design, populations may reflect a group of people, a set of organizations, a set of documents, archived data, etc. Describe why the population is appropriate in relationship to the study problem and purpose. Distinguish between the population and the sample drawn from the population.

Identify the sampling method and explain selection of participants or relevant sample, including known population characteristics and recruitment or selection strategy. Describe *and justify* the sampling method and sample size:

1. Quantitative studies: when determining a minimum sample size, consider sampling error, representativeness and the assumptions of the proposed statistical tests.
2. Qualitative studies: since sample size is typically small; explain sample election process.

As appropriate: Describe how existing data were originally collected and for what purpose, and justify validity of size and selection criteria.

Describe how participants were selected and solicited. Access to potential participants must be described. Sampling procedures (e.g., "random", "random stratified", "convenience", "purposive") must be described and cited in sufficient detail so that the process could theoretically be replicated.

Your selection of your population and sample will involve assumptions and limitations that will affect the various forms of validity present (or not present) in your study. Please discuss these in this section as well. Describe delimitations to your population and sample. As delimitations are how you chose to limit your study, this is the most common section of your paper to discuss delimitations.

Materials and Instruments

This section will include the items and tools used for the study. Materials can include the (a) data sources: *archived data*, include a description of how the original data were collected and for what purpose along with information regarding validity and reliability; (b) physical *materials* used for the study – sources and descriptions of the materials used. Instruments can include anything used to collect primary data such as (a) surveys and observation or interview protocols; adequately reference the original source of the instrument and its original use (population and sample and purpose) and detail any modifications made to fit your study (include the instrument in an appendix); (b) criteria developed to include or exclude secondary sources of data from the study (used for meta-analysis): (c) *apparatus* (fancy equipment) used to collect primary data in experimental settings - adequately describe any apparatus including model/make and what exact data is measured as well as how it is used.

Note: Instrument (survey) self-development is strongly discouraged. If an appropriate existing validated instrument is not located after a thorough search, the development process and tests for instrument and construct reliability and validity must be described in detail within Chapter 3 and the resulting validity and reliability measures reported in Chapter 4.

Discuss the validity challenges you may have due to assumptions and limitations present because of your instruments (specifically, survey instruments have many assumptions and limitations involved).

Operational Definition of Variables (Quantitative/Mixed Studies Only/if necessary)

Operational definitions

Sometimes you will use a term in a very specific way that you need to clearly define for the purposes of your individual study.

But more

Christensen actually talks about operationalism in your readings, so if you remember back to that or took a few notes, you should be able to implement some of the ideas within the reading to help guide you in deciding whether or not you need any.

Literature

If you use any operational definitions, be sure to include support (cite peer reviewed literature) justifying how or why you are defining your variables in the way you chose.

Data Collection, Processing, and Analysis

Describe the collection, processing, and analyses in enough detail so that the study could be replicated. Describe the steps utilized to complete study. Provide specific details relative to the execution of the design in each appropriate section. Describe type(s) of data collected, how data were coded (qualitative), and what statistical analysis and software you used (as appropriate). This is where your step-by-step reproducible procedure should be. I should be able to pick up your paper and your materials and run your entire project from start to finish.

For your statistical analysis, each statistics test has certain criteria and assumptions that must be met and/or justified before the test may be used. You need to discuss your actions for justifying your chosen test with your data (before your actual analysis). Introduce and discuss your null and alternate statistical hypotheses here.

1. Quantitative: Describe analysis strategy utilized to test each hypothesis. The discussion must be sufficiently detailed so that the appropriateness of the statistical tests chosen is evident. Discuss and justify all statistical assumptions have been (or how they will be met – concept paper) for your test.
2. Qualitative: Describe how the data were processed and analyzed. Provide primary qualitative design support for proposed analytical strategy. Explain your role as the researcher. Discuss your themes and qualitative coding technique in excruciating detail.

Assumptions

If you have further assumptions that have not be covered by the design, method, sample and population, or statistical analysis, you should include them here with cited justifications and the validity concerns that arise because of them. If your Assumptions, Limitations, and Delimitations are very strong in each of your individual sections, you may not need these three headings. But if you are weaker in the sections, this is a good place to strengthen and JUSTIFY.

Limitations

If there are further limitations imposed by conditions beyond the design, method, sample and population, or statistical analysis, you should include them here with explanations of how they were addressed to the extent possible as well as the validity concerns that arise because of them.

Delimitations

Describe any study delimitations (specific choices made to narrow the scope of the study) and justify that choice. Explain and justify why the topics, population, variables etc. that were excluded are not relevant to the goals of the study.

Ethical Assurances

Discuss compliance with the standards for conducting research as appropriate to the proposed research design. Describe informed consent procedures and how you will maintain confidentiality of the participants (as appropriate). Describe how you obtained assurances for approval of your study. You would also include a potential conflict of interest from commercial entities (products you use or test) or funding sources. Business and marketing projects may need a statement of objectivity. Some studies will NOT have an ethical assurances section because there are not potential ethical issues.

Summary

Summarize key points presented in Chapter 3 and provide supporting citations. Flow into chapter four.

Chapter 4: Findings and Results

Begin the discussion with a brief overview of the problem and purpose of the research study and provide a brief overview of the design and method (same 'rules' as chapter 3 introduction). Organize the chapter based on research question(s) and hypotheses (not included in this intro). Review APA manual or online APA Style Guide, and peer-reviewed research articles for examples of how to report results of various research designs within your study area. Be sure to check proper APA formatting for tables and figures.

Results

While you do have a lot of freedom in this section to order it in a way that is logical to you, I would recommend following these generic guidelines and fitting them to your situation. Start with a brief introduction of any overarching questions and how you had subquestions to help answer the umbrella question. Report the data from subquestion one (or question 1 – whichever is appropriate). Provide summary data (descriptive statistics such as a central measure of tendency and a measure of variance) and describe the data. Share a graph as appropriate or a summary table of the data. Report all raw data in appendix A or B (if you have a survey).

After you have described your data thoroughly, analyze the data according to your statistical plan (t-test, anova, chi square, etc). Report the full test (chi square) or the test statistics (anova, regression, t-test). Report the p-value, correlation coefficient, f-value, or other helpful statistics for your chosen test and state whether the null hypothesis is rejected or is failed to be rejected. Do not go into the implications or rationale of the failure to reject or rejection in this chapter. That is for Chapter 5.

You would then repeat this process as necessary to provide data for each of your questions and subquestions.

For Quantitative analyses,

a. Give appropriate descriptive statistical information,
b. Present the results in a logical fashion, answering the research question(s)/hypotheses as stated and appropriate to the type of data collected,
c. Review assumptions of statistical tests and address justification of and any violation of assumptions,
d. Make decisions based on the results of the statistical analysis (for example: Are the results statistically significant?). Include relevant test statistic and *p* values.
e. Refer to APA manual or online APA Style Guide for information regarding how to present results in text, tables and figures,
f. Present sufficient information so the reader can make an independent judgment regarding your results, but do not interpret it yourself here.

2. **For Qualitative** analyses
   a. Present results logically and in a way that answers the research question(s),
   b. Present sufficient information so the reader can make an independent judgment about your results, but do not interpret it yourself here.
   c. Review published articles that use similar designs for examples of how to present qualitative, thematic findings,
   d. Ensure that no potentially identifying information is published.

Note: Table and figures, where appropriate, are necessary and referred to in the text. You should convey the entire 'picture' in the body of the text and in the figure and figure legend.

While this seems redundant, it is necessary. Ensure compliance with APA format of tables, table titles, figures, and figure captions. A general guideline is that if a table or figure take up more than half of a page, it should be included in an appendix and referred to in-text. Smaller figures and tables may be embedded in the section while being discussed.

Evaluation of Findings

This section is used to briefly address the quality and reliability of the data and data analysis. You are not telling the reader what the data means, only how good or the level of quality of your data. This ties into the reliability and validity directly and it should be integrated fully. Describe whether the results obtained were expected given the literature and provide potential explanations for unexpected or conflicting results. Did you collect 'good' data and why? How are you justifying it? The discussion of data will be expanded in Chapter 5 to include the meaning and interpretation of the findings, but it is not needed here.

Summary

Discussion summarizes key points presented in Chapter 4 and flows into Chapter 5.

Chapter 5: Implications, Recommendations, and Conclusions

Begin the discussion with a brief review of the problem statement, purpose, design and method, and a review of the main findings from chapter 4.

Implications

Discuss each research question and (when appropriate) hypothesis individually, and draw logical conclusions. Follow the same logical sequence that you used for Chapter 4. This is best done using a framework similar to making a claim, supporting that claim with evidence and following the evidence with reasoning that supports both the claim and the evidence (Claim : Evidence : Reasoning). Avoid drawing conclusions that are beyond the scope of the study results. Discuss how any potential limitations may have affected the interpretation of the results. Place the results back into context by describing how the results respond to the study problem, fit with the purpose, demonstrate significance, and contribute to the existing literature described in Chapter 2. Describe the implications of the study results in light of the literature described in chapter 2 and place in the applied study context and profession/field of study. Remember, if you are discussing Chapter 2 (Lit Review), you should be including all of the citations when you discuss them. While you have not used many references in the past two chapters, this should be reference-heavy. Discuss the contribution of practical utility in terms of potential ways of applying in real contexts, specifically related to the particular study context.

Recommendations

Present all recommendations for practical applications of the study. Support all recommendations with the research findings. Present recommendations for future research. If you are in a business setting, report recommendation for best business practices as well.

Conclusions

In this section, summarize all key points in Chapter 5. Finish up your conclusions in a way that wraps up your entire paper. You should be proud of this paper and finishing it without much thought is an absolute travesty.

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Appendix A: Title

You need to include your survey or other instrument if you have one. You need to include an appendix with a table including all of your raw data. Any figures or tables that are too large (takes up more than a half page of space) should have an appendix. All tables and figures in the body of your paper and in your appendices should be APA format including a full figure/table legend. Figures and tables are numbered within each appendix (Appendix A Figure 1 and Appendix A Table 1). If a figure or table is in the paper, it should not also be in the appendix because that is redundant.

Appendix B: Title

[Insert/type Appendix B content here]

Sample Appendix Types

- Survey or Data Collection Instrument
- Raw Data
- Evidence of Meeting Statistical Assumptions
- Pictures of Laboratory Setup
- Statistical Analyses (if you have many and only report specific ones or an abbreviated summary of all