Establishing a Crowdsourcing-Based Data Collection Tool to Identify Sources of Build Failure in Novice AM Designs

Ethan Gross, Nicholas Meisel*
The Pennsylvania State University, University Park, Pennsylvania
*Corresponding Author

Abstract

The maker movement has led to an increase in publicly available makerspaces, where communities can work with design and manufacturing equipment, including additive manufacturing (AM) machines. A low barrier-to-entry is essential to maintaining inclusivity, allowing inexperienced patrons to use AM technology. However, this lack of experience subsequently encourages frequent print failures, which contributes to increased maintenance or user frustration. Build failures are caused by several variables, but commonly stem from build preparation, the slicing process, or user interference. To identify key causes behind failed AM builds in a student-focused makerspace, this paper outlines how a crowdsourcing-based data collection tool was formulated that automatically extracts design and print information through printer files and correlates this information with student evaluations of their part's build quality. This data allows for common sources of failure within the space to be readily identified. A case study is analyzed to demonstrate the tool's general effectiveness and applicability.

1. Introduction

The rise of the maker movement, a recent culture inviting many to use a wide range of equipment to suit their creative and building wants has led to the increased availability of open-access makerspaces. Makerspaces offer a location where communities of practice can come together to work with various pieces of potentially costly equipment at a low barrier to entry. Areas of interest commonly found in makerspaces where users can take part in creating any number of projects include woodshops, metal shops, textile labs, and additive manufacturing labs. Additive manufacturing (AM), the process of creating a desired object or assembly by layering material together in a constructed pattern aided by a 3D model, is especially common in makerspaces due to their low machine and material cost. AM machines can waste less material than traditional subtractive manufacturing processes such as woodworking or machining and can offer many unique benefits including rapid prototyping and enabling geometries that are normally difficult or impossible to machine [1]. Instead of having to realize a mistake in a traditionally manufactured part and have to redesign major aspects in order to properly machine it, AM enables users to take digital part designs and quickly reproduce them to confirm their validity.

The inclusive nature of a makerspace is evident by the common philosophy of welcoming individuals regardless of their level of experience and helping them begin to create [2,3]. There is often initial training available to educate newcomers on different shop spaces. However, after this initial safety training, it is common practice for users to advance their understanding of the different technology, such as AM, simply through trial and error until they fabricate a part with its desired features [4,5]. Users with minimal experience may download a 3D model from the internet from sources such as Grabcad.com or Thingiverse.com, prepare the files in a slicing software and immediately try to produce the part. However, if the proper settings are not selected, the AM machine may fail to produce the desired object, causing novice users to return to the settings and begin to learn the necessary metrics involved with a successful AM tray [6]. When the machine is calibrated correctly and the user is well-knowledged in the printing process, the manufacturing of AM trays can become more successful; however, novice makerspace users will likely see many failures when first starting to use AM technology.

Material Extrusion (MEX) machines are the most common type of AM technology found in makerspaces, due to their low cost, risk, and time to generate the desired object [7,8]. Despite these advantages, by making these systems available to novices in a makerspace, there is the potential for a more frequent maintenance schedule. All AM machines are delicate in some manner and unfortunately MEX machines can malfunction often, and due to the low cost of spare parts and availability of online guidance, it is often the owner's responsibility to repair the machine [9]. While MEX machines can malfunction through regular use, they can also break as a result of a failure during the printing process. For example, a poorly prepared tray can cause an error during the process causing material to flood the extruder which can lead to clogged nozzles or misaligned gears. These issues may remain in the machine, so when a properly prepared tray is being produced, a failure may still occur, due to effects from previously failed builds.

In an open-access makerspace where most users are novices to AM, frequent MEX print failures and increased machine maintenance are likely. Makerspaces and everyone involved, the owners, staff, and users, would benefit from a validated resource that helps to predict whether a prepared MEX tray has a high success or failure probability. There exists an opportunity in makerspaces to crowdsource a large amount of AM data from their users, including the geometric details in their design part, how they setup the MEX tray, which machines are historically prone to failure, and if and any interference from the user during the printing process affects the probability of a tray succeeding. This paper introduces a crowdsourcing-based survey tool that has a makerspace's user upload their current tray's slicing data alongside a personal evaluation of their printed tray. A MATLAB script is used to automatically extract slicing information from the user's uploaded G-Code file, associated alongside the results of the tray. Through such an approach, data collected at scale within a makerspace may be used to correlate novice AM inputs with the possibility of build failure, which can, in turn, be used to help offer preventative measures to guide future novices. A two-design case study is discussed to show the process of the survey and its ultimate applicability toward helping to identify potential sources of failure in large makerspaces.

2. Background

To contextualize the proposed framework in this paper, it is first necessary to explore both the roles of makerspaces and MEX in AM education, as well as the potential to use crowdsourcing as a path for AM support.

2.1. The Role of Makerspaces and MEX in AM Education

Makerspaces are an essential part to the Maker Movement, a growing phenomenon that incorporates hands-on experience into learning regardless of the skill level of its patrons, allowing for participants of all ages to make, learn, and grow. A study at the University of San Diego found that formal learning spaces such as classroom-based machine shops can be daunting and unengaging to students, especially novices. By contrast, makerspaces that act as informal learning spaces, unrestrained and openminded, contribute to a more welcoming and creative environment [10]. A core value of makerspaces is their inclusive nature, a goal that many spaces strive to maintain and thus employ welcoming philosophies as to attract and retain their student body [2,11]. Dedicated programs, trainings and staff within a makerspace are typically present to provide assistance to those who request it, however it has been found that self-guided learning and the personal experience of exploring how to make within a makerspace has a positive effect on a user's confidence in design and engineering [12,13]. This philosophy of self-guided learning in a makerspace holds true for each piece of equipment that the user works with, including MEX machines.

AM machines continue to be one of the most common technologies associated with makerspaces, especially machines that make use of MEX [7,8,14]. Makerspaces can provide a more profound and foundational MEX learning experience for novices than they might find in traditional classroom lectures, due to the makerspace's dependency of hands-on experience as the primary function of teaching. Because of the rise of AM and MEX in many industries in recent years, universities and even K-12 schools offer lectures and entire courses focused on AM, providing knowledge of the technology [15,16]. However, AM covers a wide range of technologies including MEX, vat polymerization, powder bed fusion, and material jetting, among others. Because AM classes are typically meant to prepare students for industry, there is a large amount of information about AM as a collective and not its individual system types [17]. These courses focus largely on the theoretical and advanced side or advanced of AM, but not necessarily hands-on learning where the student can apply the taught knowledge, as opposed to a makerspace where the student would regularly interact with the machine and employ self-directed learning [15,18]. An observational study in a makerspace with casual learners, those without proper training or experience, showed that inexperience with AM related processes, tools, and software can lead to print failures becoming a regular part of the experience, where the user would have to learn what they did wrong [6]. Learning in community-focused makerspaces is a hands-on process of experimentation where the user will encounter failure and be prepared to learn from their mistakes and try again [14,19,20].

Though trial and error is a recognized path for novices to learn MEX, failures can be a problematic part of the experience and should be minimized in their severity to lessen the user's frustration with AM and reduce the frequency of machine maintenance. A failed MEX tray can serve as an opportunity for learning more about the printing process, however an unsuccessful part can be a hindrance to the user's timeline, budget, and disposition, causing the makerspace wasted filament, staff time, and increased maintenance. The previously mentioned observational study with casual learners shows how instances where AM novices encounter tray failures can become upset and on occasion, cause their interest in AM to significantly decrease; this is not unique to novices but can apply to all users of AM [6,21]. At a university open shop space, Song and Telenko found that over the course of three months, 19% of all ABS plastic filament was being discarded due to print failures on MEX machines, which would cost the makerspace 80 1kg spools of filament every year [22]. It would be beneficial to develop a tool that could discover where makerspace novices regularly encounter failure so counter measures can be applied to improve their learning without hindering the makerspace, its staff and other users.

2.2 Current Practice of Crowdsourcing AM Information and Collection of Failed Trays

With the large number of novices routinely entering a university makerspace, crowdsourcing offers a unique opportunity to collect massive amounts of information regarding MEX tray successes and failures. Crowdsourcing is a way of finding a solution to a significant problem through the means of outsourcing the task to a specific crowd and collecting vast amounts of data in return for some reward [23,24]. This reward may be intrinsic, where the crowd participates knowing that the data will be collected and utilized for a good reason, or extrinsic, where the crowd participates because there is some monetary prize or acknowledgement [23,25]. The key benefit of using crowdsourcing here is that the data provided will give a better understanding of the common failures occurring within a specific makerspace with their target consumer group: novices [26]. There have been crowdsourcing studies performed that collect design information from novices and compare results to expert opinions. The results illustrate how a novice crowd's opinion comes close to expert judgement, yet the novice crowd is easier to access and collect information from [27,28].

Collecting design information regarding AM is not new; past studies have aggregated data from STL and G-Code files from users, which enables researchers to connect the information to MEX tray failures to a certain extent. Bacciaglia et al used a MATLAB script to read through each line of a MEX tray's G-Code and extract information from lines that contain certain triggers; from this they were able to create 3D models that accurately represented the printed part [29]. Similarly, Budinoff and McMains designed a MATLAB tool that pulls information from an STL file to determine any issues that are likely to occur during the MEX process, such as poor quality, warpage, and tipping; however the tool was limited in its ability to recognize all relevant geometric details and lacked a straightforward user interface [30]. A survey was done by Song and Telenko in the Georgia Institute of Technology makerspace, where print failure information was collected and correlated to the amount of experience that the user has with computer-aided design (CAD) modeling and AM processes [31]. The results did not show a strong correlation between experience and the chance of a tray failure; however, they had an overall small sample size [32] and a significant portion of their data meant to show how the designer is responsible for tray failures included results where the subject did not create the CAD models themselves, but instead found on the internet from sources such as Thingiverse.com. Designs from Thingiverse.com have previously been evaluated and multiple issues with downloaded parts can cause print failures and quality issues, regardless that the website is meant to be a depository of 3D models meant for AM [30]. Song states that 26 of the 95 prints were downloaded from experts online, however it is challenging to claim these parts to be expertly designed when others have had immediate issues producing Thingiverse models, undermining the desired connection between the designer's experience level and their CAD models. The limitations in previous work present an opportunity where a crowdsourcing-based tool would thrive in capturing novice MEX information by taking place within a makerspace, where a rich source of novice AM users exist.

3. A Proposed Framework for Identifying and Collecting Failure Information to Support Crowdsourcing Efforts with MEX

With the opportunity to crowdsource build information in an open-access makerspace for later correlation with build quality, two efforts are required. The first is to identify and categorize the many potential factors that drive build quality in MEX systems. The second is to establish a robust means to collect this factor information from user builds in order to create a crowdsourced database of build quality that can be later used for correlation analysis.

3.1. Identifying and Categorizing Potential Factors in Build Quality

To establish a rich set of crowdsourced data, potential factors that drive MEX build quality in an open-access makerspace must first be identified. There are many parameters and variables in the MEX process that can affect the final printed part, with some affecting the part to the extent that the entire tray fails, while others may simply leave features less detailed. Though there are many possible sources of error in an MEX tray, they can be sorted into one of four general categories that characterize the entire MEX process chain: (1) the part's design, (2) the slicing process, (3) the machine system being used, and (4) the user's actions during the physical printing process [6,31,33,34]. These variables can be described further based on how large of an impact each one has on the likelihood of a successful printing process, broadly separated into (1) affecting printability, (2) affecting functionality, or (3) affecting quality. Larger, more significant effects in these categories can cause the entire tray to fail, moderate effects can change how functional the piece is, and minimal effects may only change the quality of the finished object [6,30,35].

To further enumerate the potential sources of failure, a fishbone diagram, seen below in Figure 1, was constructed to discretize possible factors driving failure into the four main categories, with individual factors noted in terms of their likely severity. Parameters highlighted in red, brown, or yellow signify that they are characterized to have an effect on the MEX tray's printability, functionality, or quality, respectfully. The level of severity for a given parameter was selected based on previously researched effects and guidelines provided by the MEX machine's company. It should be noted that the designated severity for each parameter may differ from machine-to-machine and personal interpretation. **S**pecific factors underpinning each category are discussed in turn.

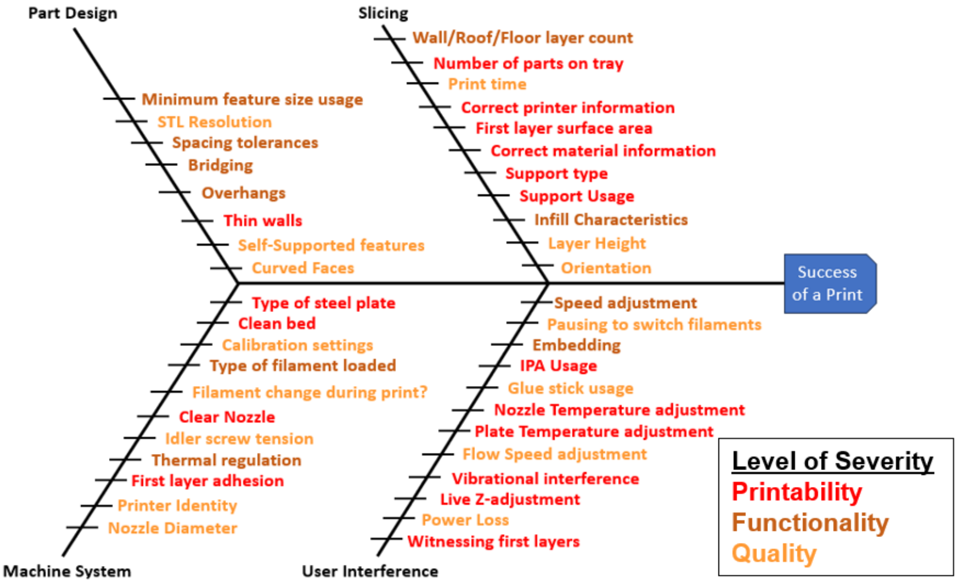


Figure 1. Fishbone diagram of parameters that can affect the success of an MEX tray. Variables noted in red, brown, or yellow signify the general severity of effects on printability, functionality, or quality, respectfully.

Part Design Factors: This first category of Part Design Factors encompasses features such as thin walls, spacing tolerances, and the resolution size of the STL file that may affect the printing process. As an example, if an unsupported printed wall exceeds a prescribed height-to-width ratio, the feature can collapse while being formed due to elastic buckling, causing a print error that cannot be resolved during the MEX process [36]. Additionally, objects part of a larger assembly require specific spacing tolerances between interlocking regions to allow for a proper connection; however if this value is set incorrectly, the part can be fabricated successfully though it may not fit with the remaining assembly, affecting the functionality of the part [37]. An STL file holds all of the surface information by roughly estimating features with triangular faces; as such, the precision of the part's geometry depends on the set resolution of the STL and can therefore cause the printed mesh to lack details [38]. In comparison with the previous two discussed points of failure, the likely effect of poor resolution is a degradation of final quality, not outright failure of the build or the functionality of the final part.

Slicing Factors: This second category of Slicing Factors includes settings such as use of support material, prescribed infilled percentage, and the set layer height of the desired part. As with Part Design Factors, the impact of such factors on the likely success of the final build can be highly variable. For example, support material may have the negative effect of lowering the surface quality of the created part, but is necessary in regions with overhangs in order for the MEX machine to properly fabricate the remainder of the part [39]. By contrast, the amount of infill within a part has minimal effect as to whether the part will fail during the printing process, but largely accounts for the strength of the part and thus its functionality [40]. Finally, the set layer height has a large effect on the fabricated part's surface finish, which can drive a user's assessment of the quality of the complex curved surfaces [41].

Machine System Factors: The third category of Machine System Factors include components or characteristics of the MEX machine itself that can influence the fabrication of the part. This includes the condition of the nozzle, the system's thermal regulation, and the nozzle diameter. As an example, since the filament must by necessity flow through the nozzle, a nozzle blockage makes it impossible to lay material down to build the part. Without a detection system to recognize this, the machine continues the process without understanding a problem has occurred [34]. Such blockages can act as a common, and severe, factor on the success of submitted parts. Similarly, for certain materials require a higher melting temperature, such as ABS, inadequate thermal retention around the build volume can cause warping, cracking, or a deficiency of function in the resulting part [42]. The diameter of the nozzle also contributes to the surface quality of the printed object, where a smaller nozzle diameter can print finer details than a larger one and may reduce the overall surface roughness [43], influencing quality assessment.

User Interference Factors: Though many user decisions are made during the part design and slicing steps of the MEX process, there is also the possibility that they may introduce certain User Interference Factors during the printing process itself. Users may intentionally or unintentionally interact with the MEX process while the part is being fabricated and, in doing so, can change settings that significantly impact the process. Such interference could include adjusting the temperature of the nozzle and the speed at which the machine will extrude. The temperature of the nozzle needs to be within a certain range around the melting point of the filament material, too cold and it cannot extrude, too hot and it will fail to retain its shape. The speed of the extruder as the part's infill is fabricated can affect the object's tensile modulus, and thus affect its functionality [44]. There are many variables that the makerspace users might adjust while a print is ongoing, and it would be valuable data to understand which are particularly frequent with novices.

3.2. Collecting Relevant Build Information to Establish a Crowdsourced Quality Database

Now that potential impactful MEX parameters have been identified, a way of collecting information about the selected metrics is necessary for each MEX tray seen within a makerspace. A questionnaire could be created that asks users about their current sliced tray regarding variables within the four categories of the MEX process and how well the finished parts were fabricated. However, it greatly diminishes the mental load on the user if the number of questions is reduced. Here, metrics selected in the slicing software leave a footprint in the tray's G-Code and thus can be extracted without needing to be input by the user. However, because the assessment of how the MEX tray finished lies with the user, questions regarding if the parts were fabricated, function properly, or have an acceptable quality will need to be answered by the user. Though the type of MEX machine the tray was prepared for can be found in the G-Code, the specific machine used within the makerspace will need to be asked, which can allow for a catalog for print successes or failures for each machine. Parameters adjusted during the printing sequence are also not recorded, so the user must answer questions regarding this category.

To increase the likelihood of users completing the survey, returning to take it again, and reduce survey fatigue, a MATLAB script was formulated to extract metrics that are stated in the prepared G-Code, leaving a limited necessary number of questions for the user to answer. Data will be gathered from users in two ways: (1) through submission of their prepared G-Code file and (2) by answering a series of survey questions about their finished MEX tray. A flowchart was created to visualize how data collection happens and the order in which the user answers the questionnaire, seen below in Figure 2.

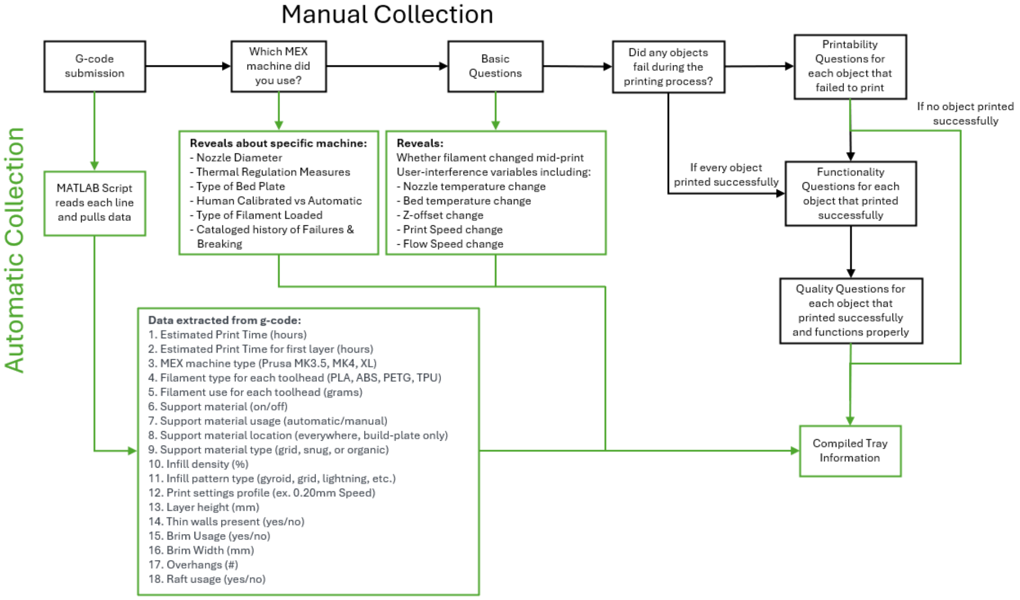
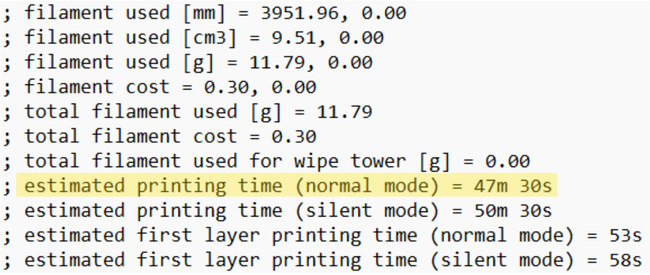


Figure 2: MEX tray survey flowchart, showing the progression of the questionnaire and where data collection occurs. The black outlined boxes represent the survey that the user would see, whereas the boxes outlined in green show the automatic data collection occurring.

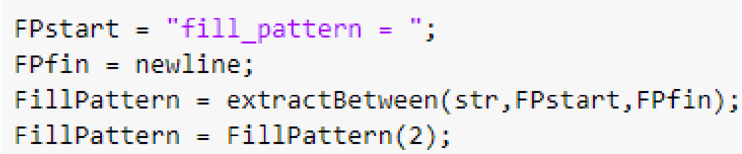
Automated Data Collection from G-Code: The user begins the questionnaire by uploading their PrusaSlicer [45] generated G-Code file for their current MEX tray. The automated data collection tool in MATLAB is designed to extract data from an ASCII G-Code. Depending on the user's initial slicing approach, they may need to convert from binary G-Code to ASCII before uploading. The MATLAB script is used to pull several variables spelled out within the G-Code file, including but not limited to, the estimated print time, MEX machine model, type of filament for each tool head, amount of filament used, whether support material was used and the type of it, the type and percentage of the infill, print settings, whether a brim or raft was used, and whether overhangs are present. These extracted parameters are chosen within the second part of the MEX process chain, the slicing process. The script functions by first creating a variable that stores the entire G-Code text. Then, for each variable that holds information of interest, the script reads through the G-Code text, searching for particular verbiage that exists on the same line as the variable information. For instance, to determine the estimated print time for a prepared MEX tray, the verbiage on the particular line is "estimated printing time (normal mode) =" followed by the desired value, seen highlighted below in Figure 3.



```
; filament used [mm] = 3951.96, 0.00
; filament used [cm3] = 9.51, 0.00
; filament used [g] = 11.79, 0.00
; filament cost = 0.30, 0.00
; total filament used [g] = 11.79
; total filament cost = 0.30
; total filament used for wipe tower [g] = 0.00
; estimated printing time (normal mode) = 47m 30s
; estimated printing time (silent mode) = 50m 30s
; estimated first layer printing time (normal mode) = 53s
; estimated first layer printing time (silent mode) = 58s
```

Figure 3. Sample text from a prepared G-Code file, with the estimated printing time highlighted.

Using the extractBetween function in MATLAB, the value "47m 30s" is saved as a variable; however these saved values are strings, so they are then converted into variables that hold number information, doubles, with the str2double command. The estimated printing time value in particular has an additional step of the entire time being converted into hours then saved as a double variable. This extraction and conversion code segment is similar for each variable being extracted from the G-Code; for instance, seen below in Figure 4 is a piece of the MATLAB code that finds the pattern for the internal infill.



```
FPstart = "fill_pattern = ";
FPfin = newline;
FillPattern = extractBetween(str,FPstart,FPfin);
FillPattern = FillPattern(2);
```

Figure 4. Snippet of MATLAB code that extracts information about the infill pattern of the printed object.

Manual Data Collection from Users: After the user uploads their prepared G-Code file, they then answer a few introductory questions before declaring how the MEX tray performed. Firstly, they select which MEX machine was used for this tray from a list; each machine in this makerspace has a short code specifying its location and number (ex. 'FloorFour-P1'). By selecting the specific machine used, machine system metrics declared in the fishbone diagram can be determined, including the nozzle diameter, if the machine is enclosed for thermal regulation, the type of build tray, if it is calibrated manually or automatically, and the type of filament loaded. Next, the user answers whether the filament spool was changed mid-print, as it can cause a quality blemish due to inconsistent cooling [46]. The user then declares whether any sliced parameters were adjusted mid-print and what they were changed to, including the temperature of the nozzle or build plate, distance between the nozzle and build plate, the extruder speed, or the flow rate of material. Figure 5 below illustrates how the questions appear to the user in a simple Qualtrics survey questionnaire.

Did you adjust any of the following parameters after the print had already begun?

☐ Nozzle Temperature
☐ Bed Temperature
☐ Print Speed
☐ Flow Rate
☐ Nothing was adjusted

Did the filament spool get changed after the print had already begun?

○ Yes
○ No
○ Unsure

How many individual objects were you printing on this tray?

Figure 5. Introductory questions posed to the user in the Qualtrics questionnaire.

These parameters do not leave a footprint in the G-Code file, so the user must be responsible for recording the information. The final question that every user will answer is how many objects were being fabricated on this tray and which of them failed to complete. The question displayed to them next depends on whether any of the tray's objects failed to print, if so then the survey begins posing questions directly related to printability outcomes, otherwise they are asked questions from the functionality series.

Within the printability question set, the user is first asked whether the MEX machine was disturbed by some vibrational impact and if any registered error occurred during the printing process. An external impact to the machine system can cause the printed object to disconnect from the print bed [34] or cause the system to register a crash. The Prusa brand MEX systems used in this research may display registered errors that indicate problems with the G-Code file, a slicing factor issue, or inform the makerspace about a malfunctioning piece of the machine; for instance, a MINTEMP error can reveal that the nozzle's heating system is not working properly and needs to be replaced [47]. This information can be cataloged with the machine system's maintenance log to keep track of its condition. Then, for each printed object that failed to fabricate, the user is asked three questions: (1) if the issue occurred during the first five layers, (2) if the object is oriented in a strategic manner such as the largest flat surface is touching the build plate, (3) and to select how the part failed to print from a few prescribed options. An object that fails within the first few layers of the MEX process tends to be due to a low adhesion to the build plate, caused by either an unclean plate or more likely, a small surface area of the part serving as the foundation [33,34]. Understanding how the part failed to print is also important information that only the user can answer, which can reveal either faulty slicing metrics or a fault of the MEX machine. For instance, if the user selects that the part failed to complete because there was a lack of extrusion, then the fault would lie somewhere in the machine system.

Upon completing the printability questions for each part that failed to print, the user is next asked if the part has a functional purpose and, if so, whether it seems to function properly. If the part does not function properly, then the user selects the reason for this from a list of prescribed options, including too tight connections, too loose connections, and non-removable support material. These reasons can reveal the fault to be either in the design phase or the slicing settings. If the part either does not serve a function or does function correctly, then the user is finally asked about the general quality of the part. If they are pleased with the result, then the questionnaire ends, otherwise they must select from a list of options why they are displeased with the part such as warpage, a layer shift, or stringing. These results can then be analyzed to determine which parameters have such an effect on the quality of the printed part.

4. Demonstrating the Framework with Two Case Studies

To demonstrate the workflow of the survey and its applicability in a makerspace, a case study was created and used to record sample information. This mimics the data collection method discussed in Section 3. Two designs chosen for this case study included a “Benchy”, a benchmarking model commonly used for MEX owners to test how well their AM machine is performing [48] and a 3D model of a Nittany Lion. These models were chosen for this case study because of their design properties, in that the Benchy is designed to be easily fabricated with a range of MEX technology and does not require supports or any additional material to be used. By contrast, the Nittany Lion has features such as a long bridging underbelly and an overhanging chin that would require support material to be printed properly; both models can be seen below in Figure 6.

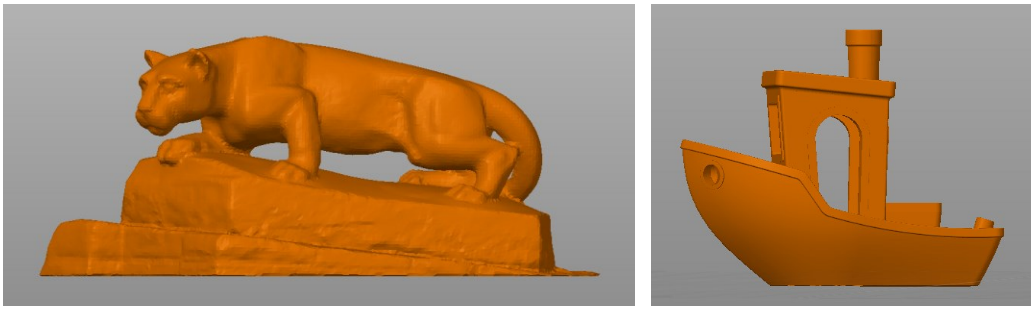


Figure 6. Side profiles of the Nittany Lion and Benchy 3D models.

These models were sliced and prepared individually to be printed on a Prusa XL MEX machine with identical settings chosen in PrusaSlicer; important selected parameters include a layer height of 0.20mm, printer model of “Original Prusa XL - 2T Input Shaper 0.4 nozzle”, filament type of “Generic PLA”, a 15% infill, no brim used, and support material turned off. The PrusaSlicer slicing software displayed a warning to the user when the Nittany Lion model was sliced without any support material, claiming that it detected print stability issues including a “floating object part” and “collapsing overhang” and that the user should consider enabling supports. The Benchy model triggered a warning regarding “low surface adhesion” to the tray and that the user should consider enabling a brim. Figure 7 below demonstrates the areas that are considered overhangs, areas where no model material can support the structure and thus the slicer presented a warning.

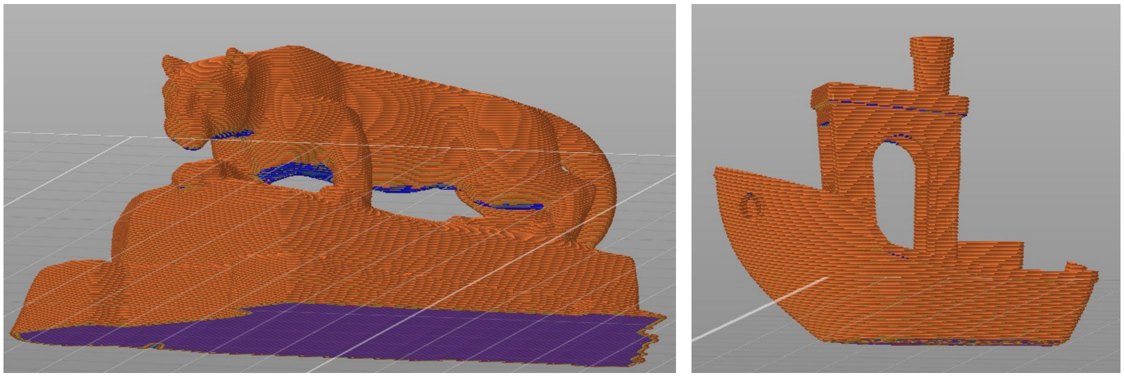


Figure 7. Sliced views of Nittany Lion and Benchy 3D models, where the blue regions represent where PrusaSlicer states support material should be necessary.

The user can ignore these warnings, however, and decide to proceed with the process, which is what occurred in this study. When fabricating these models on the MEX machine, there was no interaction with the user during the physical printing process. The result of the Nittany Lion model is seen in Figure 8. This sliced file prepared on the Original Prusa XL failed to print, due to the underside of the head causing a “spaghetti” failure, where the desired shape is nonexistent and there was no chance of recovery or a finished print.

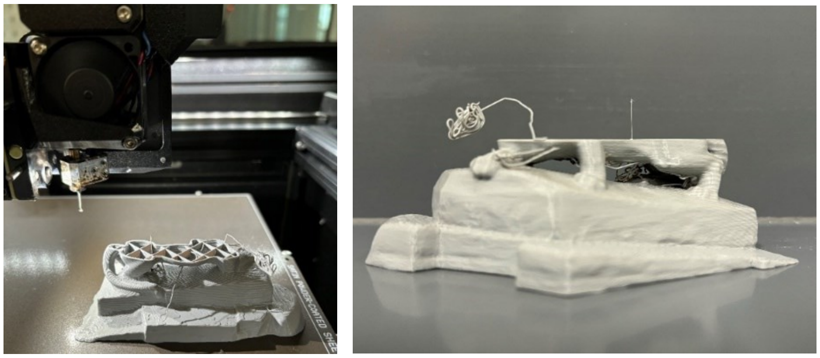


Figure 8. Model of the Nittany Lion shrine that failed to fabricate on the Original Prusa XL MEX machine and resulted in a spaghetti failure at the base of the head.

After the printed part was taken off of the tray, the Qualtrics survey was opened on the same computer where the G-Code file was initially sliced and is immediately uploaded to the questionnaire. The G-Code is then read through by the MATLAB script, detailed in Section 3.2, and extracts key information regarding the tray parameters that hold interest. The result of the MATLAB script is an exported table containing each slicing metric presented in Figure 2, which can be seen below in Table 1.

Table 1. Results of MATLAB script extraction of the Nittany Lion MEX tray G-code.

	Nittany Lion Tray
Print Time (hrs)	1.268888889
Estimated First Layer (hrs)	0.078055556
Printer Type	Original Prusa XL - 2T Input Shaper 0.4 nozzle
Filament One Type	"Generic PLA @XLIS"
Filament Two Type	N/A
Filament One Use (g)	26.1
Filament Two Use (g)	0
Support Material?	Off
Support Material Usage	Support Off
Support Material Location	Support Off
Support Material Style	Support Off
Infill Percentage	10
Infill Style	grid
Print Settings	0.20mm SPEED @XLIS 0.4
Custom Layer Height	0.2
Thin Walls Present?	No
Brim Usage	Off
Brim Width	0
Overhangs Present?	Yes
Raft Usage	Off

When answering the survey for this specific tray, the user answered that the object failed to print, due to the printer not completing the final desired shape. Because only a single object was part of this tray, the questionnaire goes through one cycle of the printability questions and thus, does not ask anything regarding the functionality or quality of the object, since the object ultimately did not print. The flowchart diagram can be seen below in Figure 9, with the red highlighted arrows demonstrating the path of questions the user would answer based on the failed printing outcome, with the questions answered below in Figure 10.

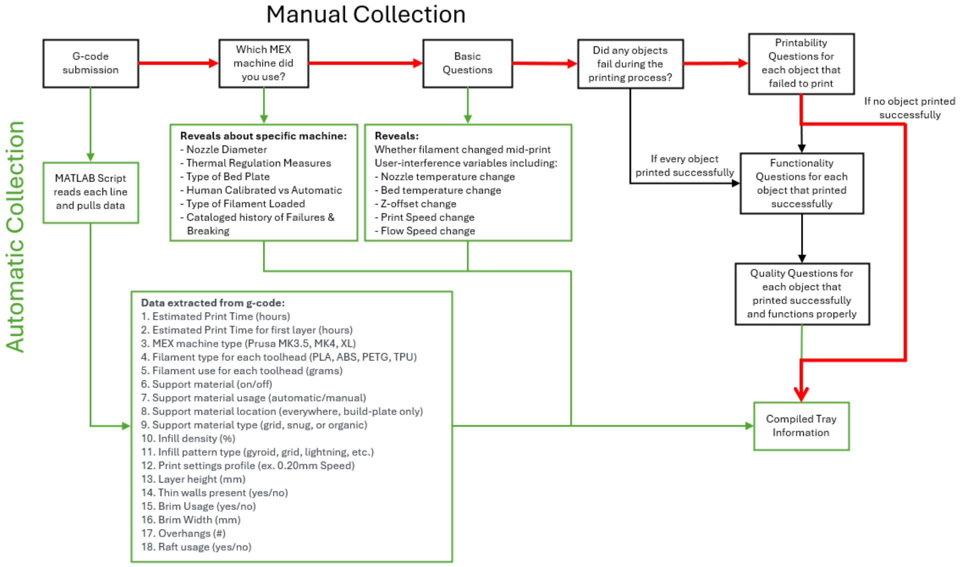
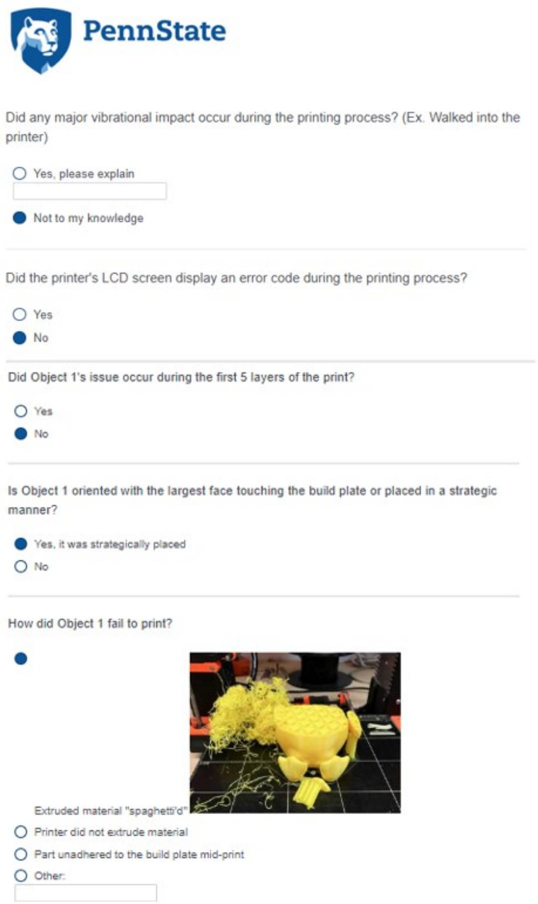


Figure 9. MEX tray survey flowchart, updated with red arrows to demonstrate the questions posed to the user in this first case study.



Did any major vibrational impact occur during the printing process? (Ex. Walked into the printer)

○ Yes, please explain

● Not to my knowledge

Did the printer's LCD screen display an error code during the printing process?

○ Yes

● No

Did Object 1's issue occur during the first 5 layers of the print?

○ Yes

● No

Is Object 1 oriented with the largest face touching the build plate or placed in a strategic manner?

● Yes, it was strategically placed

○ No

How did Object 1 fail to print?

● Extruded material "spaghetti'd"

○ Printer did not extrude material

○ Part unadhered to the build plate mid-print

○ Other:

Figure 10. Questions posed and answered by the user for the first case study, regarding how the MEX machine failed to fabricate the Nittany Lion.

Contrast to the Nittany lion model, the Benchy was successfully fabricated on the Original Prusa XL, seen below in Figure 11. The Benchy model was modeled to not need support material when being produced on an MEX machine, so having the support material parameter turned off does not cause any issues in its fabrication, unlike the Nittany Lion model.

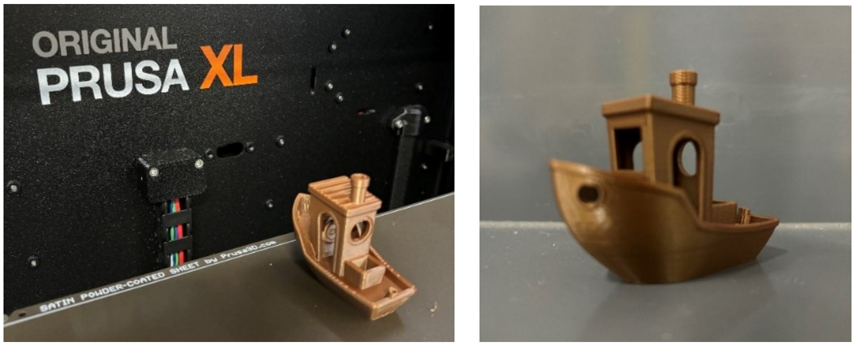


Figure 11. Model of a “Benchy” that was successfully fabricated on the Original Prusa XL MEX machine.

As before, the user first uploaded their prepared G-Code file to the questionnaire. The results of the MATLAB script can be found below in Table 2. In contrast to the Nittany Lion tray, the Benchy tray can be completed 28.6 minutes faster and requires 14.31 fewer grams of filament. Having MEX trays with identical slicing settings yet different fabrication results can narrow the search for the source of build failure; in this case, the slicing settings for the Nittany Lion tray should have been adjusted to account for the 3D model's necessity of support material. Collecting a large number of prepared MEX trays is necessary to represent the diversity of MEX process parameters in order to correlate where failures are likely to occur with novices.

Table 2. Results of MATLAB script extraction of the Benchy MEX tray G-code.

	Benchy MEX Tray
Print Time (hrs)	0.791666667
Estimated First Layer (hrs)	0.014722222
Printer Type	Original Prusa XL - 2T Input Shaper 0.4 nozzle
Filament One Type	"Generic PLA @XLIS"
Filament Two Type	N/A
Filament One Use (g)	11.79
Filament Two Use (g)	0
Support Material?	Off
Support Material Usage	Support Off
Support Material Location	Support Off
Support Material Style	Support Off
Infill Percentage	10
Infill Style	grid
Print Settings	0.20mm SPEED @XLIS 0.4
Custom Layer Height	0.2
Thin Walls Present?	No
Brim Usage	Off
Brim Width	0
Overhangs Present?	Yes
Raft Usage	Off

Compared with the Nittany Lion part, the Benchy part was successfully completed and had an acceptable quality. The user answered again that they only printed one object, but that in this case, it did not fail, which brought them to the functionality and quality questions. The survey flow in this case can be seen below in Figure 12 and images from the Qualtrics survey can be seen below in Figure 13.

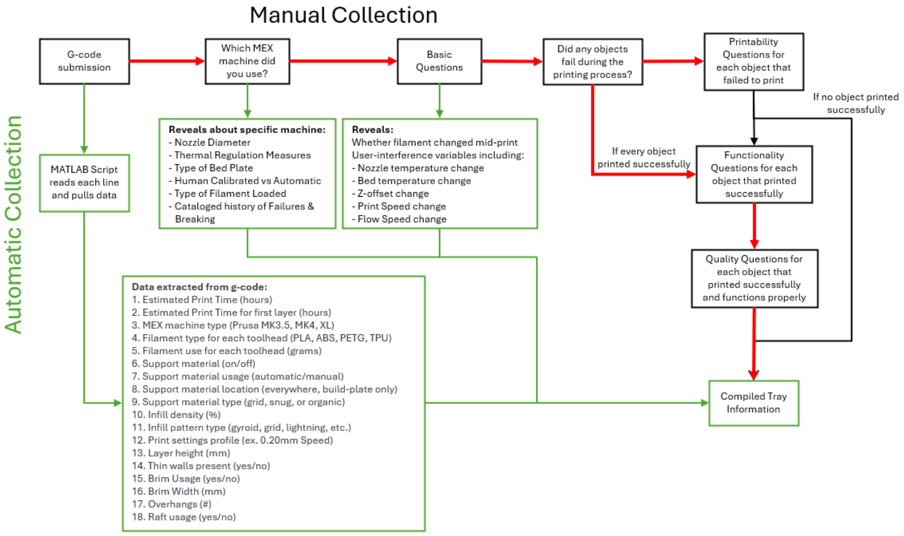
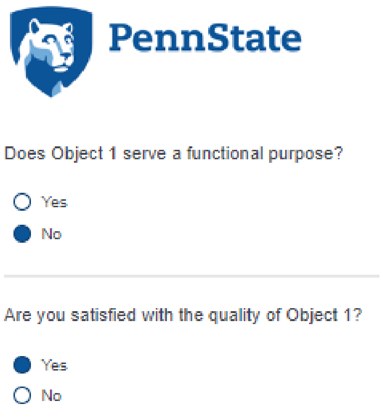


Figure 12. MEX tray survey flowchart, updated with red arrows to demonstrate the questions posed to the user in this second case study.



Does Object 1 serve a functional purpose?

○ Yes
● No

Are you satisfied with the quality of Object 1?

● Yes
○ No

Figure 13. Questions posed and answered by the user for the second case study, regarding how the MEX machine succeeded to fabricate the Benchy.

It is important to showcase parts that both succeeded and failed to fabricate on an MEX machine and review how the questionnaire and MATLAB tool respond. By keeping track of successful and failed trays, failure rates on each particular machine can be cataloged and reviewed, beneficial parameters can be encouraged to novices, and the source of fault can be identified.

5. Conclusions and Future Work

This paper described a tool to crowdsource data within a makerspace to readily collect information about how users use MEX machines and where tray failures arise. This tool relies on a questionnaire taken by the users after they remove their objects from the current tray regarding how well the parts printed and a MATLAB code to extract metrics defined within their uploaded G-Code file. The sources of failure for a given MEX tray that the tool currently focuses on lies within the slicing protocol, the specific MEX machine, and any interaction the user has with the machine during the printing process. Future work with this tool involves integrating more MEX parameters from the design process, which is currently the section with the fewest variables present, by capturing information from the 3D models being sliced. This integration will allow a greater understanding as to where build failures most commonly arise from in a novice MEX tray.

Upon completion of in-situ data collection in a university makerspace, correlation analysis will begin in order to determine the crucial driving factors of MEX tray failure in a makerspace. Parameters shown in the fishbone diagram will be investigated to determine how common of an impact it has on a novice tray's printability, functionality, and quality. With this crowdsourced information, advice and countermeasures can be applied in makerspaces that reduce the number of build failures. In doing so, the ultimate hope is that makerspaces that integrate this tool into their users' MEX process will see a reduction in filament waste, machine downtime, and user frustration.

6. References

1. Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., and Campbell, R.I., “Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints,” *CIRP Annals* 65(2):737–760.
2. Noel, A., Murphy, L., and Jariwala, A., “Sustaining a diverse and inclusive culture in a student run makerspace,” *International Symposium on Academic Makerspaces* First.
3. Wilczynski, V., “Academic Maker Spaces and Engineering Design,” Seattle, Washington, 2015.
4. Kantaros, A., Piromalis, D., Tsaramiris, G., Papageorgas, P., and Tamimi, H., “3D Printing and Implementation of Digital Twins: Current Trends and Limitations,” *Applied System Innovation* 5(1), 2022.
5. Abdollahi, S., Davis, A., Miller, J., and Feinberg, A., “Expert-guided optimization for 3D printing of soft and liquid materials,” *PLoS ONE* 13, 2018.
6. Hudson, N., Alcock, C., and Chilana, P., “Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers.”
7. Barrett, T., Pizzico, M., Levy, B., and Nagel, R., “A Review of University Maker Spaces.”
8. Kantaros, A., Diegel, O., Piromalis, D., Tsaramiris, G., Khadidos, A., Khadidos, A., Khan, F., and Jan, S., “3D printing: Making an innovative technology widely accessible through makerspaces and outsourced services,” *Materialstoday: Proceedings* 49(7):2712–2723, 2022.
9. Tadeja, S., Bozzi, L., Samson, K., Pattinson, S., and Bohne, T., “Exploring the repair process of a 3D printer using augmented reality-based guidance,” *Computers and Graphics* 117:134–144.
10. Hoople, G., Mejia, J., Hoffoss, D., and Devadoss, S., “Makerspaces on the Continuum: Examining Undergraduate Student Learning in Formal and Informal Settings,” *International Journal of Engineering Education* 36(4):1184–1195, 2020.
11. Forest, C., Moore, R., and Jariwala, A., “The Invention Studio: A University Maker Space and Culture,” *Advances in Engineering Education*.
12. Hilton, E., Smith, S., Nagel, R., Linsey, J., and Talley, K., “UNIVERSITY MAKERSPACES: MORE THAN JUST TOYS,” *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Quebec, Canada, 2018.
13. Koole, M., Anderson, K., and Wilson, J., “Unleashing the Learners: Teacher Self-Efficacy in Facilitating School-Based Makerspaces,” *IN Education* 26(1).
14. Wong, A. and Partridge, H., “Making as Learning: Makerspaces in Universities,” *Australian Academic & Research Libraries* 47.
15. Huang, Y., Leu, M., Mazumder, J., and Donmez, A., “Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations,” *Journal of Manufacturing Science and Engineering* 137(1), 2015.
16. Go, J. and Hart, A.J., “A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation,” *Additive Manufacturing* 10:76–87, 2016.
17. Standard Terminology for Additive Manufacturing Technologies.
18. Burke, J., “Making Sense: Can Makerspaces Work in Academic Libraries?,” 2015.
19. Browder, R., Crider, C., and Garrett, R., “Hybrid innovation logics: Exploratory product developmentwith users in a corporate makerspace,” *Journal of Product Innovation Management* 40(4), 2023.

20. Wilczynski, V. and Adrezin, R., "HIGHER EDUCATION MAKERSPACES AND ENGINEERING EDUCATION," Phoenix, Arizona, 2016.
21. Richardson, M. and Haylock, B., "Designer/Maker: The Rise of Additive Manufacturing, Domestic-Scale Production and the Possible Implications for the Automotive Industry," *Computer-Aided Design and Applications* 33–48, 2012.
22. Song, R. and Telenko, C., "MATERIAL WASTE OF COMMERCIAL FDM PRINTERS UNDER REALSTIC CONDITIONS," 2016.
23. Xiao-Jing, N., Sheng-Feng, Q., Vines, J., Wong, R., and Hui, L., "Key Crowdsourcing Technologies for Product Design and Development."
24. Simperl, E., "How to Use Crowdsourcing Effectively Guidelines and Examples."
25. Onuhoa, M., Pinder, J., and Schaffer, J., Guide to Crowdsourcing.
26. Barbier, G., Zafarani, R., Gao, H., and Liu, H., "Maximizing benefits from crowdsourced data," *Computational and Mathematical Organization Theory* 18:257–279.
27. Luther, K., Tolentino, J.-L., Wu, W., Pavel, A., Bailey, B., Agrawala, M., Hartmann, B., and Dow, S., "Structuring, Aggregating, and Evaluating Crowdsourced Design Critique," 2015.
28. Green, M., Seepersad, C., and Holtta-Otto, K., "Crowd-Sourcing the Evaluation of Creativity in Conceptual Design: A Pilot Study," *IDETC-CIE*, 2015.
29. Bacciaglia, A., Falcetelli, F., Troiani, E., Di Sante, R., Liverani, A., and Ceruti, A., "Geometry reconstruction for additive manufacturing: From G-CODE to 3D CAD model," *Materialstoday: Proceedings* 75(1):16–22, 2023.
30. Budinoff, H. and McMains, S., "Will it print: a manufacturability toolbox for 3D printing," *International Journal on Interactive Design and Manufacturing* 15:613–630.
31. Song, R. and Telenko, C., "Causes of Desktop FDM Fabrication Failures in an Open Studio Environment," 2019.
32. Nayak, B., "Understanding the relevance of sample size calculation," *Indian Journal of Ophthalmology*, 2010.
33. Jaksic, N., "What to Do When 3D Printers Go Wrong: Laboratory Experiences."
34. Baumann, F. and Roller, D., "Vision based error detection for 3D printing processes," 2016.
35. Perez, B., Anderson, D., Holtta-Otto, K., and Wood, K., "CROWDSOURCED DESIGN PRINCIPLES FOR LEVERAGING THE CAPABILITIES OF ADDITIVE MANUFACTURING," 2015.
36. Wolfs, R. and Suiker, A., "Structural failure during extrusion-based 3D printing processes," *The International Journal of Advanced Manufacturing Technology* 104:565–584, 2019.
37. Grgic, I., Karakasic, M., Glavas, H., and Konjatic, P., "Accuracy of FDM PLA Polymer 3D Printing Technology Based on Tolerance Fields," *Processes* 11(10), 2023.
38. Hu, J., "Study on STL-Based Slicing Process for 3D Printing."
39. Karasik, E., Fattal, R., and Werman, M., "Object Partitioning for Support-Free 3D-Printing," *Computer Graphics Forum* 38(2):305–316, 2019.
40. Nguyen, V., Huynh, T., Nguyen, T., and Tran, T., "Single and Multi-objective Optimization of Processing Parameters for Fused Deposition Modeling in 3D Printing Technology."
41. Bual, G. and Kumar, P., "Methods to Improve Surface Finish of Parts Produced by Fused Deposition Modeling," *Manufacturing Science and Technology* 2:51–55.
42. Rastogi, P., Gharde, S., and Kandasubramanian, B., "Thermal Effects in 3D Printed Parts," *3D Printing in Biomedical Engineering* 43–68, 2020.

43. Wang, P., Zou, B., Xiao, H., Ding, S., and Huang, C., “Effects of printing parameters of fused deposition modeling on mechanical properties, surface quality, and microstructure of PEEK,” *Journal of Materials Processing Technology* 271:62–74, 2019.
44. Abeykoon, C., Sri-Amphorn, P., and Fernando, A., “Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures,” *International Journal of Lightweight Materials and Manufacture* 284–297, 2020.
45. PrusaSlicer.
46. Morales, N., Fleck, T., and Rhoads, J., “The effect of interlayer cooling on the mechanical properties of components printed via fused deposition,” *Additive Manufacturing* 24:243–248, 2018.
47. Print Error Messages, *PRUSA Research*.
48. CreativeTools, “#3DBenchy - The jolly 3D printing torture-test by CreativeTools.se,” https://www.thingiverse.com/thing:763622/files.