Utilization of Resin-Based Additive Manufacturing for Investment Casting

Final Design Review
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1.0 ABSTRACT

Dr. Xuan Wang, an Industrial & Manufacturing Engineering (IME) professor at California Polytechnic State University, San Luis Obispo, has sponsored the resin-based 3D printing investment cast senior project. The objective of the project was to thoroughly research the process and document the findings of using a resin-based 3D printed part as the pattern for investment casting. While this manufacturing process is not necessarily a new idea, the lack of technical research and documentation limits its ability to be reproducible. The research portion of the senior project included analyzing the limitations to the printing/casting manufacturing process. Measurements of part thicknesses, hole radii, depths, protrusion heights, and fillets were quantitatively studied, and surface finish, pattern clarity, and overall success were determined qualitatively. Three test coupons were manufactured and measured, both for limitations and statistical analysis on growth rates. The features measured for a statistical analysis of the growth included side lengths and diameters for intrusions and extrusions. Once the manufacturing process was sufficiently analyzed, the findings were used to produce a curriculum package for the IME 470 foundry course at Cal Poly. This included a detailed lab manual and video tutorial to promote student learning, as well as a library of CAD models for the students to manufacture. This library contains several models, including dice, rings, and die-casting molds for actions figures. To validate the completeness of the curriculum materials, a group of five students were walked through the process, and useful feedback was gathered to improve the course contents. In total, the project was a success for determining the technology's limitations and providing educational content to the IME 470 course.

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KEY TERMINOLOGY

Before introducing the project, common terminology and their definitions will be summarized to provide the necessary language to understand the research:

- *Stereolithography Apparatus (SLA)*: A 3D printing process which uses a photochemical process that utilizes a UV light to cross-link chemical chains within the resin to form a solid.
- *Fused Deposition Modeling (FDM)*: A 3D printing process which utilizes a continuous feed of thermoplastic material that is melted and deposited to build up layers of plastic into a final part.
- *Resin-based 3D print*: The 3D printed part is created with a photochemical process in which UV light cures a resin mixture to form a solid layer of material.
- *Curing process*: After the 3D-printed part has been created, it must undergo a process in order to full cure the resin material. This can be done in a number of ways but is most commonly done with a photochemical process where UV light chemically changes the composition of the resin, which strengthens and hardens it. Additionally, heat can be used to cure the resin as well, either in conjunction with UV light exposure or by itself.
- *Investment casting*: A manufacturing process in which a consumable material is submerged into either a slurry or investment material in order to form a shell around the shape of the material. The pattern is then burned out of the cavity, leaving it open for metal to be poured in to take the molded shape.
- *Pattern*: The 3D printed part is the *mold* or *pattern* that will form the cavity of the investment casting, which metal will fill to produce a casted part.
- *Gating system*: In order to control the flow of liquid metal into the cavity, a network of sprues and runners are created as paths for the metal to flow through to enter the cavity. The *gating system* as a whole is the collection of all pathways for metal to flow into the cavity in order to fill the void efficiently.
- *Burnout*: The process of burning the wax/resin to leave a void where metal can flow into the investment to form the desired shape. This is done in a furnace with a specific temperature schedule.
- *Lost Wax*: The current process used in the IME 141 lab, where liquid wax is injected into a silicone mold, and once hardened, placed into a flask to be burned out.

2.0 INTRODUCTION

Dr. Xuan Wang, a professor within the Industrial and Manufacturing Engineering (IME) Department at California Polytechnic State University, proposed researching the use of resin-based 3D printed parts as investment casting patterns due to the lack of technical documentation available on the process. The technology is mainly used in the jewelry industry, but formal records and analysis on the printing settings or casting process have not been documented. The first goal of this senior project is to test several models, print settings, and casting aspects to identify the most successful procedure for the process. This will include analyzing the limitations of the technology, which include limits of thicknesses, radii, sharpness of corners, and surface details. Once sufficient research has been gathered, the process will be implemented into the IME 470/471 lab at Cal Poly, which will allow students the ability to get hands-on experience with this evolving manufacturing method. Originally, the goal was to implement this lab into the IME 141 lab, but due to the cost of materials and paying for a technician, it makes more economic sense to present the lab to a more advanced group (and fewer students – important for resource/budget reasons). Within these two primary goals, secondary goals such as casting creative/intricate models, making a video tutorial, or performing student testing can be done in order to delve deeper into the topic and gain valuable feedback. The major stakeholders in the project include the sponsor, Dr. Wang, as well as the students and instructors of the IME 470 course. The senior-project team includes two Mechanical Engineering students at Cal Poly – Matthew Frost and Isaiah Hong.

Figure 1. A 3D printed resin pattern (left) used to cast the investment casted part (right) [1].

Within this Final Design Review report, the chosen final design, manufacturing achievements, and testing results of the resin-based 3D printed investment casting project will be described. The goal of this report is to document the findings gained from the ongoing testing and to document the lab procedure for the IME 470/471 course. The report is divided into several chapters. The background section will identify the introductory research to clearly understand similar products/processes and summarize the initial interviews with stakeholders. The objectives section will discuss the scope of the project, including the problem statement, boundary sketch, Qualify Function Deployment table, and the customer's needs and wants. The concept design chapter will discuss the ideation generation and controlled convergence techniques used to narrow down the prototype concept to a final chosen design. A manufacturing and testing section will be included to discuss results of analyzing the manufactured products. Next, the project management section will cover the timeline and major deliverables for the project, shown as a Gantt chart. Finally, the conclusion will summarize the project and document and give recommendations for future work.

3.0 BACKGROUND

Initial research was performed to gain knowledge about the current manufacturing process, including research done on similar projects, technical findings, and stakeholder interviews.

3.1 INTERVIEW WITH SPONSOR

Two interviews were set up with Dr. Wang to solidify the scope of the project, where the two major objectives were outlined. These were a methodical approach to determining the best printing and casting conditions and curriculum to supplement the current foundry class at Cal Poly. This interview also allowed for a formal 'meet and greet' where the team could make a personal connection with the sponsor.

The sponsor has several needs and wants for the project. It is desired to know the best print settings, curing procedures, and casting methods to create an easy and reliable process that works in Cal Poly's labs. The sponsor would like a test coupon with varying print settings/geometries to undergo different curing methods to evaluate the modifiable parameters of the process through measurements on the model. These findings will be summarized in a document at the end of the three quarters. Included in the documentation will be a summary of the limitations to the technology, including tolerances on part thicknesses, radii, intrusion depths, surface textures, and corner features. Once the best print settings have been determined and process limitations identified, full implementation into the IME 470 curriculum will include a library of 3+ easy to print/cast models that students can customize a portion of. To constitute a complete curriculum package, a detailed lab manual will be expected.

While the IME department has a few resin 3D printers, no research has been performed at Cal Poly regarding this field of technology. The goal of the senior project is to experiment with different printer settings, surface finishing processes, and gating systems in order to improve the process and produce detailed parts for the IME 470 lab. Specifications like surface treatment and gating structures are necessary when ensuring the casted part mimics the level of detail of the CAD model; a bad surface finish or poorly designed sprue network will cause defects in the casted part. Success of the part will be measured based on visual inspection, along with quantitative measurements like thicknesses, radii, lengths, etc. Qualitative measurements will be also evaluated on satisfaction surveys for a group of test subjects that will undergo the process; a 75% satisfaction rate for these surveys will suffice for the project. Additionally, a budget of a few hundred dollars was specified by Dr. Wang.

3.2 STUDENT & INSTRUCTOR INTERVIEWS

A large part of the senior project is directed toward implementing a new lab into the IME 470 curriculum; thus, it was important to interview both the lab instructors and the students as they will be key stakeholders for the project.

When interviewing the student, the conversation revolved around the current lab setup, issues with the lab, and input on the proposed lab. It was found that currently, the students watch pre-lab videos explaining the theory/industry process of casting (not specific to the lab they will be performing), fill out a short questionnaire, and do a quiz on the material. Then, the instructor leads them into the lab and without a demo, allows them to complete the lab. The student interviewee proposed that a better way to implement the lab was to do a video recording of the process with step-by-step instructions, have the instructor do a demonstration, and then perform the lab. While this senior project cannot enforce in-class demonstrations, it could provide a video demonstration that will help with the process specific to the lab they will be performing. The student would also like to make something of purpose (keychain, ring, etc.) with some aspect that could be detailed and customizable. However, since this is an introductory class, there's a likely chance that the students won't have CAD experience, so models should be provided with detailed instruction on how to customize it.

Through interviewing the lab instructor, it was found that they liked the idea of the lab and were more than happy to allow the testing to be performed within the foundry lab. Additionally, the instructor noted that Aluminum 356 is a commonly casted material used in the labs and provided a set of material specifications that would help with the design of flasks and molds. Detailed instructions will need to be provided in order to successfully implement the lab into Cal Poly's curriculum and the overall cost per student is about $20 per quarter, making this specific lab under $4 per student.

3.3 PROCESS RESEARCH

Resin 3D printing and investment casting are both technologies that allow for a higher level of precession then their alternatives [2]. Resin printing is a process in which a part is built up in layers through the use of a photopolymer and a light source that cures that polymer in a specified layer pattern [3]. This process allows for highly detailed parts, unique internal features at the cost of intensive post processing such as cleaning off the extra resin and hardening the final part. Because of the method of creating the layers, SLA has a much finer resolution than the classical FDM, as shown in Figure 2.

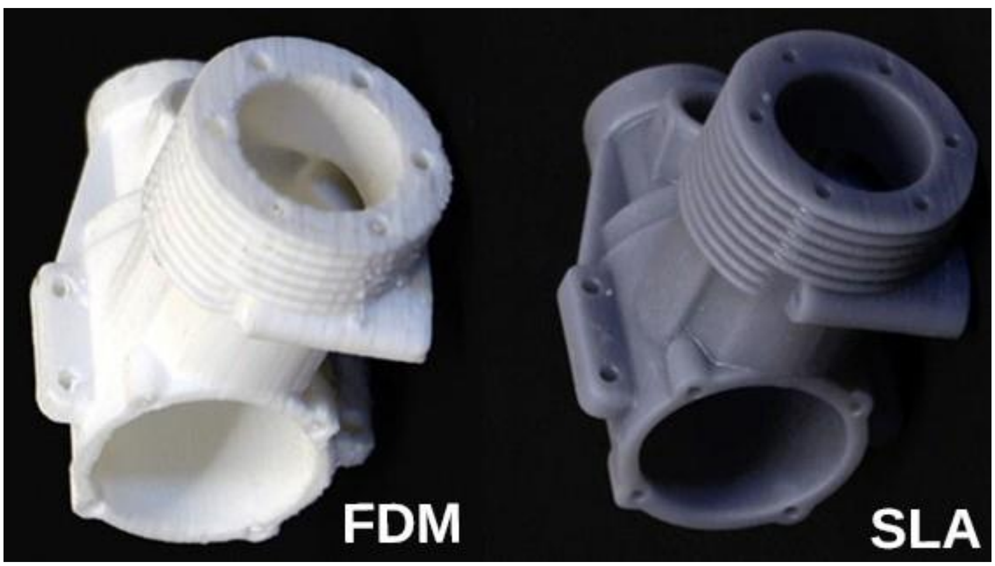


Figure 2. SLA resin printing versus FDM plastic printing [4].

Investment casting starts with investment powder and liquid mixture, similar to plaster, that surrounds a consumable pattern of the part to be casted. Once the investment is set, the pattern is then melted or burned out using a furnace which simultaneously fires the investment, increasing its strength. Metal is poured into the cavity, hardened, and removed through breaking of the investment shell. Although gravity is the simplest method of filling the mold, centrifuges and vacuum chambers are also common to help fill all the detailed cavities. This viscous style of molding allows for higher detail capturing compared to a sand-based mold [5].

3.4 CURRENT PRODUCTS

The concept of using resin 3D printed parts as molds for investment casting has deep roots within certain industries – jewelers are well-known to have created intricately designed rings from the manufacturing technique. However, the technology hasn't been documented well, thus the reason for this senior project.

One great source of information has come from a "Jewelry Technology Forum" conference, in which jeweler James Binnion [6] discusses his successes and failures while performing similar resin 3D printing investment casting processes. From his work, a foundation for the project can be established and part/process iteration can begin where he left off. Specifically, it was found that uncured resin is the major contributor to bad burnout and poor casts, so it will be important to focus on the curing process when performing the tests. This was found using a heated vacuum chamber, which generally worked better than a standard UV curing chamber. This will be explored, as the laboratory may have access to a heated vacuum chamber. The differences between UV, heat, and vacuum heat curing processes are shown in Figure 3.

(a) (b) (c)

Figure 3. Three identical models with different curing methods. (a) had the standard UV cure, (b) had a heated cure, and (c) had a heated cure in a vacuum. The images show the increase in quality from the UV cure to the vacuum-heated part [6].

Additionally, there are many other research papers that have dealt with some aspect of the project. First, the research for the printing process will be summarized. When using 3D printed parts, depending on the shape and thicknesses, they might be more prone to warping during the print process, which will carry over into the casted results [7]. The thickness should be uniform where possible to allow for even cooling, and corners/holes should have rounded features to prevent hot spots, shell fracture, and stress concentrations [8]. Minimum recommended layer thickness of 0.2mm, 30% infill, and a printer speed of 60mm/s are suggested as good printing parameters, and although these were for a FDM printer, some of the characteristics will be useful in the SLA printing setup. [8].

Next, several research articles focused on the casting portion of the project. With regards to the burnout, along with a detailed burnout schedule (with amount of hours required at each temperature level [9], [10]), it was found that in order to reduce the amount of ash/residue left in the investment, firing the part in the furnace over 600˚C will reduce the amount of debris left behind [11]. An issue with the resin is that its thermal expansion coefficient will cause the part to grow and shrink with temperature differences. This is not ideal, but unavoidable. It will be expected that the relative change in length of the part is about 3% for heating up to 300˚C, so models will be adjusted accordingly [12]. Another useful piece of advice is that deionized water should be used when mixing the investment powder, as other water can have up to a 70% decrease in strength due to impurities in the liquid [13].

3D printing companies such as Formlabs have also developed their own guides [14], [15] for the process, but most of the documentation focuses on the usage of their products and lacks quantifiable limitations of the printing and casting. Online 3D printing site, All3DP [16], also has a guide to resin printing, but while full of information on standard photopolymers, it lacks the information needed on the available castable resin material. Additionally, a company named 3DSystems provides a great guide to 3D printing investment casting jewelry, which will be used for sizing the rings that are planned to be manufactured [17].

While all this research is useful information, the objective of this senior project is to formally define the limitations of the manufacturing process. Potential limitations mentioned in the research, including minimum thicknesses of material, sharpness of features (minimum radii), and resolution of intricate features, will serve as a baseline, however, the lack of formal documentation on each of these values is the reason for this senior project. It's expected that these limitations will need to be experimentally determined and won't be readily available through the background research that has been performed.

3.5 PATENT SEARCH

Several patents were discovered that mention variations in resin compositions (specifically polymer types and ratios), as well as results from the burnout and cast. It is noted that most resins melt between 200-300˚C, and that shrinkage occurs when cooling the part back down, which will be measured to verify these claims [18]. When considering the different resin compositions, several patents claim to change the makeup of the resin with positive results after burnout [19], [20]. For context, it's necessary to have several different polymers that create the structure of the resin, including epoxy, acrylate, photo-initiator, and light stabilizer monomers. By changing the amount of each component, cast, cure, and burnout results can be improved [21], [22]. These would be useful if the scope of the project expanded to creating custom resin makeups or analyzing burnout defects but is unlikely to happen. The research is nonetheless useful to have as background information on resin structures.

4.0 OBJECTIVES

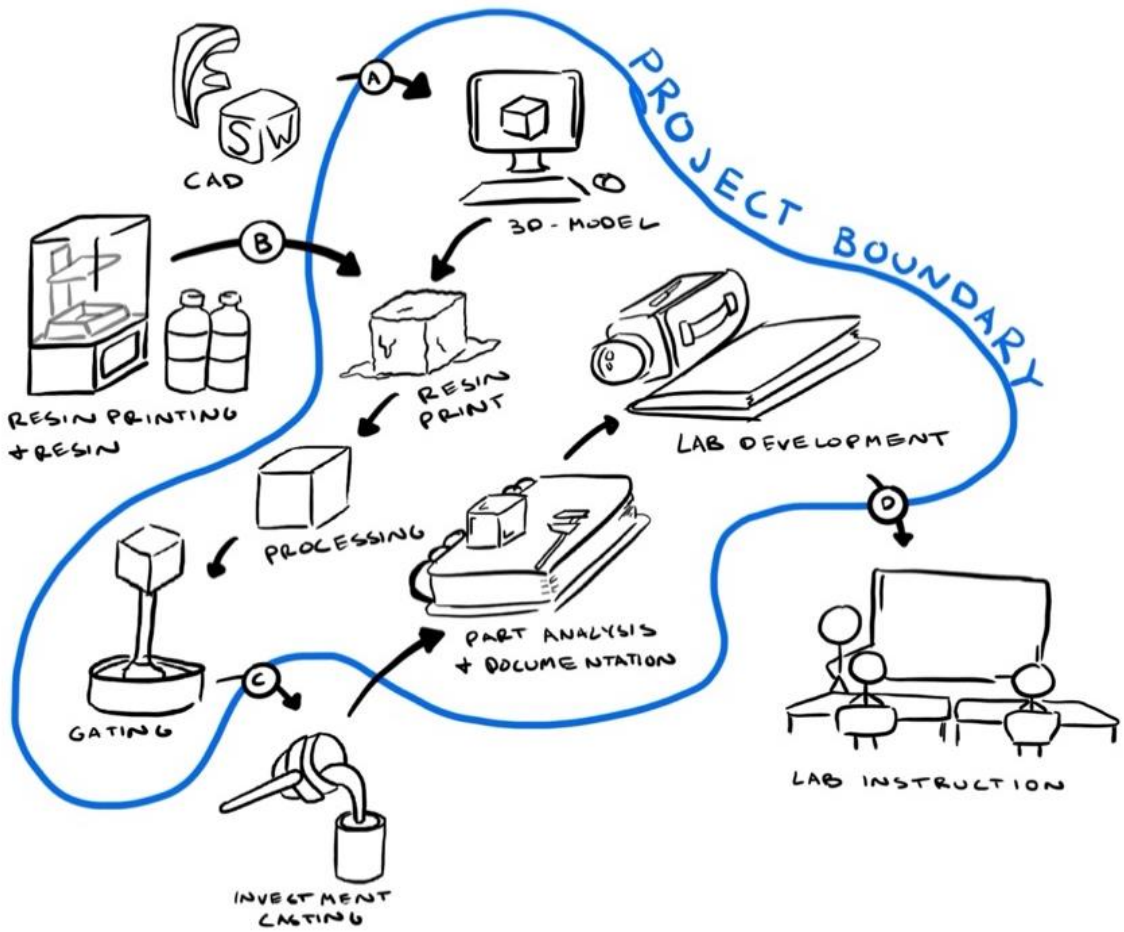
This section will start by defining the problem statement, in which the stakeholder, their needs, and the purpose of the project will be described. Additionally, a boundary sketch will be drawn to identify the aspects of the project that are within the scope of the project. A needs and wants table will document the requirements specified by the stakeholder, which will be fed into a Qualify Function Deployment (QFD) for an inclusive analysis on the purpose of the project. Lastly, a specification list and risk assessment will be made from the QFD.

4.1 PROBLEM STATEMENT

The IME Department at Cal Poly needs a fully developed curriculum package to implement a resin-based 3D printed investment casting lab because the technology is under researched yet an advancing method of manufacturing. This will provide students the opportunity for new hands-on learning with the knowledge gained from the extensive testing that will be performed on the manufacturing process.

4.2 BOUNDARY SKETCH

Figure 4 shows a boundary sketch to specify which systems are within the project scope's control and which are not. To summarize what can be seen, this project will focus on primarily on creating the 3D model, printing and post-treating the part while varying several parameters, attaching/testing the gating system, and documenting the process for a final curriculum package. Aspects out of the scope of this process include developing CAD software, constructing the resin 3D printer, designing different resin compositions, modifying the casting procedure, and teaching the class.



Arrow	Description
A	Existing CAD software
B	Existing resin printing technology, Dr. Wang
C	Existing investment casting processes, Dr. Carter (IME professor)
D	Usage of research by instructor for lab and instruction purposes, Dr. Carter

Figure 4. Boundary sketch for the project.

Also included on boundary sketch are the people and technologies that are needed at each arrow across the boundary. These will be used as guidance when performing the corresponding transition.

4.3 NEEDS AND WANTS TABLE

Table 1 describes the needs and wants of the stakeholders. A ‘need’ is defined to be required of the project and is essential for full completion. A ‘want’ is any additional aspect that could be included for further developing the project. The three stakeholders – students, lab instructors, and sponsor – will each have different wants and needs, and thus the project must cater to all.

Table 1. Stakeholders needs and wants table.

Needs	Wants
Lab curriculum instructions	Lab curriculum video tutorial
Analysis/measurements from modifying 3D print settings (layer thickness, radii, etc.)	Student testing prior to finalizing curriculum
Analysis/measurements from modifying casting settings (surface finish, feature defects)	Analysis with different types of metals
Documentation of casting failures/successes	Low cost (under ~$4/student)
Documentation on surface finish of parts	Library of possible 3D printable parts
Documentation on curing techniques/outcomes	Set of example models
Documentation for attaching gating systems	Analysis of different resin types
Maximum of 1.0 in^3 amount of resin for each print	Clear lab layout/process layout
Safe procedure for printing/casting in lab	Pre-lab quiz

The needs column includes analysis/measurements on modifying 3D print settings and casting settings that will encompass qualitative measurements – surface finish, voids, fine-detail on features, and post-processing effort – as well as quantitative features – side lengths, thicknesses, radii, protrusions – to determine the success of the part. These will be documented for the research portion of the project. The documentation must also include the method for attaching the gating system (whether that be in CAD and printed or by attaching sprues after the print), as well as any necessary surface treatment (sanding, cleaning in isopropyl alcohol, grinding). The curing technique will also be analyzed and will include results from cleaning with/without isopropyl alcohol and curing in either a UV light chamber or heated vacuum oven. Other needs include a maximum allowable volume of 1.0 in^3 (defined by the sponsor for budgetary purposes), as well as general lab safety. Lastly, the curriculum must include a detailed lab manual so that the instructors can perform the lab.

The wants column includes a video tutorial, laboratory setup, and pre-lab quiz to aid with integration into the IME 470 education and to improve student learning. The video was specifically requested by the interviewed student. Functionality testing (at least 5 students) would be beneficial to gain feedback on the process flow within the lab and allow for revisions before submitting the final curriculum package. Additional wants are a library of successful parts to aid in student CAD success, as well as keeping the cost within the expected budget of $4/student for resin, investment, and metal. If resources allow, it would also be interesting to test different metal or resin types to compare to the current lab materials. The sponsor voiced concern over the current resin brand, as it’s a small company that has the potential to be discontinued. Research into different resin manufacturers has been performed in order to have back-up options. These have been listed in the Bill of Materials, Appendix A.1.

4.4 DESIGN CONSIDERATIONS

After thoroughly considering the needs and wants of the stakeholders, several design considerations were created in order to quantify the project and its success. These are included in the "Target Requirements' of the QFD (Appendix B.1) but are summarized here.

The research side of the project will make use of extensive documentation for the quality of prints/casts while varying parameters such as geometry detail, post-processing, and curing methods. The quality of the part will be determined based on the precision of the intricate features, surface defects, or inclusion defects. The research will be documented for the stakeholders and perspective manufacturing professionals.

The curriculum side will be catered toward student learning with the goal of implementing an innovative manufacturing process for an emerging-industry experience. This will come in the form of an educational instruction video and detailed lab manual. The lab will be created as to prioritize minimization of risks/hazards while maximizing the student learning. Since PDR, the planned implementation into IME 141 has changed to IME 470/471. This is partly for economic reasons, as the resin and other lab materials are expensive. However, the main reason is that the IME 141 course generally has >180 students, whereas the IME 470 course has < 24 usually. This will increase feasibility of 3D printing the models, as 3D printing 180 models would take several days at ideal conditions (i.e., if none of the prints fail).

4.5 QUALITY FUNCTION DEPLOYMENT (QFD)

To ensure the scope of the project is meeting the desired goals of the stakeholders, a Qualify Function Deployment (QFD) was created for the process. To construct the QFD, the stakeholder needs were identified and ranked on necessity. Competitors and their current rankings on each customer requirement were then evaluated. Competitors included the current IME 141 lost-wax lab, as well as four similar research articles or company guides. This was followed with a 'how,' which identifies the quantifiable measures that will ensure completion of each customer requirement. These measures were given target values (time, percentage of satisfaction, etc.) to help establish benchmark targets for the project. Please see Appendix B.1 for the full QFD.

After completing the QFD, several new aspects of the process were discovered. First, the sponsor used language of wanting "easy" processes. While this is ideal, quantifying the term "easy" is not simple. Instead, the request was broken down into several quantifiable measurements that, if passed, could allow for the conclusion that the process was "easy." For example, if the sponsor wants an "easily printable part," this was broken down into several categories. First, a library of successful CAD models will jumpstart the process, where the student only needs to customize a small section of the part instead of building it up from scratch. A satisfaction survey will provide feedback on the overall process of printing and customizing; it's aimed to receive over 75% satisfaction in order to claim the process is 'easy.' Additionally, the amount of time cleaning the part and performing any post-processing should not exceed 15 minutes, which is a reasonable benchmark time. Lastly, reducing the number of stations to complete the process will help indicate if the process is too complex.

The previous example is just one of many that the QFD shed light on. In the following section, more of the specifications will be outlined with reasoning as to why the benchmarks are set to where they are.

4.6 SPECIFICATIONS AND RISK ASSESSMENT

The engineering specifications from the QFD are included in Table 2. These are the quantifiable measures that will be used to accomplish the customer requirements specified on the QFD. Table 2 mentions the parameter, the benchmark value, any tolerance, and project risk/importance. The last column, "compliance," is the method for measuring each requirement, and is named as follows: (A) Analysis, (T) Testing, (I) Inspection, and (S) Similarity to existing designs. Risk of meeting the specification is measured as (H) High, (M) Medium, or (L) Low.

Table 2. Specifications table for customer requirements

#	Parameter Description	Target	Tolerance	Risk	Compliance
1	Library of successful models	5 models	Min	M	A, I, T
2	Library of student-ready models	3 models	Min	H	A, I, T
3	Number of customizable features	1 per model	Min	M	A, I
4	Process satisfaction survey	75% satisfaction	Min	H	T
5	Customization satisfaction survey	75% satisfaction	Min	H	T
6	Curriculum satisfaction survey	75% satisfaction	Min	H	T
7	Time to clean/post-process	15 minutes	Max	M	T
8	Time for respective process (print vs cast)	8 hours each	Max	L	S, T
9	Reliability	90%	Min	M	I, S, T
10	Quantifiable Features	5 features	Min	H	T
11	Number of stations	4 distinct stations	Max	L	S, I
12	Floorspace occupied	9 ft^2	Max	L	I
13	Resin material cost	$2/student	Max	L	S
14	Metal material cost	$2/student	Max	L	S
15	Volume	1.0 in^3	Max	L	A, T
16	Video Time	15 minutes	Max	L	S, T

Below, more detail is provided for each of the specifications

Spec 1 – 2: Because CAD classes are not a prerequisite for the IME 470 course, a library of parts must be created to aid the modeling process. Three models must be available to the students, whereas five models should've been tested and deemed a success. The three student models will be included in the five tested parts. The compliance will be tested through manufacturing and casting these models to view their success.

Spec 3: The students will be engaged if they are able to customize their 3D printed part, thus it'll be important to provide at least one feature on each model for the student to customize. This will be tested by counting/analyzing the number of customizable regions on the part.

Spec 4 – 6: When determining whether the processes is easy, satisfaction surveys will be given to the student testers. These are documented in Appendices C.1-C.3, but will include separate surveys for the customization process, printing/casting process, and lab curriculum material. A benchmark of 75% was deemed appropriate from Dr. Wang.

Spec 7: If the print parameters are configured properly, the amount of time that's spent cleaning up the model can be reduced. A benchmark of 15 minutes was considered allowable, which includes the time of sanding/smoothing the print. This time will be recorded in testing the different models.

Spec 8: The time spent in the printing and casting phases is of little importance, as these aren't easily controllable. However, it would be ideal to reduce the required time such that the lab instructors don't have a long time to wait for parts to finish.

Spec 9: The reliability of the student models will be important if the lab will be a success. This 90% benchmark was set by the sponsor so that the students in the IME 470 course have a good chance at producing a working model. This benchmark will be met by testing several parts and seeing the percentage that pass.

Spec 10: The number of quantifiable features is one of the most important aspects of the research portion of the project. When choosing the concept designs in Section 5, the final selections of test coupons must have many methods for measuring the part. These include thicknesses, depths, radii, lengths, fillets, and protrusions.

Spec 11-12: The number of stations and floorspace occupied is an attempt to reduce the footprint on the current laboratory. This will aim to also improve simplicity, as having too many stations will clutter the space and confuse the students. A benchmark of 4 stations and $9ft^2$ was determined to be reasonable given the size of the 3D printer and curing stations. This will be measured in the lab.

Spec 13-15: The cost and volume go as a pair; as volume increases, cost increases. Dr. Wang specified a target of 1.0 in^3 of resin material, which would amount to $3.33/student for resin budget. For this reason, models will be made under 1.0 in^3 to prevent overspending. These risks are low, as the current expected budget should not exceed the set limits. These will be measured in CAD prior to printing.

Spec 16: A video length of 15 minutes was set as a benchmark value to concisely demonstrate the lab without boring the students. This ideally will be cut down further.

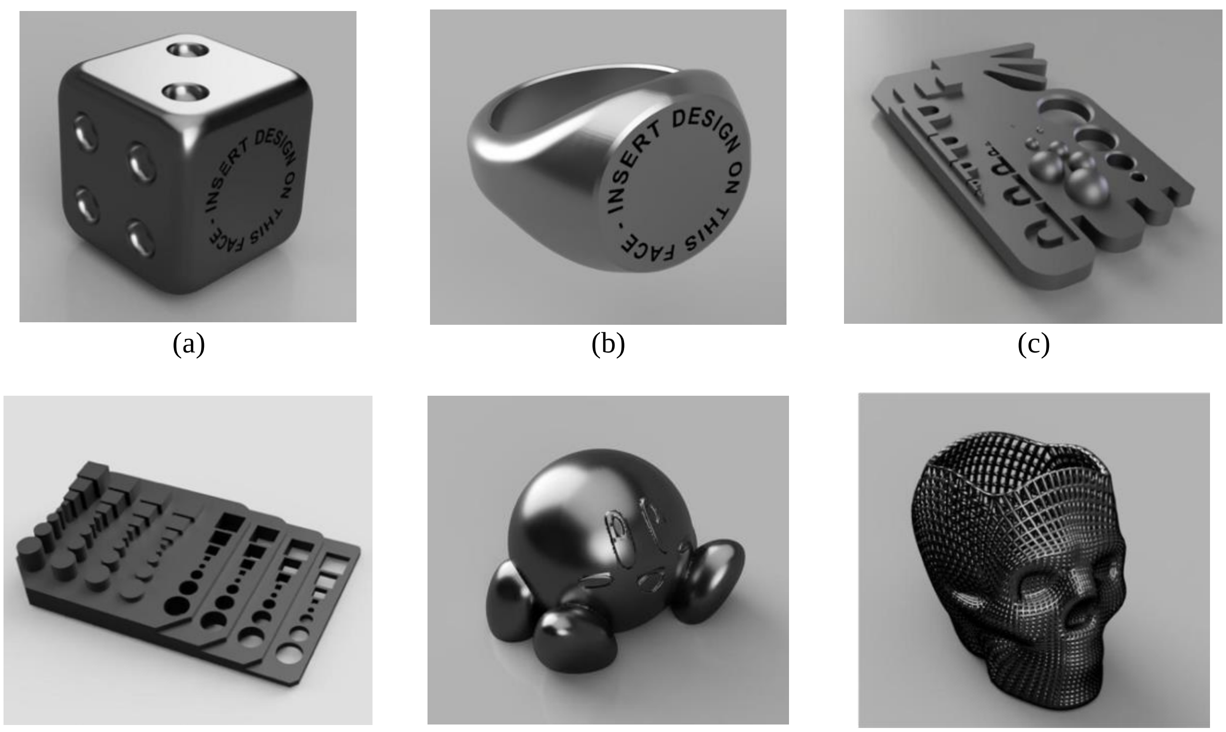
As seen in Table 2, the parameters labeled as "high" risk are those that are most important when considering the success of the project. The curriculum must have high satisfaction rates, which includes the overall lab process, ability to customize the model, and overall curriculum/education delivery. Other high-risk specifications include the student-ready test models, in which at least three different models will be supplied with expected reliability and customizable features. Lastly, when considering the research side of the senior project, there must be at least five quantifiable features to measure before/after each step of the manufacturing process.

In order to measure the compliance of most of the specifications, a few methods will be used. First, for the satisfaction surveys, ideally a small test group will be gathered to run through the entirety of the process, in which their feedback will be very useful for improving the project. These surveys are shown in Appendices C.1 – C.3. Additionally, measurements (dimensions, time, etc.) and visual inspections will be used to determine the success of parts in the testing phase of the research portion. This will be done primarily with calipers (or micrometers depending on the desired resolution).

5.0 CONCEPT DESIGN

The ideation and concept selection stage consisted of a functional decomposition breakdown, ideation generation, and initial concept prototypes that were fed through Pugh, morphological, and weighted decision matrices to solidify the final concept design for the student models, example parts, and test coupons. This controlled-convergence method provided justification for the selected concept. Additionally, initial plans for the curriculum package were created as part of the concept design phase.

The selected student models include dice and rings, as they ranked high in manufacturability, customizability, and wow factors. The top two test coupons hold a variety of unique shapes and features that will encapsulate several qualities to test the limitations of the manufacturing process. The example models are an action figure and wireframe skull to show the class due to their added complexity. These are shown in Figure 5. The reasoning behind each decision is further documented in this chapter.



(a) (b) (c)

(d) (e) (f)

Figure 5. The final models for the concept design selection. (a) and (b) are the selected student models for their customizability, intricate design, and wow factors. (c) and (d) are the chosen models for test coupons, as they provide a large quantity of measurable features. (e) and (f) show the example parts of an action figure (Kirby) [23] and wireframe-patterned skull [24] that will be showed to the class.

5.1 IDEATION & CONCEPT MODELS

To develop many concept ideas, a functional decomposition flowchart was created to identify the structure of the project, which was followed with braindumping ideas for the student models, example parts, and test coupons. Functional decomposition required breaking the major functions into sub-functions, where each sub-function works to complete the function above it. At the lowest level are specific requirements needed to complete the sub-functions above them. When reading the functional decomposition tree, reading down the branches explains the steps necessary to complete the function. Two functional decomposition charts were created, one for the curriculum portion of the project and the other for the research. These helped outline the steps that would be required to fully complete each function.

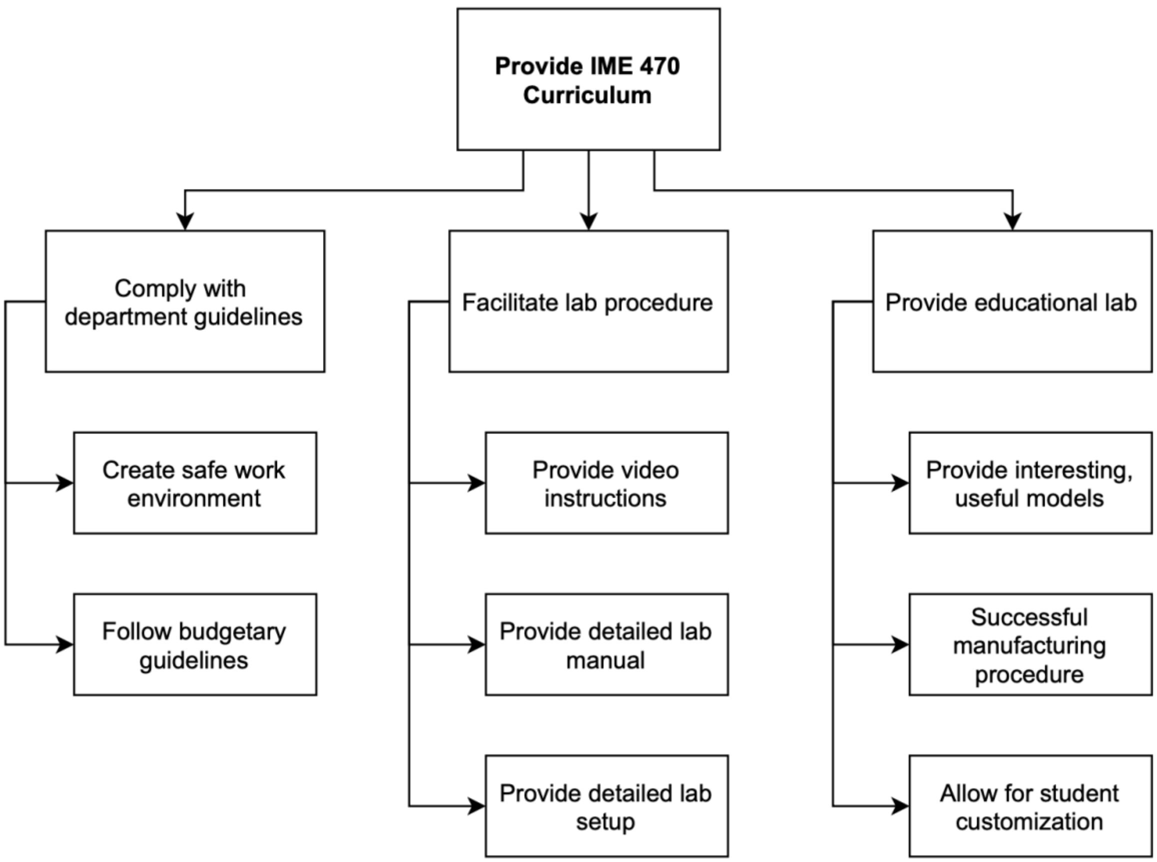


Figure 6. Functional decomposition of curriculum package.

Figure 6 highlights the major function and three sub-functions to provide the IME 470 course with an appropriate lab experience. The three sub-functions include complying with current department/lab guidelines, facilitating a lab procedure for improving student success, and providing an educational lab experience. With regards to department guidelines, the budget has been specified by the stakeholders for $4/student, and the safety hazards have been outlined in Section 5.6. To facilitate the lab procedure, tentative plans for the lab manual and video tutorial have been summarized in Section 5.7. Providing an educational lab will include a library of models with customizable features. These will be tested during the research portion of the senior project; once the parts have been verified to have a high reliability, those models will be deemed ready for student testing.

The other functional decomposition chart revolved around the research aspect of the project, as seen in Figure 7.

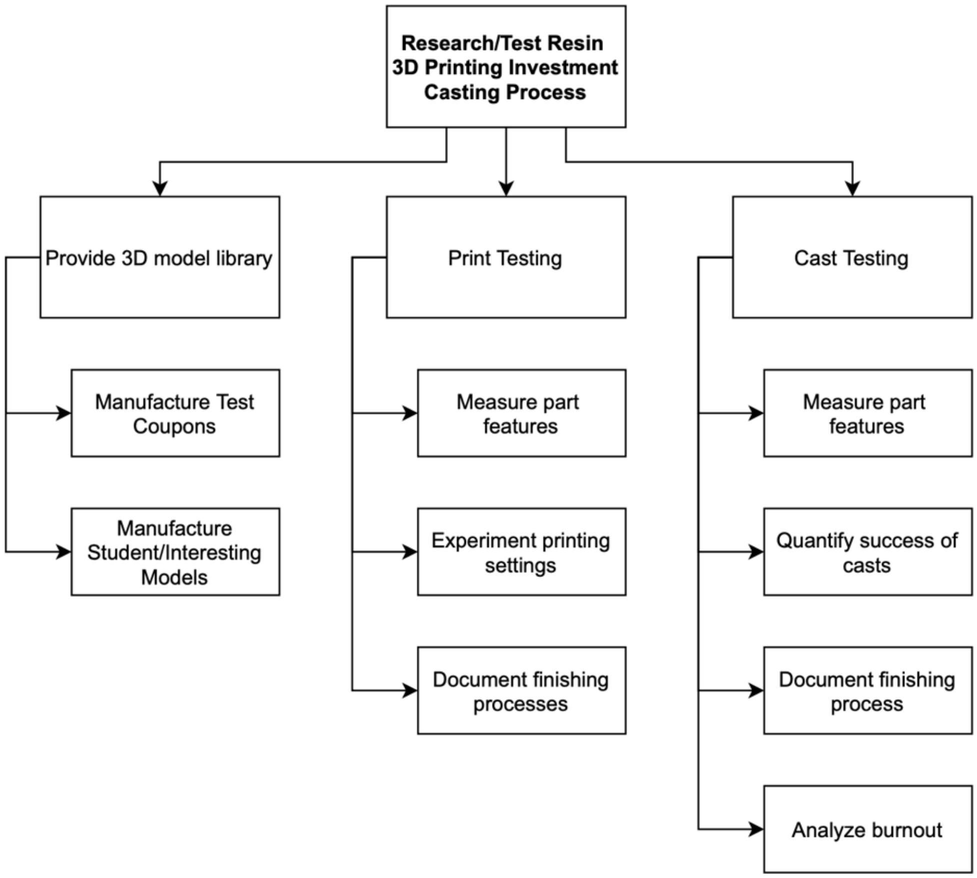


Figure 7. Functional decomposition of research and testing.

There are three sub-functions in Figure 7 to complete the necessary research: testing variations in the printing and casting processes and providing a library of successful models for testing and student learning. To accomplish these sub-functions, several quantities will be measured on the test parts between the printing, curing, and casting phase, which are detailed in the Appendix D.1. Documentation and analysis on these measurable features, along with qualitative measurements such as burnout success and surface finish, will fulfill the steps needed to complete the research portion. The library of models will be a result of the tested parts, as successful parts will be kept for students to manufacture. Overall, the main takeaway from both functional decomposition charts was a further understanding of the work needed to complete each project.

The next step was an ideation stage to determine the 3D models. In order to generate ideas for the student, examples, and test parts, a braindumping method was utilized, where the team members individually wrote as many ideas as possible without judgement or feasibility analysis. After a pre-defined limit of 10 minutes, members shared their ideas and discussed reasoning behind them. Time was allowed to add ideas if one member spurred an idea in the other. This was done for student and example models. For the test models, instead of coming up with specific models/shapes, a braindump of measurable features, interesting patterns, and other parameters were collected to develop a list of quantities that will test the limitations of the manufacturing process. A formal list of all generated ideas can be seen in Appendix D.1.

Following the ideation stage of the concept selection, initial prototypes were created. These were constructed from cardboard and modeling clay in order to gain a feel for the size and complexity of the shapes. Each team member built five prototypes, and the results can be viewed in Appendices E.1 and E.2. It was found that the 1.0 in^3 material limit is very generous since most parts are less than half that volume. This is good, as the gating system may also require material and must stay within the 1.0 in^3 limit. It was also noted from the prototypes that some parts weren't customizable, such as the dog. When choosing models for the Pugh matrices, the customizability helped reduce the list of all model ideas to only a few.

5.2 PUGH MATRICES

Controlled convergence from the ideation generation was performed to narrow down the options. This began with Pugh matrices, which compare the top few concept ideas to a datum. The first datum was the current lost-wax investment cast keychain from the IME 470 curriculum. Each model was compared to the keychain and evaluated on specifications from the customer's requirements, QFD, and additional categories such as a 'wow' factor or uniqueness due to new manufacturing capabilities. Rankings of '+', '-', or 'S' represented a positive, negative, or same change with respect to the datum. These were then totaled up, with a positive sum indicating a model that exceeds the datum when compared to the criteria, and vice versa for a negative sum; a sum of 0 means it's similar to the datum. After summing, a second Pugh matrix was analyzed where the highest-scoring model became the datum, and the other concepts were ranked against it to reveal more about the designs. The Pugh matrices can be viewed in Appendix F.1-F.3.

STUDENT MODELS:

For the student models first, 13 models were selected from the ideation list and compared against the keychain. The dice ranked the highest, as it exceeded the keychain in 5 categories: complexity to cast, cost, post processing, 'wow' factor, and aesthetics. Next highest models were the necklace pendant, earrings, coin, ring, and novelty guitar pick (i.e., a guitar pick for show, not for playing a guitar). It was found that when the dice became the datum in the second Pugh matrix, no other concept had a sum over 0, meaning the dice is expected to perform the best in future convergence tests. This can be seen in Appendix F.1.

EXAMPLE PARTS:

For the example models, the same specifications from the student models were used with the addition of uniqueness due to new manufacturing capabilities and the difficulty of the part. These example parts will be shown to the class to highlight complex, interesting pieces that seem hard to complete in a foundry setting. The top model was the action figure, followed by shoelace pendants, rhinestone rings, shot glasses, and different patterns/textures. The action figure was the highest due to its uniqueness and relatively easy manufacturability. When the action figure became the datum, the shoelace medallion and shot glass ended with a positive sum, meaning that these could potentially meet the criteria more than the action figure, and will be explored further in the weighted decision matrix. This can be seen in Appendix F.2.

TEST COUPONS

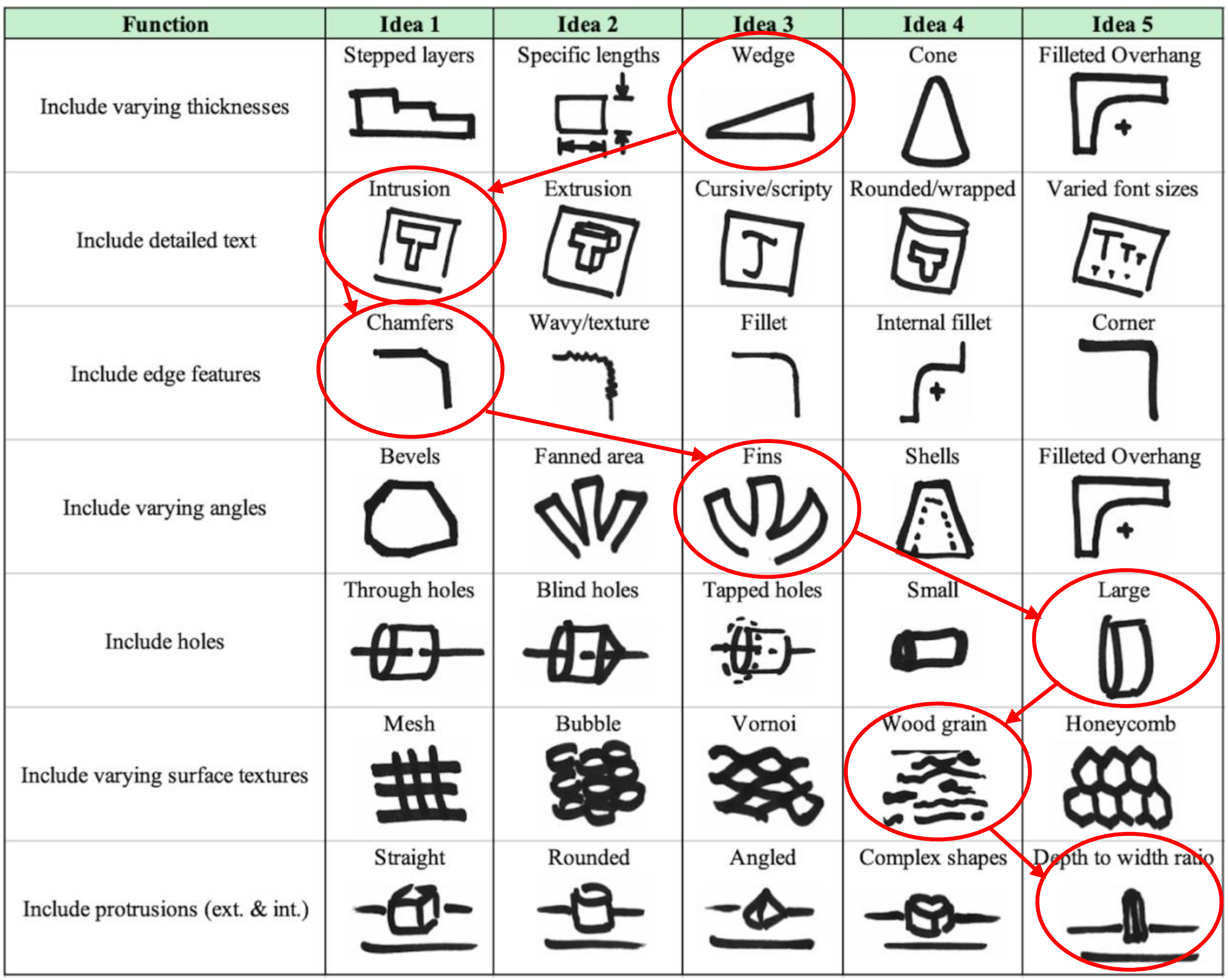
Lastly, the test coupons were evaluated against ability to measure certain features (thicknesses, holes, text, protrusions, etc.). When creating the Pugh matrix, simple ideas of the test coupons were created that accomplished one task (such as several textures or hole sizes). As shown in Appendix F.3, the test coupon and test cube ideas were the highest ranked models due to their ability to test several features at once. The morphological matrix will combine some of the best aspects of these models (specifically the repeatability of features and overall quantity of features) in order to generate coupon shapes.

5.3 MORPHOLOGICAL MATRIX

Following the Pugh matrices, a morphological matrix was created for the test coupons. The reason to not create a morphological matrix for the student/example parts is simply because those models need to have high reliability while looking interesting and allowing students the ability to customize. There isn't any need to string together functions in order to generate models, as these models should be desired shapes/parts that students would enjoy. The reliability will be measured from casting the parts several times.

The test coupons, however, don't need to look as visually appealing, so it could be a combination of several functions that, when strung together, allows for quantifiable testing of the part. Table 3 shows the seven categories of required features from the ideation generation shown in Appendix D.1, with five ideas each to solve each function.

Table 3. Categories for morphological matrix for the test models.



Function	Idea 1	Idea 2	Idea 3	Idea 4	Idea 5
Include varying thicknesses	Stepped layers	Specific lengths	Wedge	Cone	Filleted Overhang
Include detailed text	Intrusion	Extrusion	Cursive/scripty	Rounded/wrapped	Varied font sizes
Include edge features	Chamfers	Wavy/texture	Fillet	Internal fillet	Corner
Include varying angles	Bevels	Fanned area	Fins	Shells	Filleted Overhang
Include holes	Through holes	Blind holes	Tapped holes	Small	Large
Include varying surface textures	Mesh	Bubble	Vornoi	Wood grain	Honeycomb
Include protrusions (ext. & int.)	Straight	Rounded	Angled	Complex shapes	Depth to width ratio

Once the functions and ideas were chosen, many new ideas were generated by stringing together one idea from each function. An example is shown in Table 3: a wedge-shaped part with intrusion text, chamfered surfaces, angled fins, wood grain texture, and a large hole with a specified depth-to-width ratio. Each member generated five ideas while keeping manufacturability and measurability in mind. The variations are shown in Table 4.

Table 4. All 10 options generated from the morphological matrix functions.

		Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10
Thickness	Stepped layers		■				■				
	Specific lengths					■		■			■
	Wedge	■							■		
	Cone			■						■	
	Filleted Overhang				■						
Text	Intrusion		■						■		
	Extrusion					■	■			■	
	Cursive/scripty	■						■			
	Rounded/wrapped			■							
	Varied font sizes				■						■
Edge	Chamfers	■							■		
	Wavy/textured			■							■
	Fillet		■				■				
	Internal fillet				■					■	
	Corner					■		■			
Angles	Bevels				■						
	Fanned area			■			■				
	Fins					■			■		
	Shells							■		■	
	Filleted Overhang	■	■								■
Holes	Through holes			■			■				■
	Blind holes		■							■	
	Tapped holes	■									
	Small				■			■			
	Large					■			■		
Texture	Mesh			■						■	
	Bubble				■		■				
	Vornoi					■		■			
	Wood grain	■							■		
	Honeycomb		■								■
Protrusions	Straight				■						
	Rounded		■				■			■	
	Angled					■		■			
	Complex shapes										■
	Depth to width ratio	■		■					■		

Following the selection of features, each of the ten options were sketched in order to gain a basic schematic to judge the feasibility. After completing the morphological matrix, one more design was sketched as a team, which will be included in the following drawings. These sketches can be seen in Figures 8-18.

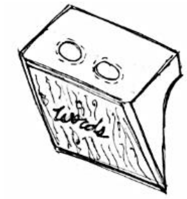


Figure 8. Option 1 for test coupon.

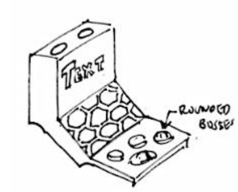


Figure 9. Option 2 for test coupon.

Figure 10. Option 3 for test coupon.

Figure 11. Option 4 for test coupon.

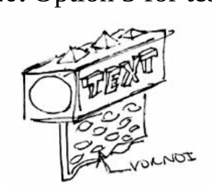


Figure 12. Option 5 for test coupon.

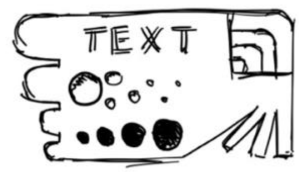


Figure 13. Option 6 for test coupon.

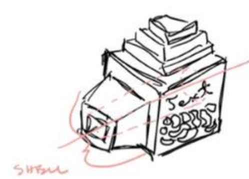


Figure 14. Option 7 for test coupon.

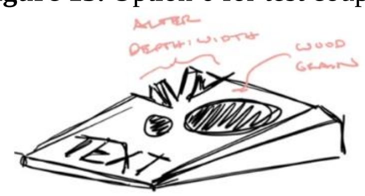


Figure 15. Option 8 for test coupon.

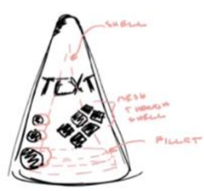


Figure 16. Option 9 for test coupon.

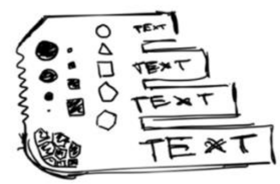


Figure 17. Option 10 for test coupon.

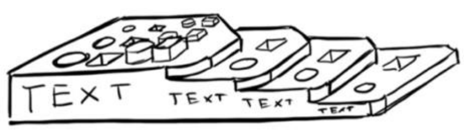


Figure 18. Option 11 for test coupon.

Seven of the eleven options were chosen to filter through the weighted decision matrix. Those that didn't move forward were discarded due to feasibility of casting and the inability to measure large quantities of features, which were Options 3, 4, 5, and 7. From the morphological matrix post-discussion, the best models are those that have repeatability, such as text at different font sizes, holes at decreasing radii, etc., when evaluating the limitations of the features. Textures and angled features became less of a priority, since these won't be vital features to have the students cast. The major concern at this stage is that putting too many features on one test coupon could clutter the piece and produce unreliable data – for example, it might be hard to test the radii of the holes if the step thicknesses or inclusions affect the overall performance of the part. It might be best to consider limiting the number of quantifiable features to avoid this issue, but testing will be done to determine this.

5.4 WEIGHTED DECISION MATRICES

Three weighted decision matrices were created for the test coupons (using results from the morphological matrix), the example models, and the student models. Each concept idea was ranked against specifications given by the stakeholders, as well as items from the QFD and the morphological matrix. These specifications were given a weight between 0-10, 10 being of high importance specified by the stakeholders, such that low-importance categories have less of an effect on the outcome. The ideation designs were then ranked from 1-10 for each specification, where a 10 meant the concept does an excellent job at completing the requirement. By summing the weighted performance, an overall score for the model could be determined. These decision matrices are shown in Appendix G.1.

STUDENT MODELS

For the student models, the top seven choices from the Pugh matrices were ranked against stakeholder specifications as defined in the QFD and Pugh matrix. The metrics included ease of printable/castable, cost/volume, expected reliability, the time to clean/post process the model, customizability, and wow factor. The highest categories included ease of printing/casting and the ability to customize, as this is the complete basis for the lab and will help ensure student success. Customizability was also important for the student models.

The dice and ring models ended with the highest score. These rose to the top due to their ability for customization and 'wow' factors, while also having good scores for manufacturability and cost. Other ideas ranked lower due to their boring nature, expected issues with casting (especially the small features such as a small earring or necklace pendent), or forethought reliability issues (also related to size/thickness).

EXAMPLE PARTS

The five highest-ranked example models were chosen from the Pugh matrices and evaluated in a weighted decision matrix with the same specifications as the student parts. A new category of uniqueness was added to highlight the ability to cast new shapes. The action figure continued to dominate over other options, as it scored high in the easily printable/castable, cleaning time, and 'wow' factor categories. The second highest model was the patterned shape, as this will allow for the display of new capabilities of the technology that will amaze the students. The selected shape for the pattern was a skull, as it would feature a wireframe pattern well. Other options had lower scores due to foresight into casting issues from their thin features or lack of student excitement.

TEST COUPONS

For the test coupons, the seven top choices were ranked against a set of metrics to converge to two final concepts. The metrics included sponsor specifications of easily printable/castable, the cost/volume, the expected reliability, and the time to clean/post process the model. Additional specifications included the ability to measure features, or simply the inclusion of features (text, edge features, textures, etc.). It was found that Options 6 and 11 from the morphological matrix were both ranked the highest for their ability to measure several limitations to the manufacturing process while also being easy to print/cast. What set these apart from other options was the fact that the layout of the parts allows for features to be added on/removed with ease, so, for example, if a cylindrical boss is a feature of interest, it can easily be added on with various heights/thicknesses since the parts are planar with room to modify.

6.0 FINAL DESIGN

This section will highlight the chosen design for the student models, example models, and test coupons as well as support the chosen designs with applicable engineering reasoning. Additionally, the plans for the lab curriculum will be discussed, with the final products listed in the appendix. Any new models that arose through the manufacturing process will also be discussed here.

6.1 FINAL CHOSEN CONCEPTS (PRIOR TO MANUFACTURING)

STUDENT MODELS

For the student model, the dice was the highest scorer – it's simple, allows customizability, and is an easy shape for printing and casting. The 'ones' face will be customizable to the student's liking. It will be created with the standard dimensions of a die (16 mm edges), so it's much smaller than the sponsor's requirement of 1.0 in^3 of material, thus decreasing the cost as well. It also requires little post processing – at most, some sanding to get smoother faces. A keychain hook has been added as an option if students would like to include it. This will require purchasing jump rings or thread to loop through, but this is a very low cost.

Figure 19. The die was the first selected design for the student model.

The second student model was the ring, as this is a unique part that is hard to manufacture yet is a common part to cast. This can also be customized and is very cost/material saving. While it could require more post processing to smooth the ring band, the 'wow' factor and aesthetics drove it to the top of model selection. The ring will be able to be scaled in CAD in order to fit a range of ring sizes, too. The geometry of the ring has been smoothed from its original shape for more visual appeal. The success rate is expected to be high since this is similar to jewelry industries that cast their parts in a similar fashion.

Figure 20. The ring was the second selected design for the student model.

EXAMPLE PARTS

The highest ranked example part was the action figure, as it's a complex shape that previous lost-wax casting techniques would be incapable of making. The model allows for customization in that several different characters could be created within CAD and printed, given that the overall shape is similar to what the team tests. The model that will be tested is Kirby (a video game character) because of its unique shape and relatively easy printing/casting settings. The model size will be approximately the size of a 1.5" cube. This model is currently planned to be included with the student models if it is easy, successful, and reliable.

Figure 21. The action figure, Kirby, was selected design for the example part [23].

The second highest-scoring example part from the weighted decision matrix was a patterned object. This pattern can be applied to any shape, but a skull was chosen for the initial test. This is because the thin features will intrigue the students and provide a challenging part to manufacture. The skull will be approximately 2" high and have several sprues in the gating system to improve metal flow. If it is too thin to manufacture, a few different models might be downloaded from online sources and casted instead.

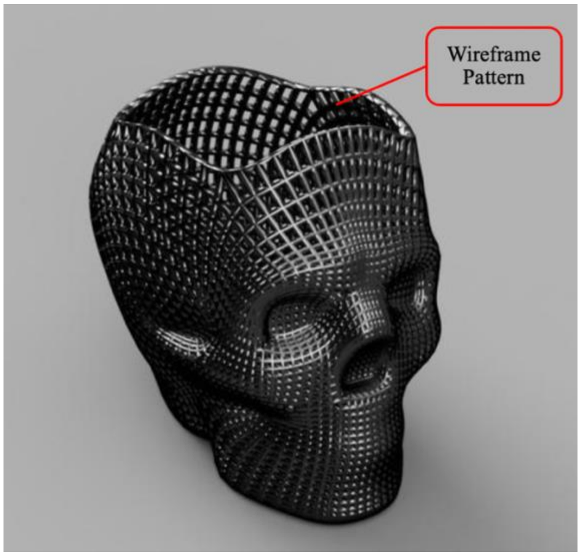


Figure 22. A wireframe skull was also selected design for the example part [24].

TEST COUPONS

The first test coupon (Option 6 from the potential options) consists of a constant thickness part where each surface contains different features, including a stepped region, angled fins, varying text size, several through holes, external protrusions, and filleted edges. These features will allow for measurements to be taken and dimensions tracked from the printing to final product stage. The ability to test multiple of each feature will be essential to see the minimum/maximum allowable dimensions. The letter 'P' was chosen as the geometry of the letter includes internal/external curves and a long rectangular section to measure width and length.

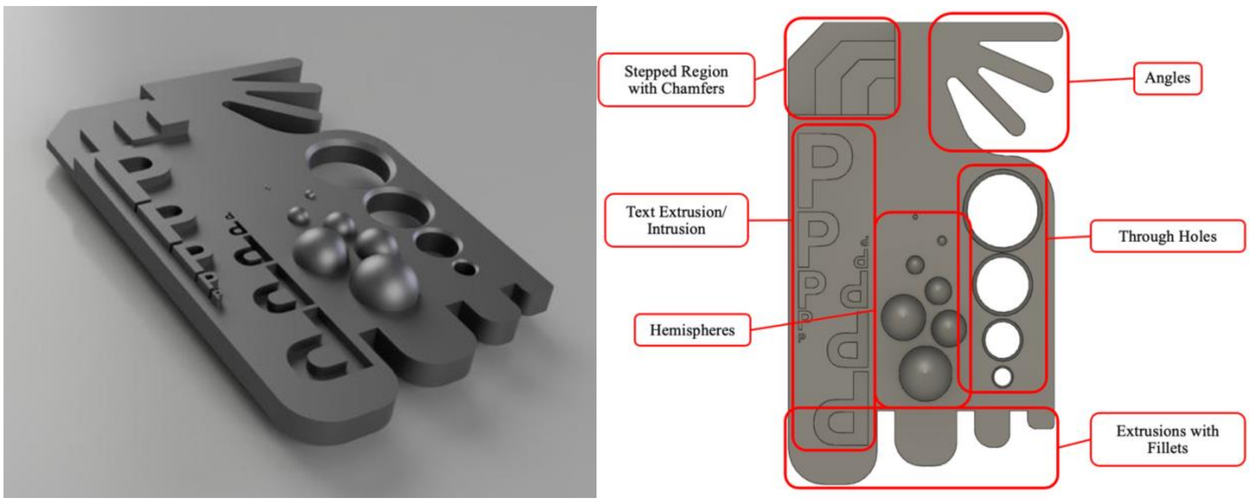


Figure 23. The first selected design for a test coupon – Option 6. Dimensions on the measurable features are shown in Appendix H.1.

The second test coupon, Option 11, is similar to Option 6, but this includes more surfaces for testing. Each step of the terraced section will have the same features, just at different sizes/heights to view the performance of decreasingly smaller objects. This simple part will be easy to print and should hopefully be fairly easy to cast. Fillets and chamfers are included on the stepped corners to provide more data collection.

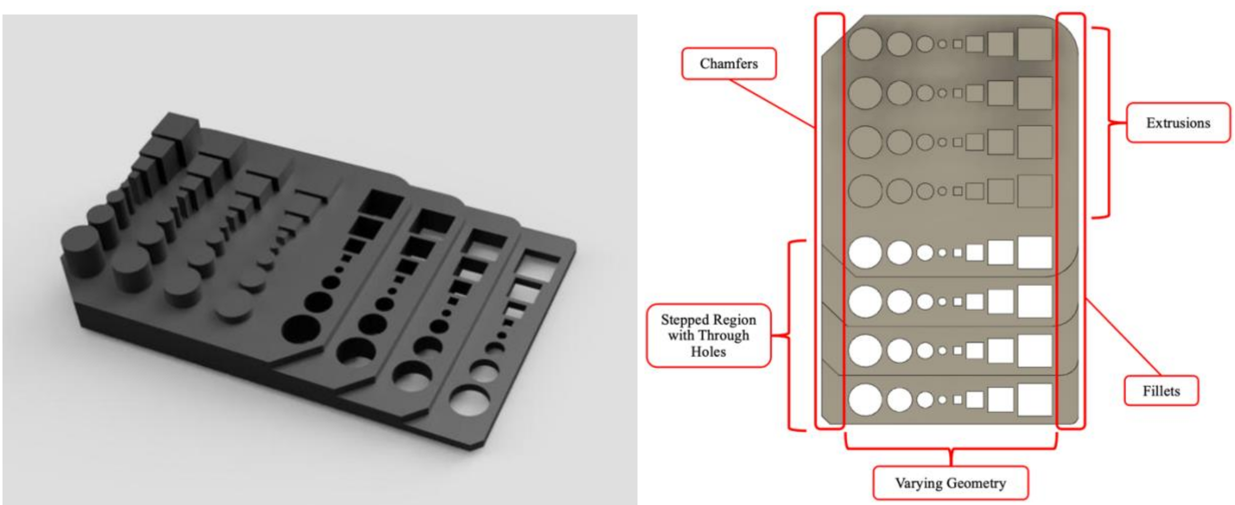


Figure 24. The second selected design for a test coupon – Option 11. Dimensions on the measurable features are shown in Appendix H.2.

Overall, these six models satisfy the sponsors specifications. For the test coupons, the main concern is quantifying the limitations to the manufacturing technology, which is achievable through the countless measurable features. Another major request is providing the IME 470 course with interesting parts that are interesting to students, allow for creativity, and are cost effective. None of the student models go over 1.0 in^3 of material (limit based on cost), and all contain some form of customizability. All six models combined will build the requested library of at least five tested models, while also fulfilling the requirements of providing the students three options to create during lab (including the action figure if it is relatively easy and successful).

6.2 POTENTIAL ISSUES (PRIOR TO MANUFACTURING)

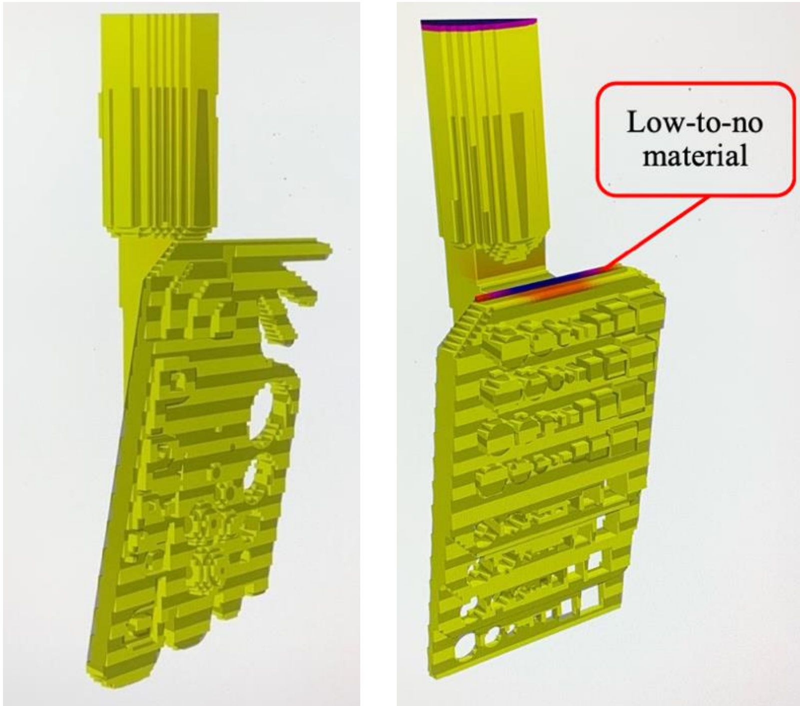
There are a few potential issues that could arise with the models. For the dice, the weight distribution is important to prevent a 'rigged' dice. Upon initial testing, we realized that these dice can't be used for games (due to the weight, bumps, or infills), so ensuring a perfectly balanced dice is unnecessary. For the student models, the skull presents the largest foreseeable issue of having too thin of features. If the part doesn't work well, the model will be simplified to ensure success, including making the wireframe structure more easily manufacturable. If that still doesn't work, since there are certainly limitations to what casting can achieve, a different (or a few different) student model(s) will be chosen to replace the skull. Lastly, issues with the test coupons could include too large a quantity of features that will affect the others around them. This will be evaluated through testing (with potentially different gating systems) to ensure the features can be quantified independently. Flow simulation has helped prevent the majority of these foreseeable dependency issues, as by iterating the gating system, the simulation now predicts the flow won't be constricted between features.

Some undetermined aspects include the two potential methods for attaching the gating. This will be either implemented in the CAD model to be printed with the part or attached separately after. Testing is required to see which method is most appropriate. If the gating is included in the model, that means that there should be no inconsistencies in the material expansion during burnout, less concern of separation, and ease of manufacturing (requires no assembly of part and gating). However, if the gating is printed out of PLA on an FDM printer, it would save money since the resin is expensive, and the gating system doesn't need the high layer resolution of the resin printers. However, a concern of the PLA expanding faster than the Castable 2 resin might result in separation in the furnace, thus scrapping the part. In the end, the gating was attached to the models and printed with the Castable 2 resin to prevent separation or additional manufacturing steps.

6.3 STRUCTURAL PROTOTYPE & SIMULATION

Before several models are printed and analyzed, a prototype was created to test both coupons. The CAD for both coupons was modified to include gating systems and analyzed in SolidCast®, a flow-simulation software that is used in IME 470. This software allows the user to import a model, select material properties of the investment and casting materials, and then simulate the flow of metal through the gating system and into the part. Once the simulation finishes, results can be analyzed to ensure material reached each crevice of the part and doesn't constrict flow to other sections.

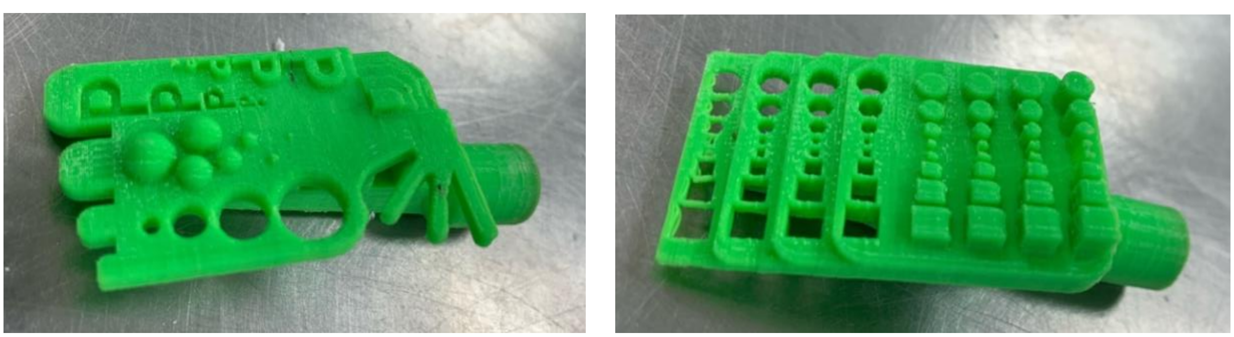
To begin the structural prototype, both coupons were loaded into SolidCast® to analyze the gating structure; without an effective gating structure, the prototype is bound to fail. The results are shown in Figure 25 – the color scheme shows material density, thus if the part has dark patches, it means there is low or no density and thus the gating system should be adjusted. Yellow means 100% density. So far, just the test coupons have been loaded into the simulation software. Once the testing phase has been completed, the student/example models will be simulated if the coupons are somewhat consistent with the simulation's predictions. If the simulation's results don't align with the physical parts, it might not be worth the time and effort to model the other parts.



(a) (b)

Figure 25. SolidCast® simulations. (a) For coupon A, material reached all zones of the part and is thus ready to be attempted in the lab. (b) Coupon B has some zones with no density (dark color), so the gating system was modified to fill the top of the part before manufacturing.

With slight modifications to the gating system for coupon B, the pieces were ready to print. For these prototypes, an FDM printer with PLA material was used to preserve the expensive castable resin for actual tests. Because of the poor print quality of the FDM printer, not all the features were clearly visible, but for a prototype, it's sufficient. Figure 26 shows the test coupons before going into the investment stage.



(a) (b)

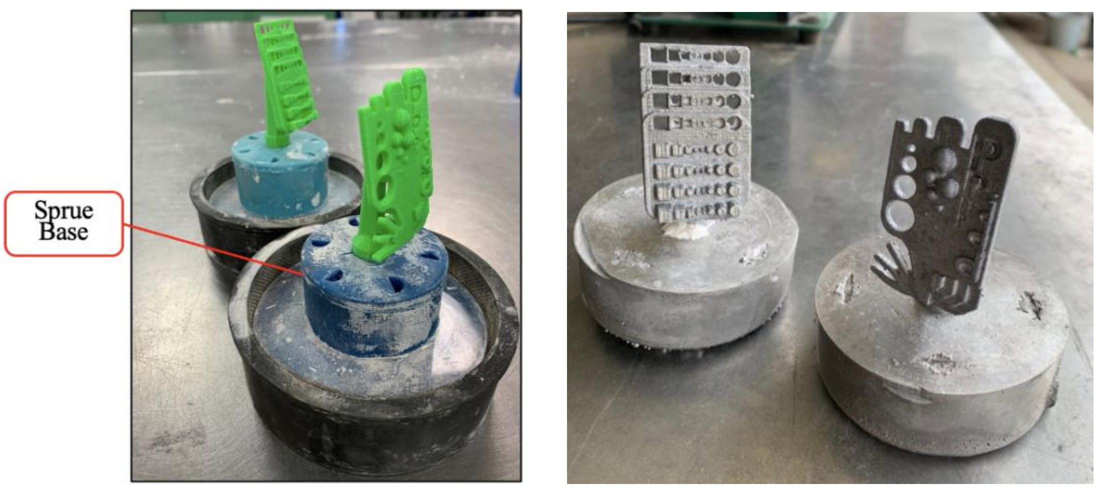
Figure 26. (a) Structural prototype for test coupon A. (b) Structural prototype for test coupon B.

These coupons were set into flasks and investment material was poured in and hardened, as shown in Figure 27 (a). The process used to make the investment plaster was documented by Professor Coch in a video for the IME 141 students. The team followed these instructions to get the investment-to-water ratios right.

After the prototypes were printed, the next step is burnout. This will function more as a process-test and gating-system test, so these parts won't be measured. Once the gating was verified to work, resin parts will be cast and measured. Plus, the structural prototypes were made from a FDM printer, and thus have a very poor layer/dimensional resolution. Table 5 summarizes the burnout schedule needed for PLA, and the final products can be seen in Figure 27 (b).

Table 5: PLA burnout schedule [25].

Time (Hr: Min)	Temp (˚F)	Description
2:00	230	Drying wet mold
2:30 (Hold)	230	Drying wet mold
3:00	500	Melt PLA without burning it
4:00 (Hold)	500	Melt PLA without burning it
2:00	700	Vaporize remaining PLA
4:00 (Hold)	700	Vaporize remaining PLA
7:00	60	Cool to room temperature



(a) (b)

Figure 27. (a) The test coupons stuck into the rubber sprue base of the flask. The top of the gating system fits snugly in the rubber stopper. (b) The casted product, which if seen up close, has a poor layer resolution and surface finish due to the FDM printing technique.

For the actual test coupons, the resin from SprintRay (named "Castable 2") has a slightly different burnout schedule. First, the oven is preheated to 800˚C, and once the investment is in the furnace, temperature is ramped to 950˚C. This temperature is held for 1 hour for the first 100g of material plus 30 minutes for each additional 100g of investment. Then, the oven is cooled back down to 800˚C before removing the flask [26]. Once the burnout process is complete, liquid aluminum will be poured into the cavity. This will be allowed to harden before breaking the plaster and revealing the finished product.

By manufacturing the test coupons, a few important discoveries were found. First, some of the incredibly thin parts had an issue being filled with material or burned out. Luckily, this only aids to the research, as it shown limitations to the technology. It was seen that holes under 1mm in diameter failed to cast properly, as well as rectangular holes of 1mm side lengths. Surprisingly, most other features came out fine. Also, several items were made for the 3D printing to aid with the process, including silicone work mats for grip, instructions for operating the printers, and a custom-made apparatus to drain excess resin back into the bottles. The structural prototype also highlighted a detail in the slicing software that needs to be addressed: setting the infill low to preserve material.

6.4 ADDITIONAL DESIGN IMPLEMENTATION – POST-CDR

Throughout the manufacturing process, limitations and shortcomings of the original final designs became apparent. These issues included failure within the casts, inability to draw substantial data from test coupons, and problems with process inconsistency. In order to make up for these faults, new designs were implemented to allow for the adaptation of the original concepts.

GENERAL ISSUES:

The goal of this project was to capture the capabilities of the investment casting process used in conjunction with SLA rapid prototyping and castable resins. In order to do this, the testing was to be performed with minimal outside influence on the process to get the highest quality of results. Unfortunately, the investment lab where the testing was performed lacked a vacuum chamber, which is crucial for degassing the investment and allowing for the removal of all bubbles within the cast. This meant that throughout testing, most of the casted parts had an issue with bubbling on the surface. This was mitigated by the vibration of the mold, which although not a complete solution to the problem, did help release some of the trapped air in the investment. Part orientations were modified to have the least number of horizontal surfaces which also lowered the number of bubbles within the final mold. An example of this modification can be seen in Figure 28 where the sprue on the die was rotated to prevent bubbles from collecting on any particular face.

(a) (b)

Figure 28. The original sprue design (a) allowed for the parts to fill but left bubbles due to the parallel bottom surface. The new design (b) allows for the part to fill as well as prevents air getting trapped.

EXAMPLE PARTS

The example parts – in particular, the skull – proved quickly that they would be too complex to cast. Although the prints would be quite simple, apart from the support removal, the test coupons dictated the limitations of the process and revealed that the dimensions of the original example parts would be too small to successfully cast. Section 7.4.2 shows pictures of the new models that were chosen, which include an Iron Man bust, interlocking rings and a chess piece. The reasoning behind these new ones came from student opinions on what they thought might look cool. This was asked during student testing, and CAD files of the three new example models were made accordingly.

Additionally, one of the example parts planned to be manufactured was a Kirby action figure. Instead of casting the figure itself, the team thought it would be a new learning opportunity for students in IME 471 to learn about die casting. The CAD model was modified to turn the action figure into a cavity to fill with molten hot glue or wax. The students would be able to clamp to halves together, as shown in Figure 29, and inject molten plastic to form a Kirby action figure rather than cast it out of metal. This allows for much more usage out of the part and a new manufacturing technique for the students. In the future, students could even make their own molds to complete a similar process.

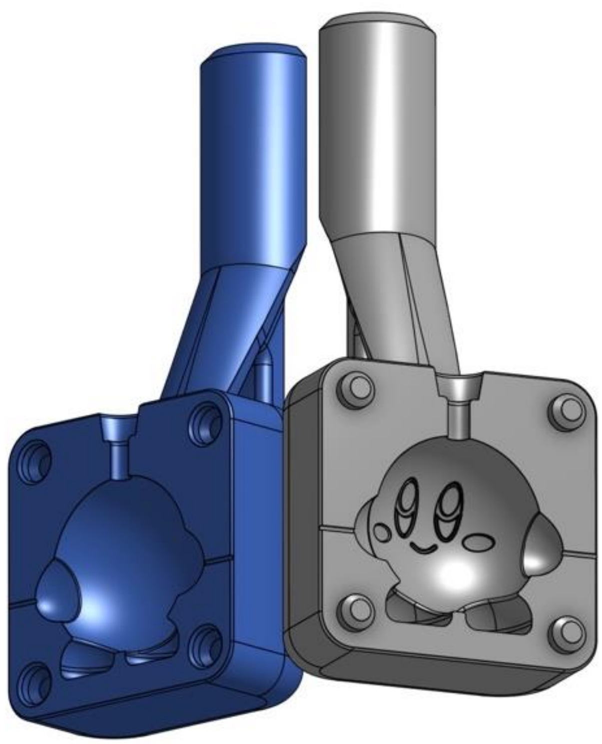


Figure 29. The die-cast Kirby action figure apparatus. As seen, there are two halves, which, when clamped together, will form a Kirby-shaped cavity in which molten plastic can fill. Once hardened, a plastic Kirby can be extracted, and the die can be reused.

TEST COUPONS

The original test coupons yielded a lot of useful data on the limitations of the process, but once a few had been measured and recorded, the team realized that obtaining a sample size large enough for repeatability testing would be unrealistic. This was based on factors such as the number of parts that could be casted at once (only two per flask) and how often the team had access to the lab. This was resolved by the development of a new coupon design. This new coupon shown in Figure 30 follows a more simplistic design with a set of round and flat sided extrusions and holes. This design also allows four coupons to be cast in one flask, and instead of having over 50 measurable features, there are only five to be concerned about. Specifications and dimensions for this part can be found in Appendix H.3.

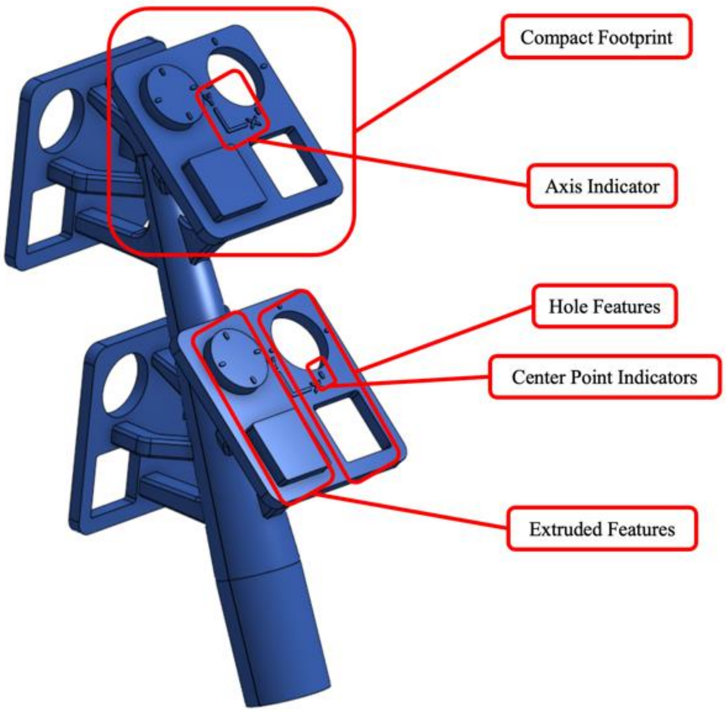


Figure 30. This design utilizes a lower number of features as well as a smaller footprint. This leads to a lower chance of features affecting each other, an easier investment and casting process, and the ability to cast 4 coupons within a single flask.

6.5 DESIGN HAZARDS, MAINTENANCE, & REPAIR

Before manufacturing and casting the selected models, a risk assessment was performed to identify any hazards and the necessary precautions needed to prevent them. These are summarized in the Design Hazard Checklist in Appendix I.1. The laboratory has dangerous equipment that can't be improperly used, such as the spinning grinding wheels, extremely hot temperature of the metal and furnace, and sharp edges on the part. The UV lights should not be pointed toward the eyes, and gloves/facemasks/goggles/pants should be worn when handling the uncured resin to prevent exposure. The preventative measures for these safety concerns will be included in the lab manual and video tutorial in order to explain the dangers to the students, especially because the identified hazards can cause serious physical harm. For manufacturing the test coupons, the senior project team will operate the machines with care to prevent physical harm. The lab will also be stocked with the proper PPE (gloves, goggles, and face masks).

Additionally, an FMEA was created to identify foreseeable failure modes, which are documented in Appendix J.1 and are broken up into two sections: failure in the curriculum and the research. There are only two main potentials for failure, or incompleteness. First, one original task in the functional decomposition was to "experiment with printer settings," but, the proprietary MoonRay printers are already optimized for the best performance. The second was "analyzing burnout," but this is likely out of scope of the project's objective and budget. Instead, the burnout can be qualitatively analyzed depending on the quality of the casted part. For the other tasks shown in Appendix J.1, there is not much concern for completing each objective. If, in some rare occurrence, something fails to be finished, it won't impose any physical safety concerns for the users, it would only restrict ease of instruction/success rate for the lab. For the two categories that likely won't be completed, these won't affect the overall performance or success of the research as it was defined in the scope of the project.

Maintenance of the lab will be a section within the curriculum plan. The largest maintenance concern is about the MoonRay 3D printers, as these are expensive machines that were gratefully donated to the IME department. Special care of these machines is crucial for their longevity and success in the future. Maintenance on these machines consists of properly cleaning all resin surfaces between 3D prints. To combat the cleaning confusion, a set of instructions has been developed to be hung in the 3D printing lab. These operators' manuals are included in Appendix K.1 and includes other instructions for setting up/removing your print. Repairs associated with this machine should be deferred to the IME technician, as proper upkeep of IME machines is one of his responsibilities. Additionally, students shouldn't attempt to fix the machines to prevent being hold liable. SprintRay (the company that donated these printers) is a great resource for proper maintenance and repair, if needed.

6.6 DESIGN COST

Initially budgeted a few hundred dollars for this project, the actual cost of this senior project is within about $150. Due to the gracious donation from SprintRay, the 3D printer, curing chamber, and castable resin costs have all been waived. The IME lab also had enough aluminum stock for our testing purposes, so the only materials needed were protective gear (goggles, mainly), investment plaster (to not deplete the shops' supply), a few scrapers/mats for ease of 3D printing, isopropyl alcohol, and a wash container. Essentially, because all the materials were donated other than investment plaster, the cost of the verification prototypes and all models the team will print werer free. When the process is implemented into the IME 470 lab, the only additional costs will be material (investment, aluminum, and resin). A purchasing list/BOM has been included in Appendix A.1. Most of these costs are for supplies that will be used in the IME 470 class, so most of the purchasing will carry on to supply the curriculum.

6.7 LAB CURRICULUM PLAN

Along with the physical models and research, the curriculum package is essential for determining the success of the senior project. This section will outline the materials within the lab manual, video tutorial, and student testing. The final products can be viewed in Appendices L.1 – L.3.

6.7.1 LAB MANUAL PLAN

The lab manual will be tailored to both students and instructors, and will contain the following sections to fully describe the manufacturing processes. The finished lab manual can be seen in Appendix L.1. Additionally, a pre-lab quiz (which was a 'want' of the sponsor, but the team figured this would be an essential portion of the curriculum) is listed in Appendix L.2.

- Safety precautions
- Customizing the 3D model
    - How to load the model into the TinkerCAD software
    - How to:
        - Extrude,
        - Create text,
        - Create shapes, and
        - Cut extrude.
    - How to export the file as an STL for 3D printing.
- Operating the 3D printer
    - How to load the model onto the printer. Instructions will also be posted on the wall of the 3D printing room.
    - How to operate the slicing software. Instructions will also be posted on the wall of the 3D printing room.
    - What to set layer thickness, part orientation, printer speed, and support settings. This should be the default settings.
    - How to set up the 3D printer. Instructions will also be posted on the wall of the 3D printing room.
    - How to start the print.
- Performing necessary cleaning processes
    - Amount of time in the isopropyl bath, any necessary sanding/cutting of support material.
- Curing the 3D printed model
    - Method for curing (UV light, thermal cure, or a combination). Instructions will also be posted on the wall of the 3D printing room.
    - Duration/temperature for the models. These will be the default settings of the curing chamber.
- Mixing and pouring the investment
    - The ratio of investment plaster to water.
    - Methodology for submerging 3D printed part into the investment.
- Operating the furnace for proper burnout settings
    - Specified temperature ranges and durations for the burnout cycle.
- Casting the investment
    - This is largely the same as previous labs, so only a general procedure will be given to supplement the manual.
- Maintenance to 3D printer and curing station.

With this manual, it will ultimately be up to the lab instructor to determine which processes the students complete; for example, the students might not be able to operate the 3D printer or burnout furnace for safety reasons or preventing violation of equipment.

6.7.2 VIDEO TUTORIAL PLAN

The video tutorial will focus on the actual in-lab processes that the student must complete. A story board of the planned video plan can be seen in Appendix M.1. Links to the final videos can be found in Appendix L.3. These videos are summarized below:

- 3D modelling
  - How to customize the pre-made models – short CAD software tutorial.
  - How to export the file to the slicing program.
  - How to slice the model and send to the 3D printer.
- 3D printing
  - An overview on how to modify the printing parameters described in the lab manual.
  - How to start the printer/fill with resin.
- Post 3D printing cleaning/curing
  - How to remove the model from the 3D printer and transfer to the isopropyl bath.
  - Proper PPE and safety concerns with handling uncured resin.
  - How to cure the model.
- Investment casting
  - The ratio of materials for mixing the investment plaster and pouring into the flask.
  - How to insert the model into the flask.
  - Proper time to allow the investment to harden before putting into the oven.
  - Burnout procedure and actual casting with liquid aluminum.

Similar to the lab manual, the entire process will be shown in the video whether or not the students complete each step, such as the furnace or 3D printer.

6.7.3 STUDENT TESTING PLAN

Once a majority of the research was completed and the project shifted toward developing the complete curriculum package, a small group of students were led through the process. This was to observe the process flow and ability for students to complete what will be implemented during the IME 470 course. Five students were taken through the process, and feedback was given in the form of satisfaction surveys. These surveys were administered for the following topics in order to improve each step of the process:

- Customization of the supplied 3D model
- Overall process flow for printing/casting
- Curriculum materials (manual and video tutorial)

The surveys can be viewed in Appendix C.1-C.3 and an example of one students' response can be seen in Appendix N.1. While not all are included, several student verbally went through the satisfaction surveys and gave feedback rather than filling them out, thus the reason to not include them. Overall, of the 5 students, 4 of them gave each survey 100%, and only one student gave a survey a 95%. With this level of success, the curriculum plan only needed a little modification before finalizing.

7.0 MANUFACTURING

This section will describe the manufacturing outcome for the senior project. This senior project, being based around manufacturing, has an unorthodox plan when compared to classical senior projects. Therefore, instead of describing how components will be manufactured (with dimensioned drawings) and assembled into a larger assembly (since there aren't parts to be assembled or dependent on others), this section will clearly describe the manufacturing process taken by all available models. It will also highlight the several models cast in the process and any other physical things manufactured throughout the entirety of the senior project. Additionally, the procurement and outsourcing will be addressed.

7.1 PROCUREMENT & BUDGET

The procurement of items has been broken down into two categories: 3D printing and casting. For 3D printing, Table 6 shows the needed items and their method of procurement. For the purchased items, a detailed budget is shown in Appendix A.1. The total cost was $130, which is far below the budget of $500. As noted in Table 6, several items were donated from SprintRay, a 3D printing company with ties to the IME department at Cal Poly – we are grateful of their donations to advanced resin printers, Castable 2 resin, and curing chambers.

Table 6. Materials needed for 3D printing/curing processes.

Item	Procurement Method
Resin 3D printer	Donated from SprintRay
Curing chamber	Donated from SprintRay
Castable 2 resin	Donated from SprintRay
Silicone work mats	Purchased on Amazon
Plastic scrapers	Purchased on Amazon
Isopropyl alcohol	Purchased on Amazon
Washing container	Purchased on Amazon
Goggles	Purchased on Amazon
Gloves	Already in IME shop
Masks	Already owned

Additionally, several items were needed for the burnout, investment, and casting procedures. Table 7 shows these items below, and detailed budget-keeping is shown in Appendix A.1.

Table 7. Materials needed for burnout/investment/casting processes.

Item	Procurement Method
Ultra-Vest investment material	Purchased on Rio Grande
Mixing tools	Already in IME shop
Flasks	Already in IME shop
Burnout furnace	Already in IME shop
Aluminum 356	Already in IME shop
Casting furnace	Already in IME shop
Casting crucible	Already in IME shop
Protective gear	Already in IME shop

7.2 MANUFACTURING STEPS FOR VERIFICATION PROTOTYPE

As mentioned, the list of manufacturing jobs differs from the classical senior project. Thus, the manufacturing process used on all models will be described below. These are the guidelines for the curriculum package/tutorial video to instruct students. Additionally, the 3D printing and curing steps are shown in greater detail with an instruction manual that the team made for the MoonRay printers. This is included in Appendix K.1 and is taped to the walls of the 3D printing room.

3D Printing Process: These steps are described in the instruction manual (in Appendix K.1)

1. Set up MoonRay 3D printer.
2. Load STL model into SprintRay slicing software, named RayWare.
3. Orient the model to print in the most optimal condition, set the support density, and slice the model. The defaults for this step should be fine.
4. Send the information via WiFi to the printers and start the print.

Curing Process: These steps are described in the instruction manual (in Appendix K.1)

1. Take the model off the build plate. Rinse in isopropyl alcohol and break off support material.
2. Place the model into the curing chamber.
3. Set the curing process to "Castable 2" and use the default preset values to cure the model.
4. Clean the printer while part is curing as shown by the instructions on the wall.
5. After curing, smooth any edges (as necessary).

Creating the Investment:

1. Follow the tutorial on the IME 141 Canvas page for making the investment slurry [27].
    a. To summarize, mix one full cup of investment and a cup of warm water (filled to the line marked on the cup). These materials are all in the IME shop in a cabinet near the door.
2. Place the 3D printed model into the sprue former, making sure that the 0.5" diameter cylinder of the gating system fits snugly into the rubber top.
3. Place the flask around the rubber lid. Press down until fully attached.
4. Fill the flask with the investment material until completely full.
5. Tap the flask for a few minutes to remove as many bubbles as possible. If accessible, use the vacuum chamber for this step.
6. Let the flask sit to harden (several hours, or just add it into the furnace and it will finish it).

Burnout:

1. Set the burnout schedule to the one specified by the Castable 2 resin. These are also described in Section 6.2 of this CDR report.
    a. Preheat to 800˚C, then place flask into furnace.
    b. Ramp temperature to 950˚C and hold for 1 hour for the first 100g of material plus 30 minutes for each additional 100g of investment material.
    c. Cool the furnace back to 800˚C and remove flask.
2. Pour while the flask is still very warm to prevent cooling the molten metal too much.

Casting:

1. Follow the common IME 141 casting procedure to fill the investment with liquid AL356.
2. Allow the material to cool.
3. Break investment plaster to remove metal model.
4. Cut off the gating structure and sand down attachment locations. Use the hacksaw and grinder in the IME lab to perform these actions.

For this project specifically, a formal drawing package was not developed since there aren't machined parts, assembly-level drawings, or an appropriate iBOM. Appendices H.1 – H.3 and O.1 – O.2 contain the dimensioned features of the test coupons, which was simpler and more organized to draw by hand than a formal engineering drawing (too many features to dimension). Table 8 shows the iBOM for the project, which is not quite like a classical iBOM, in that parts aren't reliant on subassemblies. This is because none of the parts directly affect the others.

Table 8. iBOM of different models and necessary material.

Assy Level	Part Number	Descriptive Part Name			Qty	Mat'l Cost	Production Cost	Total Cost	Part Source	More Info
		Lvl0	*Lvl1*	*Lvl2*						
0	100000	Final Assy							------	-----
1	110000		Models						------	-----
2	111000			Test Coupon A	5	$ 4.00	$ -	$ 20.00	IME Lab	Print/Cast
2	112000			Test Coupon B	5	$ 4.00	$ -	$ 20.00	IME Lab	Print/Cast
2	113000			Dice	2	$ 3.00	$ -	$ 6.00	IME Lab	Print/Cast
2	114000			Ring	2	$ 3.00	$ -	$ 6.00	IME Lab	Print/Cast
2	115000			Skull	2	$ 3.00			IME Lab	Print/Cast
2	116000			Kirby	2	$ 5.00	$ 1.00	$ 12.00	IME Lab	Print/Cast
1	120000		Materials		1	$ -	$ -		------	-----
2	121000			Castable 2 Resin	7	$ -	$ -		SprintRay	Donated
2	122000			MoonRay Printers	2	$ -	$ -		SprintRay	Donated
2	123000			Plastic Scrapers	1	$ 8.00	$ -	$ 8.00	Amazon	-----
2	124000			Silicone Mats	1	$ 10.00	$ -	$ 10.00	Amazon	-----
2	125000			Investment Material	1	$ 42.00	$ -	$ 42.00	R&R	-----
2	126000			Flask	2	$ -	$ -		IME Lab	-----
2	127000			Aluminum 356	1	$ -	$ -		IME Lab	-----
	Total Parts				**34**			**$ 124.00**		

7.3 ASSEMBLY AND OUTSOURCING

For this project, there will be no major assembly required or outsourcing. All manufacturing steps are specifically done in-house to prepare the lab for student use and ensure steps are accomplishable.

7.4 MANUFACTURING RESULTS

This section will highlight with pictures the results of manufacturing, including pictures from the student models, example models, test coupons, and student testing results. The pictures will follow the order of manufacturing. Additionally, before doing any manufacturing, a risk assessment was performed to mitigate any hazards. This can be seen in Appendix P.1.

7.4.1 3D PRINTING PROCESS

The 3D printing section of the project had a decent amount of trial and error before converging to a successful process. This included learning the limits to how much material could be printed at one time and the filtering of the resin. Through experience, it became apparent that 6 rings/dice could fit on the build plate with each part tilted at a 35˚ angle to reduce failure from the parts peeling off the build plate. As seen in Figure 31, parts easily come off the build plate if there's too much surface area to adhere to the florescent surface, thus scrapping all the parts.

Figure 31. As seen, this print prematurely separated from the build surface. This was because the print wasn't angled at 35˚, which has been shown to produce a good quality print with less likely chances of peeling failures.

However, once these kinks were worked out, the prints were much more successful. An examples of a successfully printed part can be seen in Figure 32.

Figure 32. These interlocking rings came out well, as they stuck to the build plate and had no failures prior to burnout. By angling the part, it reduces the adhesion area on the florescent surface and thus has a lower chance of failure.

Prior to talking with SprintRay, a stand was designed and constructed to recirculate the excess resin through a filter and back into the bottle. However, talking with the Director of Operations at SprintRay revealed that filtering the resin can remove the photo-sensitive compounds that cure the liquid, and thus filtering is not advised. Instead, it was deemed best to simply put a cover on the resin vat (to prevent light exposure) and simply top-off the vat each time the resin level gets too low. To streamline this, the vats have caps with tape on them to mark what is currently in the vat, and the vat trays are stored in a cabinet drawer to prevent light from curing the liquid. A picture of the drawer can be seen in Figure 33.

(a) (b)

Figure 33. (a) A custom-made stand for filtering the resin before learning to avoid filtration. (b) Location for storing the trays of resin between prints without needing to filter.

Through over 50 prints, several of which failed, the 3D printing process was honed down to work very reliably by the end of the senior project. Mainly, the resin was stopped being filtered and the parts were angled to prevent a large adhesion area. Additionally, the build plates weren't overloaded with parts, as having too much surface area curing would cause the print to fail. Looking forward, this process should be fairly easy for any future technicians. As long as they follow our recommendations for the number of dice/rings to fill the build plate with, and assuming they're in the right orientation/inclination angle, there shouldn't be an issue with the printer failing.

7.4.2 CASTING PROCESS

The curing and burnout process was consistent and reliable for the entirety of the project, and thus doesn't require much detail. As for the burnout process, the schedule and time was dependent on the professor, and the flasks of prints was included in the oven along with several other types of burnout processes. From observation, following the burnout schedule for the lost-wax process (as done in IME 141) was sufficient to burnout the Castable 2 resin. This included firing the furnace to 800˚C and having the flasks inside for about 6-8 hours. In the event that the flasks weren't directly taken out of the oven and poured immediately, (and thus the flasks cooled to room temperature), the flasks were stuck into a smaller oven to preheat them to 200˚C prior to pouring. This helped prevent premature solidification of the aluminum from the temperature shock.

The success of the cast largely depended on the success of burnout. Several time during the manufacturing stage, the plaster would crack or slightly explode if there was a large pocket of air trapped within it. Once the flask cracks, it's unable to be filled under vacuum pressure, and thus wouldn't fill as successfully. It's important that the flasks don't have pockets of air in them to ensure pouring success. Figures 34 – 38 show pictures of successful and unsuccessful casts.

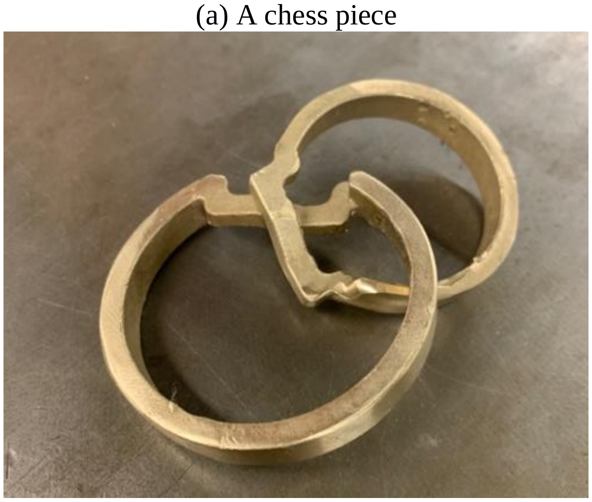
Figure 34. A few of the casted coupons. In total, 5 of each test coupon were successfully cast and used for analysis on the limitations of sizing (minimum thicknesses or diameters). These hadn't been fully washed prior to the image, and thus the reason for residual plaster to be stuck between features.

Figure 35. A new test coupon was created for statistical measures that has much fewer features to document. 12 of these were produced for a large enough sample size to accurately document the shrinkage rates.

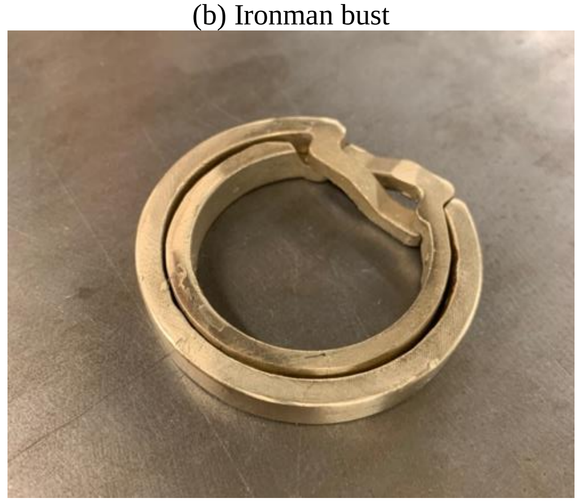
Figure 36. A few of the initial student models. These were done by students as then walked through the lab curriculum.

(a) A chess piece

(b) Ironman bust



(c) Interlocking rings (expanded)



(d) Interlocking rings (concentric)

Figure 37. After analysis over the complicated skull, it was determined that it might be overly complex and take a lot of iteration before getting the gating system to work. Instead, a few other interesting models were created and cast to pass around to students. These are (a) a chess piece, (b) Ironman, and (c)/(d) interlocking rings.

Figure 38. The other example model we wanted to prepare was the Kirby action figure, but instead we changed this to a die-cast model. As shown, the Kirby figure is a cavity that when the two pieces are clamped together, can be filled with hot glue/liquid wax and allowed to harden. This was created to show the students a different form of manufacturing and how dies can be cast instead of machined.

Overall, there was great success with casting as long as the flask didn't crack within the burnout stage. Once the flask cracks, it's unable to be poured under vacuum pressure, and the gravity-filled method had a lower success rate. This is likely because the sprues are quite thin, and metal can be stopped prematurely. An example of this is shown in Figure 38.

Figure 38. As seen, the metal barely got through the sprues since it didn't have the vacuum pressure drawing it into the cavity.

7.4.3 FUTURE RECOMMENDATIONS

The main recommendation is to ensure the flask won't crack within the furnace. As shown in Figure 38, if the flask cracks and cannot be filled under vacuum pressure, most likely the cast won't come out properly. To combat this, our recommendation is during investment, fill the flask with plaster until there is about 1" left to the top, then shake the flask vigorously (making sure to not spill the plaster) until no more bubbles rise. Then, fill the top of the flask with investment until it's full, and lightly tap to remove any bubbles that formed during the second fill. This is easier because if you fill the flask to the brim with plaster, it's much more difficult to shake the flask rigorously to remove bubbles and not spill everywhere. Tapping the edge of the flask is also beneficial to encourage the bubbles to rise to the top of the plaster. The best solution would use a vacuum pump during the investment portion, but that was out of the scope and budget for this project. If the IME department purchased a vacuum pump for the lab, this issue would likely be resolved.

Another recommendation is to get both printers running at once to increase production. To do this, connect the laptop to one of the MoonRay printers via WiFi, and after successfully sending off the print (and ensuring that the machine starts), simply switch the WiFi to the second printer and repeat the set-up process to print. While you won't be able to pause or monitor the first printer (since the laptop is WiFi connected to the second), you can view the progress if you switch back at any time. Currently, this is the only way to get both printers running from a singular laptop.

8.0 DESIGN VERIFICATION

8.1 PROJECT SPECIFICATIONS RESULTS

To validate that the senior project accomplished its goal, several specifications were identified in Section 4.6 and evaluated to constitute a successful senior project. This section will cover those planned tests. Each tests aimed to satisfy each of the specifications in Section 4.6 with a "test" (or "T" as it's labelled in Table 2) compliance method. Table 9 summarizes the specifications in Table 2 that use the "test" method. Under Table 9 is a description test and results for each specification, but the Design Verification Plan in Appendix Q.1 fully summarized the tests as they were planned.

Table 9. Specifications table for customer requirements that require testing.

#	Parameter Description	Target	Tolerance	Risk	Compliance
1	Library of successful models	5 models	Min	M	A, I, T
2	Library of student-ready models	3 models	Min	H	A, I, T
4	Process satisfaction survey	75% satisfaction	Min	H	T
5	Customization satisfaction survey	75% satisfaction	Min	H	T
6	Curriculum satisfaction survey	75% satisfaction	Min	H	T
7	Time to clean/post-process	15 minutes	Max	M	T
8	Time for respective process (print vs cast)	8 hours each	Max	L	S, T
9	Reliability	90%	Min	M	I, S, T
10	Quantifiable Features	5 features	Min	H	T
15	Volume	1.0 in^3	Max	L	A, T
16	Video Time	15 minutes	Max	L	S, T

Below, each of the tests for each specification will be described and the results noted. Any issues or incomplete tests will be noted in these sections too.

Spec 1 – 2: The compliance will be tested through manufacturing and casting these models to view their success. Success is deemed qualitatively such that the casts come out usable and completely filled with metal (no consistent cavities). From testing, it was determined that there are 6 models that were successful – dice, ring, chess piece, interlocking rings, Kirby, and Ironman – and thus this specification was met. For Spec 2, there are three models ready for students: dice, ring, and the die-cast Kirby. The successful models can be seen in Figure 40.

Figure 40. Successful models from left to right: test coupon A, test coupon B, ring, dice, new test coupon, iron man bust, chess piece, interlocking rings. There were a total of 8 successful pieces from the original design. Additionally, the Kirby die was successful, as shown in Figure 38. The Kirby, ring, and dice account for the three student models that were requested.

Spec 4 – 6: These surveys are documented in Appendices C.1 - C.3. Five students were walked through the entire process during Winter quarter to gain feedback on the process and have room to iterate any necessary changes. A sample response from the surveys is shown in Appendix N.1. A benchmark of 75% was deemed appropriate from Dr. Wang, which this was met (most gave 100% satisfaction). This test had to be modified slightly since the casting instructors didn't allow them to go into the lab, and thus they couldn't fill out certain portions of the surveys. However, this wasn't a huge roadblock as the students in IME 470 should already know how to cast/invest materials, and thus don't need to fill out a survey on completing the process.

Spec 7: This test was timed with a stopwatch to see how long it takes to remove the part, clean it with isopropyl, and cure it. On average, it only took about 1 minute per part, and thus is significantly under the benchmark. Additionally, the time required to cut off the gating system and sand down the gating-part interfaces after casting was timed. A benchmark of 15 minutes was considered allowable, and depending on the desired outcome, this was easily achievable (taking on average about 10 minutes). However, for the rings, it's possible to polish these in the machine shop for a shiny finish, which takes longer than 15 minutes. This was deemed allowable because it's dependent on the student's desire for how much they want to clean their part and/or shine it.

Spec 8: Because a technician will need to print all the parts, it's considerate to reduce print/cure time as much as possible while producing successful models. It was found that for the highest noted level of success, the parts should be oriented at a 35˚ with respect to the build plate. With this orientation, it takes about 4 hours to print 6 student models on each printer. By starting both printers, 12 student models can be printed in about 4 hours. Since the IME 470 class has roughly 25 students, this means that it would only take one day to print everyone's models, which is reasonable for the technician to handle. For curing, it was found that the preset 14-minute cure cycle for the Castable 2 resin was the most optimal. The curing chamber can hold over 12 parts (the maximum would be 12 parts coming off of both printers) so the curing chamber doesn't bottleneck the process. For burnout, the flasks are generally in the oven for 8 hours, which is the standard for the IME casting lab. There is little control over these times without risking part failure (especially inclination angle while printing not at 35˚). However, each respective process is appropriate to implement within the IME 471 lab.

Spec 9: This benchmark was met by testing several parts and seeing the percentage that pass. 12 test coupons were printed for statistical analysis, and 100% of them came out. Throughout the entire senior project, we invested 49 models and 44 came our correct, leading to a 90% success rate. To improve this, it truly comes down to getting enough bubbles out of the flask before putting it in the oven. The 5 failed parts were only because the flask cracked in the furnace and the parts had to be cast without the vacuum pressure pulling the metal into the cavity. An example of a good and bad cast that failed purely from a cracked flask can be seen in Figure 41.

Figure 41. On the right, a successful cast that was done under vacuum pressure. On the left, the flask had cracked, and the metal only halfway made it down the sprue under a gravity-pour. To improve success, a vacuum pump could be used during investment to prevent the flask from cracking due to air pockets in the plaster.

Spec 10: The number of quantifiable features is one of the most important aspects of the research portion. On the original test coupons, there were over 50 features. These coupons were used to test the minimum sizes for features, such as the smallest achievable diameter or thickness. Originally, these coupons were going to be measured for statistical analysis, thus the reason for the pre-made data tables shown in Appendix O.1 and O.2. However, since there were too many features to measure quickly, the new test coupons were created to account for a statistical analysis. The new coupons had 5 features, including two intrusion/extrusion boss lengths, two intruded/extruded diameters, and the overall coupon length. While a formal data collection table wasn't created, Excel was used to record the measurements and perform all calculations. The results for this can be seen in Section 8.3, with the data table shown in Appendix O.3.

Spec 15: Dr. Wang specified a target of 1.0 in^3 of resin material, but with the proprietary castable resin, 1.0 in^3 is about $3.33/student. Luckily, all of models are well below 1 in^3, so this is not a concern. The volume will be measured in CAD and include the necessary gating structure.

Spec 16: There are a total of 4 videos, and the combined length is about 10.5 minutes. Student feedback from specification #6 (curriculum satisfaction surveys) was used to critique the length of the video, where it was agreed that the video length was adequate. The video links are listed in Appendix L.2.

To summarize all the tests and their results, a Design Verification Plan and Report (DVP&R) is included in Appendix Q.1 The equipment needed for all the tests was located in the IME lab, which mainly included the printers, curing chambers, burnout oven, and casting supplies; some tests required no more equipment than the CAD software itself or a stopwatch. All of this information is documented in Appendix Q.1 for each specification.

Additionally, there were a few other specifications in Table 2 that were met. First, the lab space area has 4 stations (3D printers, curing chamber, investment table, and casting lab), and the 3D printing/curing station is roughly 9ft^2, and thus within the desired floorspace and station count. The cost of resin/materials is also within the guidelines as the amount of investment is the same as the current IME 141 lab (under $2/student) and the models are under 1in^3 (thus under $2/student). In total, all specifications from the sponsor were met.

8.2 DESIGN VERIFICATION CONCLUSION & CHALLENGES

Overall, each of the specification given by the sponsor were met or exceeded throughout this project. While there were some design changes to the example parts and student models, ultimately the new models continued to satisfy the needs of Dr. Wang and the IME professors.

There were several learning opportunities and challenges as the team worked through each specification. The most major challenge was with measuring the many features on Test Coupons A/B, and thus came about the design change to cast the new, simpler test coupon. Additionally, a great challenge came from preventing the flasks from exploding in the furnace, as it was dropping the reliability. The current work around is to partially fill the flask to allow for more aggressive shaking/vibrations to remove bubbles, which is the easiest and most practical way to solve the issue currently.

8.3 STATISTICAL ANALYSIS

In order to determine a reasonable measure of the expansion during burnout/the overall process, a statistical analysis of several test coupons was performed. Instead of using the Test Coupons A or B, since they have over 50 measurable features, a third test coupon was created that only had 5 key features to measure. However, Test Coupons A/B were important to the study, as it was found that the minimum hole could have a diameter of 1mm, and the smallest hemispherical protrusion could be 0.5mm in diameter. All other features came out fine. Test Coupon C is shown in Figure 42, with measurable features including side lengths of the two squares, diameters of the two circles, and the overall side length of the coupon. Additionally, the plan changed from measuring the features post-print, post-cure, and post-cast, as the variance between each step is unavoidable and unmodifiable. For example, there's nothing that can be done to reduce growth during the print or in the curing chamber, so it would be more valuable to learn the overarching growth from CAD to finalized product.

Figure 42. Test coupon used for statistical uncertainty propagation.

For this study, 12 of these coupons were printed and casted in order to get a decent sample size. Then, measurements were taken on all twelve coupons and their *deviations* from the nominal CAD dimensions were plotted to see the distribution of shrinkage/expansion. Figure 43 shows all sixty shrinkage measurements (5 locations on 12 coupons), where it can be seen that most of the measurements expanded.

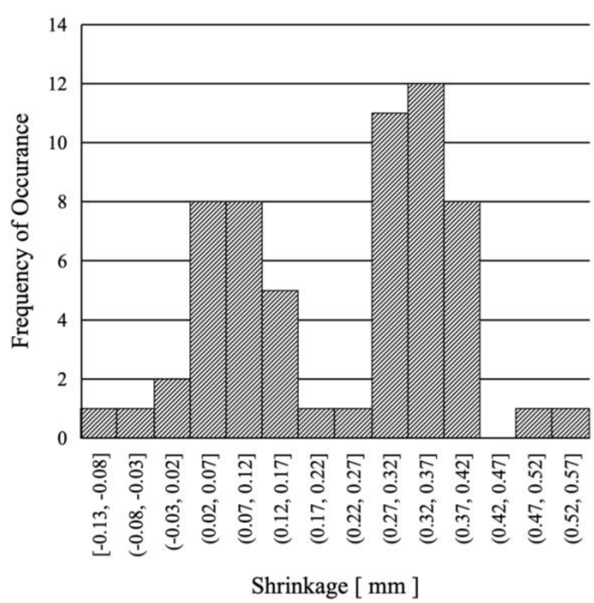
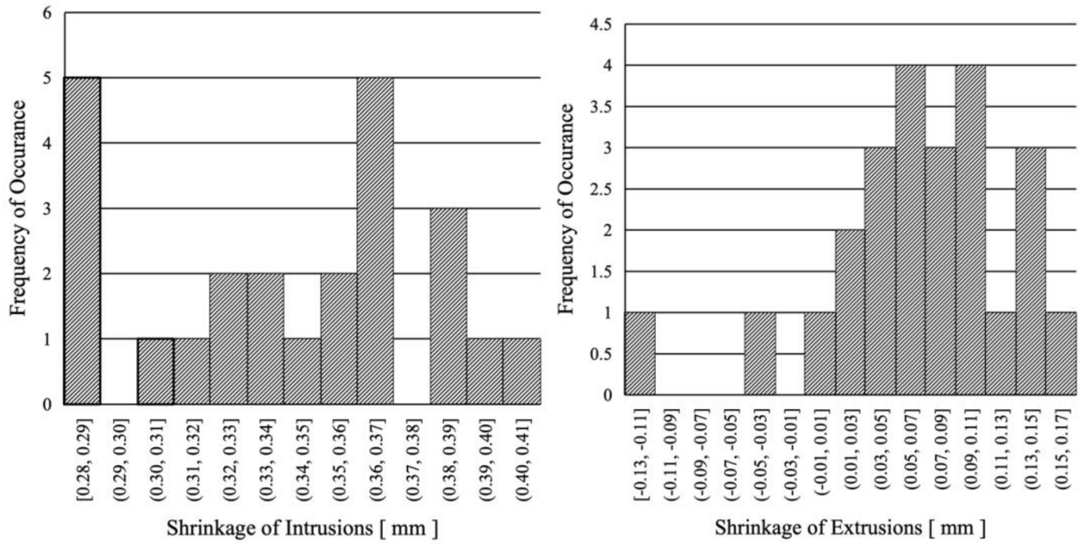


Figure 43. A multimodal distribution for all sixty measurements taken. Since there are two obvious peaks, the histogram was split into the features that were intrusions and the features that were extrusions.

As seen in Figure 43, there are two obvious clumps of data. To try and observe two different phenomena, Figure 44 shows two distributions, one for the intrusion features and one for extrusions. The features included in the “intrusion” graph are the rectangular and circular holes side lengths/diameters in the coupon, respectively. The features plotted in the “extrusion” histogram include the side lengths of the rectangular boss and overall coupon length, as well as the diameter of the circular extrusion.



(a) (b)

Figure 44. (a) The expansion of the circular/rectangular holes (the intrusion features). In general, the average growth is close to 0.36 mm. (b) The expansion of the circular/rectangular extrusions and overall coupon length. In general, the average growth is close to 0.07 mm.

As seen in the distributions of Figure 44, the intrusions had a much larger growth than the extrusions. One plausible explanation for this phenomenon is for the circular/rectangular holes, in order for the resin to expand in the furnace, it only needs to strain the small amount of material that filled the hole. For an extrusion to expand in the oven, it has to push all the material between the resin and the flask wall, and thus has much more resistance and won’t expand as much.

Along with plotting the shrinkage rates, using the data from the twelve coupons, an average growth with an uncertainty was determined. This was calculated using the student-t distributions for a small sample size (n = 12). Below is a summary of the data from each feature:

- Overall coupon side length expansion: 0.33 ± 0.11 mm or 1.11 ± 0.36 %
- Square extrusion side length expansion: 0.05 ± 0.05 mm or 0.48 ± 0.53 %
- Circular extrusion diameter expansion: 0.07 ± 0.07 mm or 0.73 ± 0.67 %
- Square hole side length expansion: 0.33 ± 0.04 mm or 3.31 ± 0.41 %
- Circular hole diameter expansion: 0.35 ± 0.03 mm or 3.48 ± 0.32 %

In general, the models grew in the furnace, but it can be seen that the intrusions changed length the most. The overall coupon length also grew a decent amount, but this may be because the side length was 30 mm long, versus all other features were only 10 mm, and thus could thermally grow more. The two extrusions had the smallest growth rates, likely because in order for the extrusions to expand, they must compress the entire flask of hardened plaster. For a more accurate representation of the data, a larger sample size would assist in preventing a skew in the data, though there was not enough opportunity to cast more coupons.

9.0 PROJECT MANAGEMENT

The senior design project consisted of three main sections – designing/planning, testing, and implementing – which were split between three quarters. A brief description of the planned timeline for the project will be given and a discussion at the end of this section will overview what worked well or poorly throughout the process.

9.1 PLANNED PROJECT MANAGEMENT

The three main sections mentioned above correlated well with the three quarters of senior project. The first quarter planned to revolve around preliminary research, a scope of work, ideation generation, and controlled ideation convergence. Preparation for testing during the second quarter would involve formulating an approved test plan, including a list of measurable quantities on the models, as seen in Appendices O.1 and O.2. During the second quarter, with the feedback gained from the sponsor on the concept models, manufacturing was planned to start. The manufacturing phase would specifically focus on printing and casting several test coupons and assessing their successes/failures after the process. This would include the measurement of part features, including thicknesses, radii, depths, and others described in Section 4.6. Lastly, the plan for the final quarter was to get students into the lab and test out the process. Once feedback would be received from the students, the curriculum package would go through the final iteration and be given to the instructors of IME 470. Additionally, throughout the second/third quarters, example parts for students would be created and casted.

9.2 PROJECT DELIVERABLES

To organize the efforts needed over the course of the project, a Gantt chart has been provided in Appendix R.1. Table 10 outlines the major milestones for the project, as mentioned in the Gantt chart.

Table 10. Major milestones for the entirety of the project.

Date	Deliverable
05/27/2021	PDR Presentation
10/15/2021	Manufacturing Plan/Final CAD
10/18/2021	Begin testing models
10/28/2021	CDR Presentation
11/19/2021	Finalize analysis of testing
01/28/2021	Perform student batch testing
02/14/2021	Finalize lab documentation
03/11/2022	FDR Due/Curriculum package sent

9.3 PROJECT MANAGEMENT OUTCOME

Overall, the time management of this project turned out very well. Potentially because there are only two members on the team, it was very easy to get things done in a timely fashion. The largest issue was communication between the team and lab instructors, because in order to cast the parts, the instructors had to have the furnace and molten metal prepared. Usually, the team could join into one of the IME 141 sections to cast after they finished their parts, but communicating about an agreed-upon time was certainly the most difficult portion of the project. Otherwise, the planned schedule complimented the pace of the project and ensured timely delivery of all sections of the senior project.

10.0 CONCLUSION

The proposed project of a resin-based 3D print investment casting analysis from Dr. Wang at Cal Poly is presented within this document with the necessary scope of work, design specifications, customer requirements, project management, chosen final design, manufacturing, and testing results. The main goals of the project was to analyze the successes and failures of different 3D print conditions and models in order to create a library of successful models to supplement the IME 470 foundry class at Cal Poly. A full curriculum package has been one of the major deliverables, which includes an instruction manual and video tutorial. As the project has since come to a successful completion, the project as a whole will be described here with all successes, failures, and advice for future work.

First, the project was very successful at finding easy-to-cast models that act as either student-ready models, example parts to show the class, or test coupons to learn about the technology. For student models, the dice and ring models were the chosen designs for their manufacturability, wow factors, and customizability. These models remained constant throughout the senior project, and with student testing, these were very successful at showing the students how to explore the manufacturing technology. There were several modifications made to these files, including different ring sizes, sprue attachment points, and overall aesthetics, however the general goal was still achieved. With the responses given by the test subjects, the two models provided a great variety and ability to learn about new manufacturing capabilities. Overall, the student models were a great success that will be implemented into IME 470.

The example models originally included an action figure of Kirby and wireframe-patterned skull to demonstrate new manufacturing capabilities to show the class. These models were the ones that changed the most throughout the senior project. First, instead of simply casting a Kirby action figure, the team decided to make a die-cast mold with a cavity in the shape of Kirby. With this slight change, students can observe the process of taking a resin-3D printed part and casting it, while also learning about die casting technology. Once this mold was prepared, students could fill cavity with molten hot glue or wax to produce a Kirby-shaped action figure out of plastic. This also demonstrates the repeatability of die casting, as hundreds of Kirby figurines can be made from just one die cast mold in this mass-production manufacturing process. The other major change to the example part models was the deletion of the wireframe skull. Once the team began casting and improving the gating systems, they soon realized that it would be very tricky to get metal flow into the entire model. With limited lab access, there was little-to-no time to iterate on gating systems to attempt the full model. Instead, the team asked the student volunteers what some interesting example models would be, and instead of the skull, an Ironman bust, chess piece, and a set of interlocking rings were cast successfully, as they required simply gating systems.

For testing the limitations of the manufacturing process, three test coupons were modeled with several features to measure thicknesses, radii, lengths, surface finish, protrusions, fillets, and depths. The first two, as originally planned, had over 50 features that could be measured. Once the team started to produce several of these coupons, it was quickly realized that it would be too difficult to produce a statistical analysis on each feature, as each piece took nearly 45 minutes to measure. Another concern with these coupons is due to the sheer number of features, there was concern that dependency between features would cause different results. For that reason, a much simpler coupon was made that had a limited number of features to interact between each other. This allowed the first two coupons to be purely for limitations (such as the smallest hold that came out properly, or the smallest text that was visible), while the third coupon could be mass produced and analyzed for repeatability and dimensional accuracy.

Through testing the first two coupons, it was seen that any hole (either square or circular) under a 1mm diameter/side length was much less likely to fill than larger sizes. Additionally, hemispherical bumps with a diameter of 0.5mm had a lower chance of being cast properly. Otherwise, all other features consistently cast properly and with a great surface finish. To summarize some of the initial concerns: fillets could be made down to a radius of 1mm, chamfers had edge lengths of 1mm, thicknesses came out properly at 1mm, and all angles of features work (assuming the gating allows metal to flow). Since the coupons were printed on the resin printers, the surface finish was qualitatively much better than any other 3D printing material/process. When testing the third (simpler) coupon, the features were measured for repeatability and dimensional accuracy in order to determine an average growth/shrinkage rate. For intrusion features, the average growth (averaged between the circular and rectangular holes) hovered around 3.4%, whereas for extrusions, the average growth was 0.77% of the original CAD dimension. These values will be useful in student projects where the final dimensions is critical, as students can scale their CAD models to attempt at accounting for the expected growth during burnout.

With regard to the curriculum package delivered to the IME 470 instructors, the contents included a lab manual, video tutorial (links to YouTube videos), a pre-lab quiz, safety data sheet for the Castable 2 resin, detailed list of purchased materials that would be required to run the lab, and the .stl model files. Additionally, a training quiz has been provided to post on the CENG Safety Technician Information Canvas page to certify individuals for 3D printer use once they pass a quick quiz on the safety and upkeep of the machines. These are all the materials necessary for an instructor to post to the IME 470 Canvas page and allow students to customize and manufacture their own dice or rings. This material was tested on 5 mechanical engineering students to gain feedback, which was useful for improving the materials before sending to professors.

In summary, this senior project, consisting of Isaiah Hong and Matthew Frost, and sponsored by Dr. Wang from the IME Department at Cal Poly was a huge success for learning about the manufacturing technology and creating course curriculum to supplement the IME 470 class. As far as learning about the limitations, several test coupons were manufactured to learn about the minimum radii/thicknesses that are achievable as well as perform repeatability and expansion rate analysis on a small sample size. For the curriculum-side of the senior project, through essential student testing, feedback was used to improve upon and deliver the course materials to the appropriate instructors. It will be rewarding if this is a lab implemented to the IME 470/471 course, as it’s currently intended to do.

While there weren’t many, there are a few aspects of the project that weren’t achieved. The most prominent is the wireframe skull that wasn’t cast. While this is likely a part that could be manufacturing using this process, there simply wasn’t enough access to the lab to iterate gating structures until it came out properly. Another shortcoming of the project, though unavoidable due to budget and accessible materials, is the equipment used. SprintRay has stopped producing the model of MoonRay printers that were used (thus explaining why they were donated), and also have moved to another Castable resin. Additionally, their software (RayWare) has a new software update coming out in April 2022. While updates on software and equipment is unavoidable, the team hopes that the curriculum package is still applicable with the new technology. Hopefully, the new Castable resin performs the same as the Castable 2 that the team used, and that the new RayWare update still functions similarly such that the video tutorials of the software still apply. If not, it will be up to the instructors/technicians to learn the new software. If the 3D printers break, hopefully it’s not too difficult to replace components, get technical support from SprintRay, or purchase a new one. While these are out of the control of the senior project, it may limit the longevity of the lab in IME 470 if the equipment becomes unusable.

If the team were to do the project over again, there wouldn’t be too much that would need changing. The only aspects that would’ve been nice to know at the start is the limited lab access, as the models could’ve been combined onto a single sprue to get more out of each flask. Additionally, starting the Fall quarter with the simplified test coupon would’ve been helpful so that a larger sample size could’ve accumulated over the quarter for statistical analysis. Instead of spending time measuring and producing Test Coupons A/B, a few of them could've been manufactured and then more time spent on casting Test Coupon C. However, this didn't affect the outcome of the project drastically, and thus is more of a want than a need.

If this project were to continue, either as a senior project or different application, there are a few recommendations from the team to try next. First, it would be interesting for the IME 470 course to have more available models to customize; using a few of the ideas generated throughout the ideation phase of this project would allow for a larger library of models for the students. This would increase diversity and interest levels by the students if they had a larger library to choose from. Secondly, getting a larger budget to pay for a vacuum pump during the investment stage would improve reliability during the investment process (not just specifically for this project, but any investment process in the foundry lab). If the budget can't be expanded, supplemental funding sources (MESFAC, CP Connect, etc.) could be pursued to gain funding for such items. Another recommendation is to try curing the 3D printed parts in a heated vacuum oven (which the foundry lab doesn't own currently, and thus more funding would be needed). In the background research section, it had been read that using a heated vacuum chamber produced finer details when compared to a UV cure, and thus might be an interesting project to look into. Otherwise, this senior project seemed to wholly cover the purpose and goal of the project, and the suggestions are only recommendations if further funding or time were to be put into the research.

Overall, the team would like to thank our sponsor, Dr. Wang, senior project coach, John Fabijanic, as well as the casting instructors, Dr. Carter, Bryan Lutz, and Dr. Coch, for assisting us through the entire process. Without your support, this project may have not finished as well as it did.

11.0 APPENDICES

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12.0 REFERENCES

[1] "Investment Casting Patterns-ODM | 3D Systems." https://au.3dsystems.com/on-demand-manufacturing/investment-casting-patterns (accessed Apr. 25, 2021).

[2] "SLA vs FDM/ Resin vs Filament 3D Printer: The Differences | All3DP." https://all3dp.com/1/sla-vs-fdm-resin-vs-filament-3d-printer-the-differences/ (accessed May 19, 2021).

[3] S. Pattnaik, D. B. Karunakar, and P. K. Jha, "Developments in investment casting process - A review," *Journal of Materials Processing Technology*, vol. 212, no. 11. Elsevier, pp. 2332–2348, Nov. 01, 2012, doi: 10.1016/j.jmatprotec.2012.06.003.

[4] "FAQs – Jinxbot 3D Printing." https://jinxbot.com/faqs/ (accessed Apr. 25, 2021).

[5] "Advantages of Centrifugal Casting | Accurate Specialties Inc." https://www.accuratespecialties.com/advantages-of-centrifugal-casting/ (accessed May 19, 2021).

[6] "A new method for preparing 3D acrylic photopolymer patterns for investment casting - Jewelry Technology Forum." http://jtf.it/en-us/memories/all-memories/13-2020/41-a-new-method-for-preparing-3d-acrylic-photopolymer-patterns-for-investment-casting (accessed Apr. 25, 2021).

[7] M. Mukhtarkhanov, A. Perveen, and D. Talamona, "Application of stereolithography based 3D printing technology in investment casting," *Micromachines*, vol. 11, no. 10. MDPI AG, Oct. 01, 2020, doi: 10.3390/mi11100946.

[8] J. Wang, S. R. Sama, P. C. Lynch, and G. Manogharan, "Design and topology optimization of 3D-printed wax patterns for rapid investment casting," in *Procedia Manufacturing*, Jan. 2019, vol. 34, pp. 683–694, doi: 10.1016/j.promfg.2019.06.224.

[9] G. S. Park, S. K. Kim, S. J. Heo, J. Y. Koak, and D. G. Seo, "Effects of printing parameters on the fit of implant-supported 3D printing resin prosthetics," *Materials (Basel).*, vol. 12, no. 16, Aug. 2019, doi: 10.3390/ma12162533.

[10] E. Bassoli, A. Gatto, L. Iuliano, and M. G. Violante, "3D printing technique applied to rapid casting," *Rapid Prototyp. J.*, vol. 13, no. 3, pp. 148–155, 2007, doi: 10.1108/13552540710750898.

[11] O. M. F. Marwah, S. Sharif, M. A. Zainol, M. Ibrahim, and E. J. Mohamad, "3D printer patterns evaluation for direct investment casting," in *Applied Mechanics and Materials*, 2014, vol. 465–466, pp. 1400–1403, doi: 10.4028/www.scientific.net/AMM.465-466.1400.

[12] S. Körber, R. Völkl, and U. Glatzel, "3D printed polymer positive models for the investment casting of extremely thin-walled single crystals," *J. Mater. Process. Technol.*, vol. 293, p. 117095, Jul. 2021, doi: 10.1016/j.jmatprotec.2021.117095.

[13] Y. Luo, G. Le Fer, D. Dean, and M. L. Becker, "3D Printing of Poly(propylene fumarate) Oligomers: Evaluation of Resin Viscosity, Printing Characteristics and Mechanical Properties," *Biomacromolecules*, vol. 20, no. 4, pp. 1699–1708, Apr. 2019, doi: 10.1021/acs.biomac.9b00076.

[14] "Introduction to Casting for 3D Printed Jewelry Patterns."

[15] "Request a Castable Sample › Learn About Casting and Jewelry Production from Formlabs › Recommended Burnout Process and Casting Guide," 2018.

[16] "SLA 3D Printing: The Ultimate Guide | All3DP." https://all3dp.com/1/sla-3d-printing-guide/ (accessed Apr. 25, 2021).

[17] "General Guidelines for Casting Jewelry General Guidelines for Casting Jewelry Using Visijet FTX Green & FTX Cast from the ProJet 1200."

[18] T. K. Dougherty *et al.*, "RES IN COMPOST ON AND PROCESS FOR INVESTMENT CASTING USING," 1993.

[19] "Photocuring wax material used for 3D printing," Jun. 2014.

[20] E. J. Murphy, D. Plaines, R. E. Ansel, H. Estates, and J. J. Krajewski, "INVESTMENT CASTING UTILIZING PATTERNS PRODUCED BY STEREOLTHOGRAPHY," 1988.

[21] "US Patent for Photopolymer composition for 3D printing Patent (Patent # 9,902,860 issued February 27, 2018) - Justia Patents Search." https://patents.justia.com/patent/9902860 (accessed Apr. 25, 2021).

[22] Liu, "Application Data (60) Provisional application No. 62/027," 2014.

[23] "Kirby - Easy to Print by ChaosCoreTech - Thingiverse." https://www.thingiverse.com/thing:1913526 (accessed May 18, 2021).

[24] "Wireframe Skull Pencil Holder (For The Love of Dog) by philnelson - Thingiverse." https://www.thingiverse.com/thing:1388237 (accessed May 19, 2021).

[25] "3D printing glass and bronze: Lost-PLA casting." https://mtyka.github.io/art/2016/12/11/lostpla-casting-glass.html (accessed Oct. 18, 2021).

[26] "Castable 2 Investment and Burnout Instructions – SprintRay Customer Support." https://support.sprintray.com/hc/en-us/articles/360035257594 (accessed Oct. 18, 2021).

[27] "Cal Poly SLO Investment Casting Key Chain Process - YouTube." https://www.youtube.com/watch?v=8_MHbUnl2go (accessed Oct. 27, 2021).

[28] "WAX Castable 3D Printer Resin for Jewelry - Burnout Casting Like Wax – powerresins." https://powerresins.com/products/powercast-wax-castable-resin?variant=7077922504758&currency=USD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&utm_campaign=gs-2020-04-19&utm_source=google&utm_medium=smart_campaign&gclid=Cj0KCQjw--GFBhDeARIsACH_kdZwFcdl27WJhPNGnkSB1fvK9bdivJuduNE266Pbwdaf7W91SrZa0YAaAnYAEALw_wcB (accessed Jun. 03, 2021).

[29] "PhotoCentric 405nm UV Laser Castable Resin Pink - 1kg: Buy or Lease at Top3DShop." https://top3dshop.com/product/photocentric-405nm-uv-laser-castable-resin-pink-1kg (accessed Jun. 03, 2021).

[30] "Special UV Resin for Casting – ANYCUBIC 3D Printing." https://www.anycubic.com/collections/uv-resin/products/dental-castable-green-uv-resin-for-photon-series?sscid=61k5_3lo0n& (accessed Jun. 03, 2021).

[31] "eSUN Castable Resin for Dental, UV 405nm 0.5KG - Green – EPAX 3D." https://epax3d.com/products/esun-castable-resin-for-dental-uv-405nm-500ml (accessed Jun. 03, 2021).

APPENDIX A.1

BILL OF MATERIALS

Table 11. Bill of Materials needed for performing the research.

Description	Link	Quantity	Purchased?	Price	Total Cost
MoonRay 3D Resin Printers	SprintRay	1	N	$3,000	$0
SprintRay Curing Chamber	SprintRay	1	N	$990	$0
Silicon Workmats (15.7" x 11.8")	Amazon	1	Y	$8	$8
Filament One Plastic Scrapers	Amazon	1	Y	$9	$9
R&R Ultra-Vest Investment	RioGrande	1	Y	$42	$42
SprintRay Castable 2 Resin	SprintRay	7	N	$205	$0
Aluminum 356	N/A	1	N	$50	$0
Rubber Gloves	Amazon	1	N	$17	$0
Protective Goggles	Amazon	2	Y	$8	$16
Wash Station Container	Amazon	1	Y	$18	$18
Isopropyl Alcohol	Amazon	1	Y	$37	$37
				TOTAL	**$130**

As shown in Table 11, certain items were initially put onto the Bill of Materials but were currently deemed unnecessary or were already available in the lab. They were kept on the bill of materials in case the lab doesn't have adequate equipment or if plans change once manufacturing begins. Gratefully, SprintRay has donated a significant portion to the IME department, so the senior project budget is reasonable. If, in the future, more supplies are needed, links to the purchasing websites are available in Table 11. Most of these are already websites that the IME 141 professors use for the course supplies.

The budget shown in Table 11 summarized all the supplies for the prototype and final product. These supplies should last the team throughout the rest of senior design and have leftover materials to kickstart the lab.

Out of caution, a few resin suppliers have been identified in case the MoonRay printers won't be used in the future. In that case, the Ember printers will be used, which has the flexibility to modify the default settings. Because of this modularity, several different resin types could be experimented if desired. Below is a short list of potential other resin sources.

Company: Power Resins, Product: "WAX Castable Resin" [28]: Link here
Company: Photocentric, Product: "Phrozen Wax Blue Castable Resin" [29]: Link here
Company: Any Cubic, Product: "Special UV Resin for Casting" [30]: Link here
Company: EPAX 3D, Product: "EPAX Castable Resin for Jewelry" [31]: Link here

Appendix B.1

QFD House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

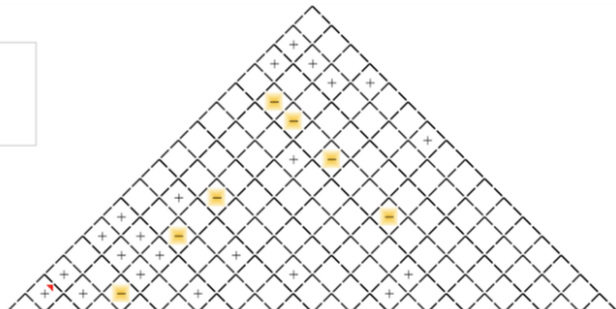
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Resin-Based 3D Print Investment Casting

Revision Date: 05/11/2021



Row #	Weight Chart	Relative Weight	Sponsor	Instructors/Professors	Students		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Library of Successful Models	Library of student-ready models	Process Satisfaction Survey	Time to clean/post-process	Number of customizable aspects	Customizing satisfaction survey (students)	Number of stations	Curriculum satisfaction survey	Floorspace occupied	Resin material cost	Metal material cost	Volume	Video time	Quantifiable features	Reliability	Time of respective process	Current IME 141 Investment Casting Lab	Comp. #1: *Journal Article #2 (Video)*	Comp. #2: VOG Youtube Lost Wax With Resin	Comp. #3: *Formlabs Jewelry Manual*	Comp. #4: *3DSystems Jewelry Manual*	Row #
	WHO: Customers							Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Curr. Products					
								Direction of Improvement	▲	▲	▲	▼	◇	▲	▼	▲	◇	▼	▼	◇	▼	▲	▲	▼						
								Lab																						
1		9%	3	8	6		9	Easily printable parts	○	●	●	○			○								○	●	5	4	3	2	2	1
2		10%	3	5	9		9	Customizable features					●	●											3	5	5	5	2	2
3		10%	4	8	7		9	Easily castable part	▽		●	○			○								○	●	0	4	3	2	3	3
4		13%	7	9	8		9	Detailed Lab Manual								●					▽				2	2	0	5	1	4
5		11%	7	10	5		9	Detailed Lab Setup								●	○								4	1	2	5	1	5
6		8%	8	9	0		9	Cost Analysis										●	●	○					5	0	0	0	0	6
								Lecture																						
7		9%	3	7	7		9	Example parts for display	●																3	2	2	5	1	7
8		12%	5	9	8		9	Video instructions								●					●				2	0	5	0	0	8
								Research																						
9		4%	8	0	0			Detailed test parts	○				○							▽		●			0	3	5	5	2	9
10		7%	10	3	1		9	Best/optimal print settings	●		○	●		○								○	○	○	0	4	2	3	1	10
11		7%	10	3	1		9	Best/optimal casting procedure	●		○	●			▽		▽					○	○	○	5	4	4	5	1	11

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	5 models	3 models	75% satisfaction	15 minutes	1 per model	75% satisfaction	4 stations	75% satisfaction	9 ft^2	\$2/student	\$2/student	1.0 in^3	15 minutes	5 features	75% reliable	3 hours each
	Max Relationship	9	9	9	9	9	9	3	9	3	9	9	3	9	9	3	9
	Technical Importance Rating	257.5	81.65	215.2	183	98.05	107.1	64.78	323.3	40.95	73.32	73.32	28.36	119	77	99.54	215.2
	Relative Weight	13%	4%	10%	9%	5%	5%	3%	16%	2%	4%	4%	1%	6%	4%	5%	10%
Curr. Products	Current IME 141 Investment Casting Lab	1	2	3	2	4	3	4	2	3	2	5	5	0	1	5	4
	Comp. #1: Journal Article #2 (Video)	1	0	1	3	5	2	1	0	1	2	2	4	0	3	3	4
	Comp. #2: VOG Youtube Lost Wax With Resin	1	1	0	2	3	0	1	0	1	3	3	3	4	2	3	4
	Comp. #3: Formlabs Jewelry Manual	3	3	1	3	3	0	1	0	1	3	2	4	0	2	4	2
	Comp. #4: 3DSystems Jewelry Manual	3	2	0	2	3	0	1	0	1	3	3	3	0	2	4	2
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

APPENDIX C.1

SATISFACTION SURVEY – MANUFACTURING PROCESS

PROCESS SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME ________________________________ **DATE** ____________

MAJOR _______________________________ **GRADE** ____________

GENERAL QUESTIONS:

Y N I'VE TAKEN THE IME 141 COURSE PRIOR TO TODAY
Y N I'VE KNOW HOW TO USE CAD SOFTWARE SYSTEMS
Y N I'VE CAST METAL BEFORE (OUTSIDE IME 141)
Y N I'VE USED A 3D PRINTER BEFORE
Y N I'VE USED A RESIN 3D PRINTER BEFORE

PRINTING PROCESS (1 FOR EASY, 5 FOR HARD):

1 2 3 4 5 DIFFICULY TO SET PRINT PARAMETERS OUTLINED IN MANUAL
1 2 3 4 5 DIFFICULTY TO OPERATE THE ISOPROPYL CLEANING BATH
1 2 3 4 5 DIFFICULTY TO SETUP CURING SETTINGS
1 2 3 4 5 DIFFICULTY UNDERSTANDING SAFETY PRECAUTIONS
____ MINUTES TIME SPEND CLEANING PART

COMMENTS FOR PRINTING PROCESS:

CASTING PROCESS (1 FOR BAD/HARD, 5 FOR GOOD/EASY):

1 2 3 4 5 DIFFICULY OF MIXING THE INVESTMENT CASTING PLASTER
1 2 3 4 5 DIFFICULTY OF POURING INVESTMENT INTO FLASK
1 2 3 4 5 DIFFICULTY OF INSERTING 3D PRINTED PATTERN INTO FLASK
1 2 3 4 5 DIFFICULTY SETTING BURNOUT CYCLE (WITH ASSISTANCE)
1 2 3 4 5 DIFFICULTY CASTING PART
1 2 3 4 5 DIFFICULTY REMOVING GATING SYSTEM
____ MINUTES TIME SPEND CLEANING PART

COMMENTS FOR CASTING PROCESS:

OVERALL SATISFACTION IN LAB PROCESS: ______%

APPENDIX C.2

SATISFACTION SURVEY – CUSTOMIZATION PROCESS

MODEL CUSTOMIZATION SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME ________________________________ **DATE** ____________

MAJOR _______________________________ **GRADE** ____________

GENERAL QUESTIONS:

Y N I'VE KNOW HOW TO USE CAD SOFTWARE SYSTEMS
Y N I'VE TAKEN A CAD MODELLING CLASS AT CAL POLY
Y N I'M CONFIDENT IN EXTRUDING/SKETCHING/TEXT

SOFTWARE PROCESS (1 FOR EASY, 5 FOR HARD):

1 2 3 4 5 DIFFICULTY FINDING THE SOFTWARE/STARTING IT UP
1 2 3 4 5 DIFFICULTY LOADING MODEL INTO PROGRAM
1 2 3 4 5 DIFFICULTY OPERATING THE CAD SOFTWARE START UP
1 2 3 4 5 DIFFICULTY SKETCHING
1 2 3 4 5 DIFFICULTY EXTRUDING
1 2 3 4 5 DIFFICULTY PANNING/ROTATING MODEL
1 2 3 4 5 DIFFICULTY INSERTING TEXT
1 2 3 4 5 DIFFICULTY COMING UP WITH A DESIGN
1 2 3 4 5 DIFFICULTY EXPORTING MODEL ONCE FINISHED
1 2 3 4 5 DIFFICULTY CUSTOMIZING MODEL (OVERALL)
____ MINUTES TIME SPEND ADDING CUSTOMIZATION TO MODEL

COMMENTS FOR CUSTOMIZATION PROCESS:

OVERALL CUSTOMIZATION SATISFACTION: ______%

APPENDIX C.3

SATISFACTION SURVEY – CURRICULUM PACKAGE

CURRICULUM SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME ________________________________ **DATE** ____________

MAJOR ________________________________ **GRADE** ____________

GENERAL QUESTIONS:

Y	N	I'VE ALREADY TAKEN THE IME 141 COURSE
Y	N	I'VE TAKEN OTHER LAB COURSES WITH LAB MANUALS
Y	N	I'VE TAKEN OTHER LAB COURSES WITH VIDEO TUTORIALS

CURRICULUM QUESTIONNAIRE (1 FOR BAD, 5 FOR GOOD):

VIDEO	MANUAL	
1 2 3 4 5	1 2 3 4 5	PROVIDED NECESSARY BACKGROUND INFO
1 2 3 4 5	1 2 3 4 5	DETAILED PROCESS OF MODEL CUSTOMIZATION
1 2 3 4 5	1 2 3 4 5	DETAILED PROCESS OF SENDING MODEL TO PRINTER
1 2 3 4 5	1 2 3 4 5	DETAILED CLEANING MODEL POST-PRINT
1 2 3 4 5	1 2 3 4 5	DETAILED CURING METHODOLOGY AND SPECS
1 2 3 4 5	1 2 3 4 5	DOCUMENTATION OF INVESTMENT PLASTER MIXING
1 2 3 4 5	1 2 3 4 5	BURNOUT SETTINGS DOCUMENTED AND EXPLAINED
1 2 3 4 5	1 2 3 4 5	POST-PROCESSING METHODS DESCRIBED
1 2 3 4 5	1 2 3 4 5	CONCISE AND GRAMMATICALLY CORRECT
1 2 3 4 5	1 2 3 4 5	VISUALS ARE ADEQUATE
1 2 3 4 5	1 2 3 4 5	SAFETY MEASURES WERE OUTLINED
____________	____________	PREFERABLE MODE OF LEARNING (CHECK ONE)

GENERAL QUESTIONS:

Y	N	THE CURRICULUM WAS EDUCATIONALLY BENEFICIAL
Y	N	THE CURRICULUM WOULD BE A GOOD ADDITION TO IME 141
Y	N	THE CURRICULUM FACILITATES STUDENT LEARNING
Y	N	THE CURRICULUM WAS BORING
Y	N	THE CURRICULUM WAS EASY TO FOLLOW

COMMENTS FOR CURRICULUM:

OVERALL CURRICULUM SATISFACTION: ______%

APPENDIX D.1

IDEATION LIST

IDEAS FOR STUDENT MODELS (NO PARTICULAR ORDER)

- Pendants
- Jewelry
  - Necklace
  - Signet rings, championship rings, band rings, class rings
- Toys
- Chain links
- Dragon
- Pokémon
- Modular parts
- Puzzles
- Action figures
- Stuff that bolts together
- Boxes/key plate/earring bowl
- Phone stands
- Lace medallions
- Rocketship
- Planes
- Pattern
  - Mesh, Vornoi
- Interactive parts
- Bag tag
- Button
- Aglets
- USB holder
- USB body
- Key hanger
- Carabiner body
- Coin
- Desk toy
- Fidget spinner
- Dice
- Rings
- Keychains
- Earrings (without the wires)
- Necklace things
- Cartoon characters/little figurines
- Fun animals
  - Octopus, cat face, dog face, manta ray, elephant, fish, etc.
- Shot glass with engraving (maybe check on this for health reasons)
- Coffee coasters
- Guitar picks
- Something to hang in a car rear-view mirror
- Name plate
- Double threaded bolt
- Interlocking cubes
- Vehicles
  - Cars, boats, planes, kayak, etc.
- Groot, Baby Yoda
- Rhinestones
- Fun injection mold
- Guitar slides/clamp
- 2D keychain (animals, vehicles, names, etc.)
- Pins
- Desk fidget
- Architectural models
-

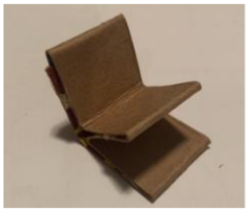
IDEAS FOR TEST COUPONS (NO PARTICULAR ORDER)

- Labelled by features
  - Protrusions
  - Thickness
  - Layer height
  - Details
  - Print angle
  - Support density
  - Speed
  - Size to depth ratio
- Tests of varying sizes
- Start with basic coupon
  - Move to more complex model exhibiting features
- Sprue arrangement
- Gating arrangement
- Movie ticket coupon
- Sphere with embosses
- Expansion ratios
- Something to work with general thicknesses (tapers, steps...)
- Test cube (measurement datums)

APPENDIX E.1

CONCEPT MODELS

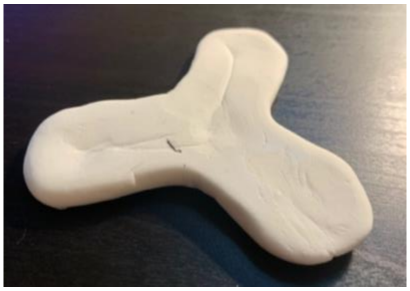
Table 12. Ideation models for the test coupons with brief descriptions.

	Ideation Model	Discussion
Angle Tests		This is a model designed to test different print angles that can be achieved with the resin. Although useful for print testing the high cost of the resin and low usefulness of this concept for casting purposes results in a waste of material. Maybe adding some surface features would allow for more use out of it.
Ticket Coupon		This seems to be by far the best style of coupon. It contains step, text, cut, extrude, and texture elements, all of which are useful for both print and cast testing. Adding 3D elements may make it even more useful since the thin profile can only provide a limited range of detail and parameters.
Step Coupon		This model all though simple is great for finding out the detail achievable by the casting process. Since the printer is already using a layering technique, using a step coupon could help find the blurred line between how thin is too thin to be able to define a feature in a cast. Adding textures and specified dimensions could help further this coupon's usefulness.
Geometry Coupon		Although simple, this coupon provides very important information concisely. Holes and extrudes of defined dimensions can be used to determine shrinkage during the process and internal features could be compared against parts meant to fit in them. Providing dimensions to the beveled corners could also help add definitive features.
Test Cube	 	The test cube is very useful for both print and cast testing. Varying orientations and print settings can greatly affect the feature clarity within the part and therefore makes it a good fit for this project. Adding edge chamfers or bevels of specified dimensions could help provide more information on the processes.
Lattice Coupon		This coupon is useful for providing not only an interesting looking piece but a look into the limitations of complexity. Pattern thickness and gaps are all useful parameters defined by this model. Depending on the results this model could make a great "pass around" for the lab.

Appendix E.2

Concept Models

Table 13. Ideation models for the student models with brief descriptions.

	Model	Description
Dog		The dog was created to show a detailed animal shape, a figure that students could customize or change into any animal they want. We learned that $1.0in^3$ of material is a lot! Maybe we should trim that down, or at least not be worried about exceeding the volume limit.
Octopus		The octopus is similar to the dog, but this was done with a .75" cube worth of material. This still is very large for a keychain, so it can be trimmed down. A hook would be nice to allow for it to attach to a backpack or keychain.
Ring		The ring was a basic test to see how much material we would need. This model only took a .25" cube's worth of material, about $1/16^{th}$ the original goal of $1.0in^3$ of material, which is good from a cost standpoint. The actual model would look much better than this, with a customizable face.
Dice		The dice is a classically made part, so we figured we should make it. The clay didn't hold the dots very well, but the real device will have all the dots with the "one" side customizable by the students. This is only about ¼ the original $1.0in^3$ of material.
Fidget Spinner		The fidget spinner shape was created, but it was determined this might be out of the scope of the project. This is because it would require bearings or other methods to spin it, which might not be in the budget.

APPENDIX F.1

PUGH MATRICES

STUDENT MODEL PUGH MATRICES:

Table 14. Pugh matrix for the student models with the wax-injected keychain as the datum.

	Potential Concepts													
Categories	Current Wax injection mold	Necklace Pendant	Rings	2D keychain with engraving	Small bowl/ key plate	Dice	Phone Stand	Coin	Pins	USB Stand	Mini models (cartoon/houses)	Earrings	Guitar slides	Novelty guitar picks
Complexity to print		S	S	S	S	S	-	S	-	S	S	S	S	S
Complexity to cast	D	+	-	S	+	+	-	S	-	S	S	+	+	S
Cost (based on volume)	A	+	+	S	-	+	-	+	+	-	S	+	S	+
Customizable aspects	T	S	S	S	S	S	-	S	S	-	-	S	S	S
Post processing (drill holes, etc.)	U	S	-	S	+	+	+	+	S	+	S	S	-	S
Fosters excitement, "wow" factor	M	S	+	S	-	+	+	S	S	-	S	S	-	S
Aesthetics		+	+	S	S	+	+	S	S	-	-	+	-	+
	SUM:	**3**	**1**	**0**	**0**	**5**	**-1**	**2**	**-1**	**-3**	**-2**	**3**	**-2**	**2**

Table 15. Pugh matrix for the student models with the dice as the datum.

	Potential Concepts												
Categories	Dice	Necklace Pendant	Rings	2D keychain with engraving	Small bowl/ key plate	Phone Stand	Coin	Pins	USB Stand	Mini models (cartoon/houses)	Earrings	Guitar slides	Novelty guitar picks
Complexity to print		+	-	S	+	-	S	+	S	S	+	S	S
Complexity to cast	D	-	-	S	S	-	S	-	S	S	-	-	-
Cost (based on volume)	A	+	+	S	-	-	S	+	S	S	+	-	+
Customizable aspects	T	S	S	S	S	-	S	S	-	-	S	+	+
Post processing (drill holes, etc.)	U	-	-	-	S	S	S	-	S	S	-	-	-
Fosters excitement, "wow" factor	M	S	S	-	-	-	S	S	-	S	S	-	S
Aesthetics		S	S	-	S	-	S	S	-	S	S	S	S
	SUM:	**0**	**-2**	**-3**	**-1**	**-6**	**0**	**0**	**-3**	**-1**	**0**	**-3**	**0**

APPENDIX F.2

PUGH MATRICES

EXAMPLE MODEL PUGH MATRICES:

Table 16. Pugh matrix for the example parts with the wax-injected keychain as the datum.

	Potential Concepts								
	Current Wax injection mold	Chain links	Action Figures	Lace Medallians	Patterns (mesh, Vornoi)	Shot Glass	Double Threaded Bolt	Interlocking Cubes	Rhinestones
Categories									
Complexity to print		+	+	+	+	+	+	+	+
Complexity to cast		+	+	+	+	+	+	+	+
Cost (based on volume)	D	S	+	+	S	-	S	S	+
Customizable aspects	A	-	+	+	+	+	-	-	-
Post processing (drill holes, etc.)	T	+	S	S	-	+	-	-	S
Fosters excitement, "wow" factor	U	+	+	S	+	+	+	+	+
Aesthetics	M	-	S	S	+	S	+	+	+
Uniqueness due to new capabilities		+	+	+	+	+	+	+	+
Difficulty of part		-	+	+	-	-	-	-	S
	SUM:	**2**	**7**	**6**	**4**	**4**	**2**	**2**	**5**

Table 17. Pugh matrix for the example parts with the action figure as the datum.

	Potential Concepts							
	Action Figures	Chain links	Lace Medallians	Patterns (mesh, Vornoi)	Shot Glass	Double Threaded Bolt	Interlocking Cubes	Rhinestones
Categories								
Complexity to print		+	+	-	+	-	+	S
Complexity to cast		-	S	-	S	-	-	S
Cost (based on volume)	D	S	+	S	S	S	S	+
Customizable aspects	A	-	+	S	+	-	S	S
Post processing (drill holes, etc.)	T	-	S	-	+	-	-	S
Fosters excitement, "wow" factor	U	S	S	+	S	+	+	S
Aesthetics	M	-	S	+	S	+	S	S
Uniqueness due to new capabilities		+	S	+	S	S	+	S
Difficulty of part		-	S	-	S	-	-	-
	SUM:	**-5**	**3**	**-1**	**3**	**-3**	**0**	**0**

APPENDIX F.3

PUGH MATRICES

TEST COUPON PUGH MATRICES:

Table 18. Pugh matrix for test coupon features with the wax-injected keychain as the datum.

	Potential Concepts						
	Current Wax Injection mold	Angle Test	Ticket Coupon	Step Coupon	Geometry Coupon	Test Cube	Lattice Coupon
Categories						 	
Varying thickness		-	+	+	+	+	-
Varying Geometry		-	+	-	+	+	+
Text		-	+	-	-	+	-
Holes		S	+	S	+	S	+
Protrusions	DATUM	-	+	+	+	+	-
Aesthetics		-	+	-	-	+	+
Study for print		+	+	+	+	+	+
Study for cast		+	+	S	S	+	+
Chamfers		S	+	S	S	+	S
Bevels		S	+	S	S	+	S
Complexity to Print		+	+	+	+	+	+
Complexity to Cast		+	S	S	S	S	+
	Sum	**-1**	**11**	**1**	**4**	**10**	**4**

Table 19. Pugh matrix for test coupon features with the ticket coupon as the datum.

	Potential Concepts					
	Ticket Coupon	Angle Test	Lattice Coupon	Step Coupon	Geometry Coupon	Test Cube
Categories						 
Varying thickness		-	S	+	-	-
Varying Geometry		-	-	-	S	S
Text		-	-	-	-	S
Holes		-	+	-	+	S
Protrusions	DATUM	-	-	-	S	S
Aesthetics		-	S	-	-	-
Study for print		-	S	-	-	S
Study for cast		-	S	-	+	S
Chamfers		-	-	-	S	+
Bevels		-	-	-	S	+
Complexity to Print		-	+	-	-	S
Complexity to Cast		+	+	-	S	-
	Sum	**-11**	**-2**	**-11**	**-3**	**-1**

APPENDIX G.1

WEIGHTED DECISION MATRICES

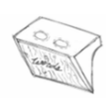
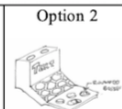
Table 20. Weighted decision matrix for student model options.

			Dice 		Ring 		Necklace Pendant 		Earrings 		Coin 		Novelty Guitar Pick 		Pins 	
Specifications	Value	Weight	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Easily printable	9	15%	10	0.15	6	0.09	7	0.10	7	0.102	8	0.12	7	0.10	8	0.12
Easily castable	10	16%	9	0.15	5	0.08	5	0.08	5	0.081	7	0.11	4	0.06	3	0.05
Cost	5	8%	8	0.06	8	0.06	8	0.06	9	0.073	7	0.06	8	0.06	8	0.06
Time to clean/post-process	5	8%	8	0.06	5	0.04	5	0.04	5	0.040	6	0.05	6	0.05	5	0.04
Volume	4	6%	8	0.05	8	0.05	7	0.05	7	0.045	6	0.04	7	0.05	7	0.05
Reliability	7	11%	9	0.10	4	0.05	3	0.03	3	0.034	6	0.07	4	0.05	4	0.05
Customizable aspects	8	13%	9	0.12	7	0.09	7	0.09	6	0.077	5	0.06	6	0.08	7	0.09
Fosters excitement, "wow" factor	8	13%	8	0.10	9	0.12	6	0.08	5	0.065	2	0.03	3	0.04	2	0.03
Aesthetics	6	10%	7	0.07	8	0.08	6	0.06	6	0.058	4	0.04	4	0.04	3	0.03
TOTAL	**62**		**86.0%**		**65.3%**		**59.2%**		**57.4%**		**56.9%**		**52.4%**		**50.5%**	

Table 21. Weighted decision matrix for the example part options.

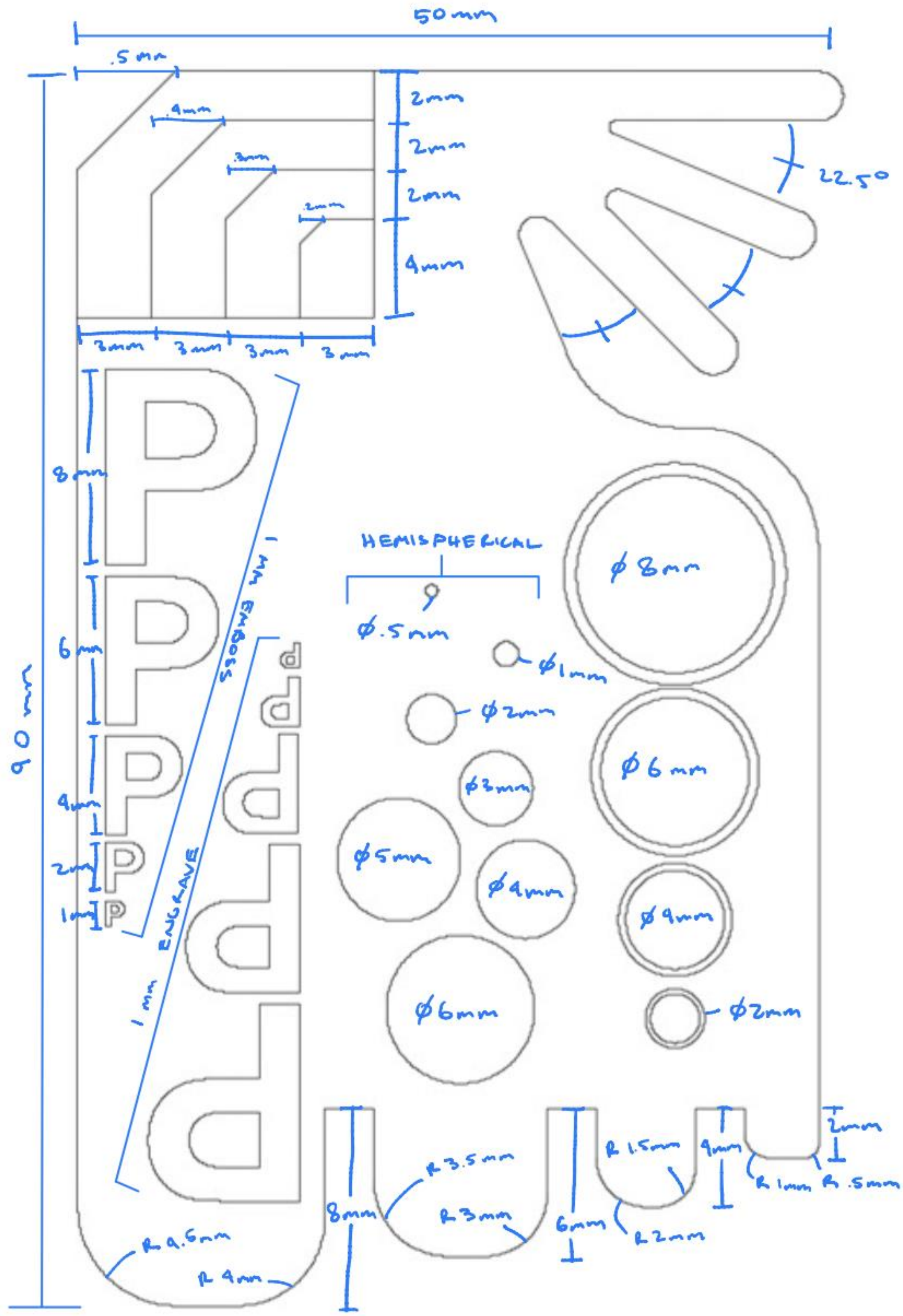
			Action Figure 		Lace Medallion 		Patterns 		Shot Glass 		Rhinestones 	
Specifications	Value	Weight	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Easily printable	9	14%	9	0.12	9	0.12	8	0.11	9	0.125	6	0.08
Easily castable	8	12%	8	0.10	5	0.06	4	0.05	8	0.098	6	0.07
Cost	4	6%	8	0.05	9	0.06	8	0.05	7	0.043	4	0.02
Time to clean/post-process	5	8%	9	0.07	5	0.04	6	0.05	4	0.031	4	0.03
Volume	3	5%	6	0.03	8	0.04	8	0.04	6	0.028	9	0.04
Reliability	7	11%	7	0.08	5	0.05	5	0.05	8	0.086	6	0.06
Customizable aspects	8	12%	7	0.09	7	0.09	7	0.09	8	0.098	4	0.05
Fosters excitement, "wow" factor	8	12%	9	0.11	6	0.07	10	0.12	6	0.074	8	0.10
Uniqueness due to new capabilities	7	11%	7	0.08	6	0.06	10	0.11	7	0.075	10	0.11
Aesthetics	6	9%	7	0.06	6	0.06	8	0.07	5	0.046	8	0.07
TOTAL	**65**		**78.2%**		**65.1%**		**73.7%**		**70.5%**		**64.8%**	

Table 22. Weighted decision matrix for test coupon options.

			Option 1 		Option 2 		Option 6 		Option 8 		Option 9 		Option 10 		Option 11 	
Specifications	Value	Weight	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Easily printable	5	6%	9	0.06	6	0.04	9	0.06	8	0.052	5	0.03	9	0.06	9	0.06
Easily castable	5	6%	8	0.05	5	0.03	9	0.06	8	0.052	7	0.05	6	0.04	9	0.06
Cost	3	4%	7	0.03	7	0.03	7	0.03	8	0.031	6	0.02	8	0.03	7	0.03
Time to clean/post-process	3	4%	3	0.01	5	0.02	6	0.02	9	0.035	7	0.03	7	0.03	7	0.03
Volume	5	6%	5	0.03	6	0.04	7	0.05	8	0.052	6	0.04	7	0.05	5	0.03
Reliability	7	9%	7	0.06	3	0.03	8	0.07	8	0.073	6	0.05	7	0.06	7	0.06
Measurable Thickness	10	13%	4	0.05	10	0.13	8	0.10	4	0.052	7	0.09	4	0.05	10	0.13
Includes text	6	8%	7	0.05	10	0.08	7	0.05	6	0.047	3	0.02	10	0.08	10	0.08
Varying edge features	8	10%	6	0.06	4	0.04	8	0.08	7	0.073	3	0.03	7	0.07	10	0.10
Measureable angled features	6	8%	8	0.06	10	0.08	8	0.06	8	0.062	3	0.02	0	0.00	3	0.02
Includes measureable holes	7	9%	9	0.08	4	0.04	10	0.09	4	0.036	8	0.07	7	0.06	8	0.07
Includes surface textures	5	6%	8	0.05	4	0.03	4	0.03	4	0.026	6	0.04	6	0.04	3	0.02
Include protrusions (ext. & int.)	7	9%	0	0.00	5	0.05	10	0.09	5	0.045	3	0.03	9	0.08	8	0.07
TOTAL	**77**		**61.0%**		**61.9%**		**79.7%**		**63.6%**		**53.0%**		**65.2%**		**76.8%**	

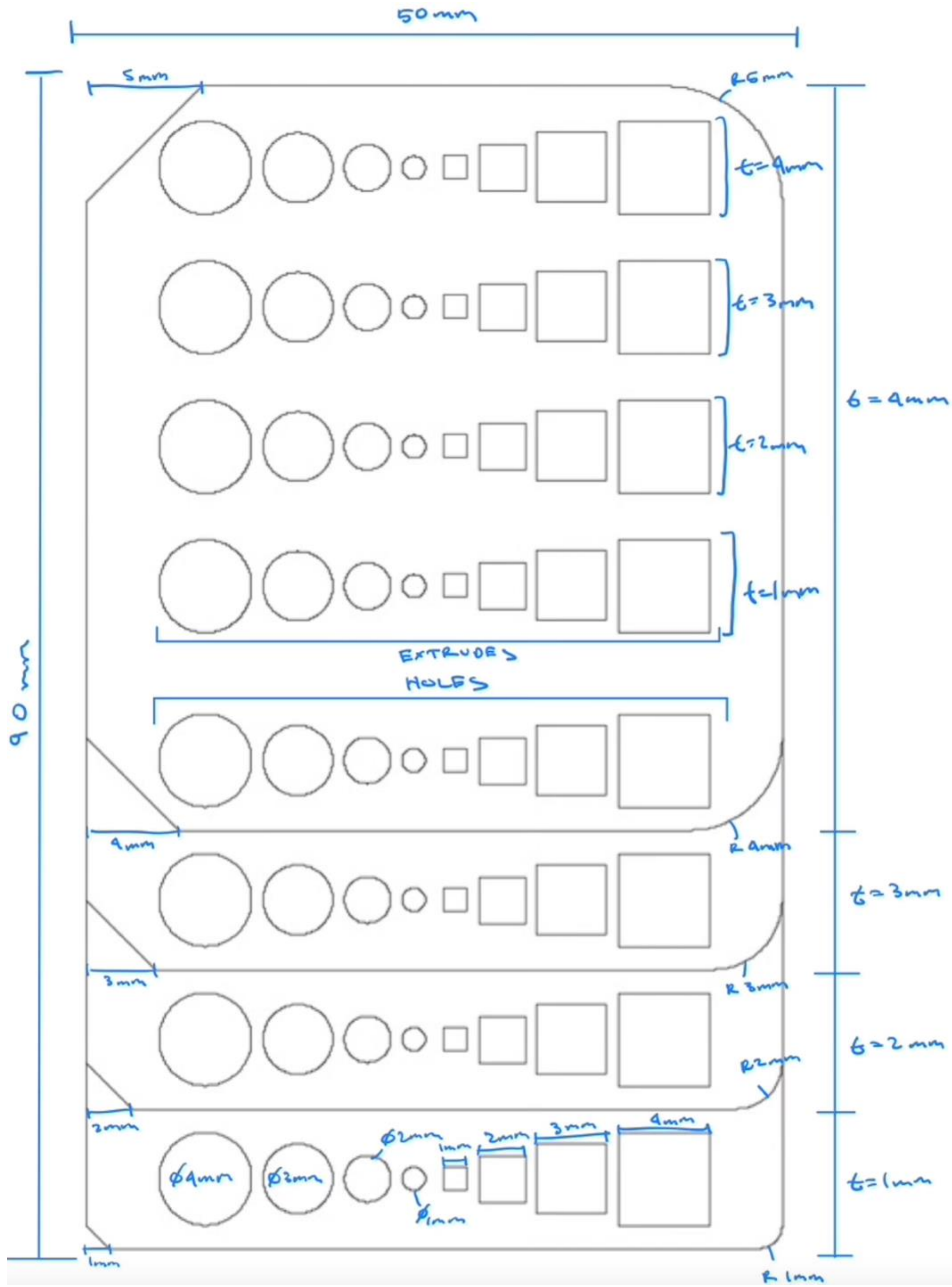
APPENDIX H.1

DIMENSIONED FEATURES OF TEST COUPON A (OPTION 6)



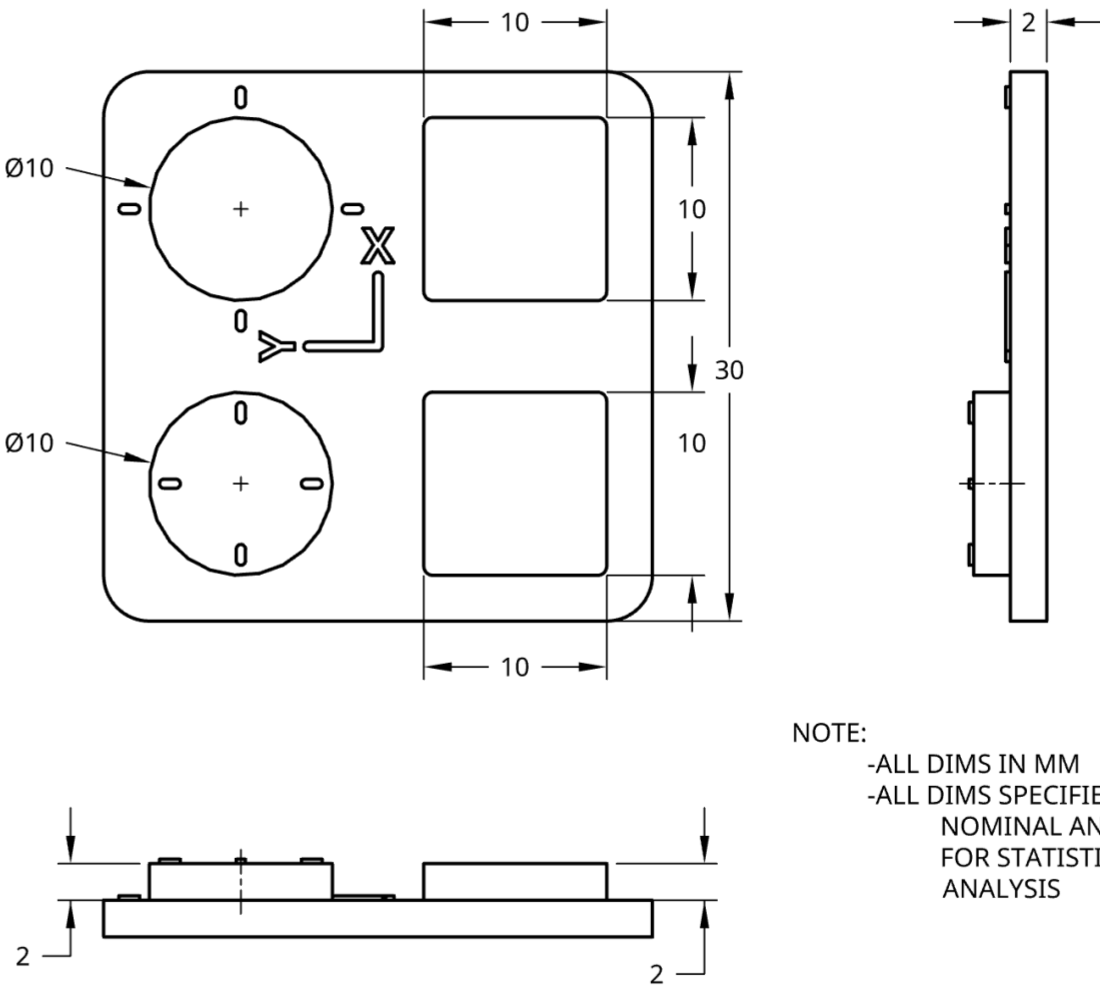
APPENDIX H.2

DIMENSIONED FEATURES OF TEST COUPON B (OPTION 11)



APPENDIX H.3

DIMENSIONED FEATURES OF TEST COUPON C (NEW TEST COUPON)



NOTE:
-ALL DIMS IN MM
-ALL DIMS SPECIFIED ARE NOMINAL AND USED FOR STATISTICAL ANALYSIS

APPENDIX I.1

DESIGN HAZARD CHECKLIST

Table 23. Hazard checklist for the manufacturing process.

Y	N	
✔		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	✔	2. Can any part of the design undergo high accelerations/decelerations?
	✔	3. Will the system have any large moving masses or large forces?
	✔	4. Will the system produce a projectile?
	✔	5. Would it be possible for the system to fall under gravity creating injury?
	✔	6. Will a user be exposed to overhanging weights as part of the design?
✔		7. Will the system have any sharp edges?
	✔	8. Will any part of the electrical systems not be grounded?
	✔	9. Will there be any large batteries or electrical voltage in the system above 40 V?
	✔	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	✔	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	✔	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
✔		13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	✔	14. Can the system generate high levels of noise?
✔		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
✔		16. Is it possible for the system to be used in an unsafe manner?
✔		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

APPENDIX I.1

DESIGN HAZARD CHECKLIST

Table 24. Preventative measures for discussed hazards.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Spinning machines, specifically grinding wheels, should be used with caution to prevent pinch point from creating injuries or pulling in hair/clothing.	The video tutorial and lab manual will highlight these dangers, even though the lab instructor should have already warned the students in previous labs.	01/10/22	01/04/22
Potential usage of UV light to cure the resin prints could be dangerous for direct viewing.	Using UV protection for the eyes when operating the curing station will prevent damage to the eyes of the operator. These should already be in the lab for other current experiments.	09/20/21	10/04/21
After casting the parts, there is the potential for unfinished edges which could be sharp.	Gloves provided by the casting lab as well as safe lab practices and etiquette will prevent the infliction of harm on the handler.	09/20/21	09/20/21
The uncured resin should not be inhaled for health reasons.	Proper N95 masks will be available in the lab for lab technicians/students to wear when handing their parts before curing. Gloves will also be available.	09/20/21	10/04/21
Since this is a casting lab, there will be metals undergoing extreme heat as well as molds being fired during the burnout process.	Proper protective wear provided by the casting lab should always be worn as specified in order to prevent injury, especially during the pouring stage.	09/20/21	09/20/21

APPENDIX J.1

FMEA CHART

Figures 45 and 46 shows our functional decomposition charts with each task rated on how risky it will be to complete it. This helps identify the most important aspects of the senior project and which tasks are less crucial for the success. Figures 45 and 46 are highlighted in three colors to show the possibility of failure, as shown in the key at the bottom.

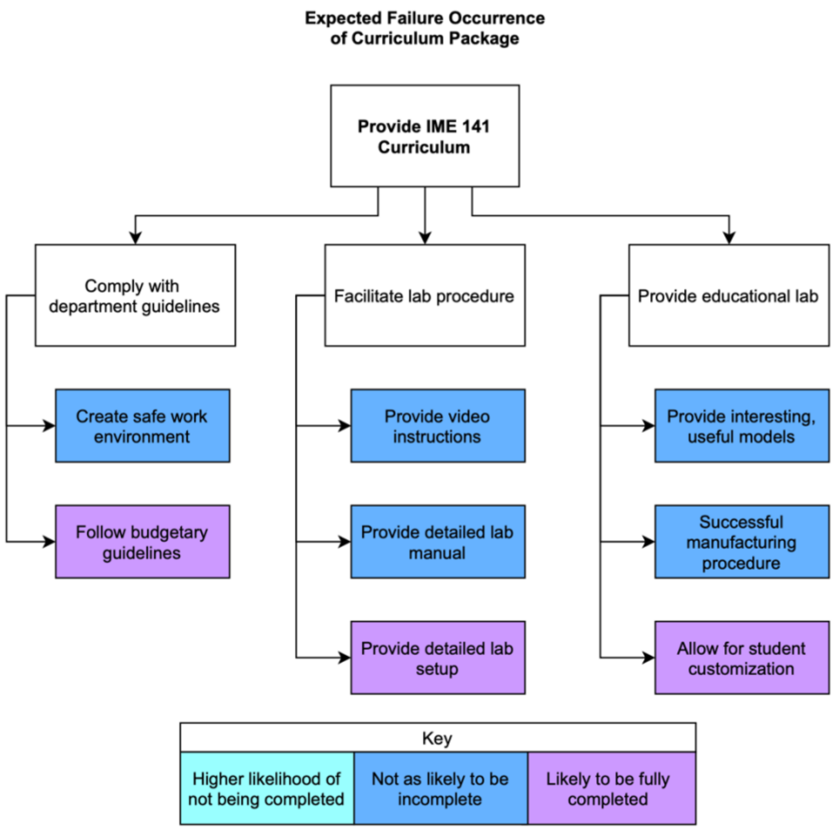


Figure 45. Risk analysis for the curriculum package. Key at the bottom explains the ratings

APPENDIX J.1

FMEA CHART

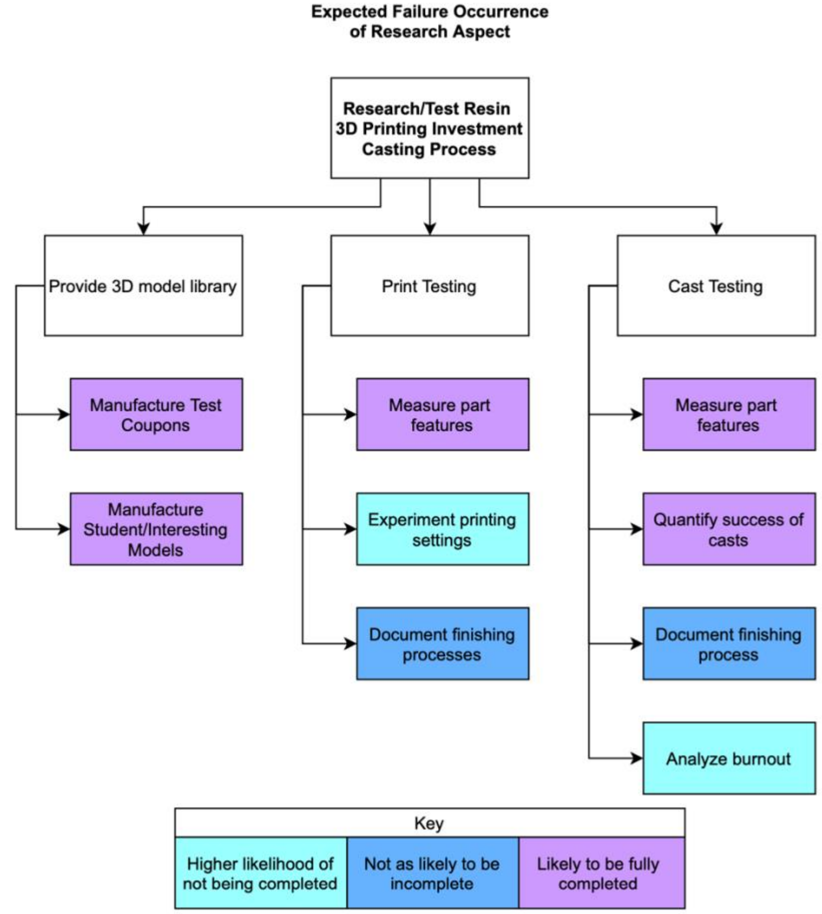


Figure 46. Risk analysis for the research package. Key at the bottom explains the ratings

There are luckily only two tasks that are marked with light blue. For the "Experiment printing settings," the uncertainty in completion comes from the fact that the MoonRay printers are already optimized for the best print, so there shouldn't be a need to experiment with settings. The other box, "analyze burnout," is not crucial for the project, and will be hard to actually analyze without expensive equipment that is out of the scope/budget of the project.

After ranking all of the tasks in the functional decomposition charts, a list of potential failures is listed below. These are recognized in order to help prevent doing them. These are shown below, where each major bullet point is a box in Figures 45 and 46, and the sub-bullet points are potential failure modes.

APPENDIX J.1

FMEA CHART

<u>IME 141 Curriculum:</u>

- Create safe work environment
    - Dangerous equipment or process
- Follow budgetary guidelines
    - Too expensive for students to manufacture parts
- Provide video instructions
    - Failure to educate students
    - Failure to captivate student interest
    - Boring/un-educational instructions
    - Failure to address safety
- Provide detailed lab manual
    - Failure to educate students
    - Failure to captivate student interest
    - Boring/un-educational instructions
    - Failure to address safety
- Provide detailed lab set up
    - Confusing lab set up
    - Missing components for lab setup
    - Failure to address safety
    - Insufficient documentation of lab materials
- Provide interesting, useful models
    - Failure to captivate student interest
    - Failure to provide models for students
    - Boring student models
    - Too expensive for students to manufacture parts
    - Too much work to aide students
- Successful manufacturing process
    - Confusing lab setup
    - Missing components for lab setup
    - Failure to address safety
    - Dangerous equipment or process
    - Lack of understanding on resin/printer operation
    - Insufficient documentation of lab materials
- Allow for student customization
    - Failure to captivate student interest
    - Failure to provide models for students
    - Boring student models
    - Too much work to aide students

APPENDIX J.1

FMEA CHART

Research/Test Resin 3D Printing Investment Casting Process:

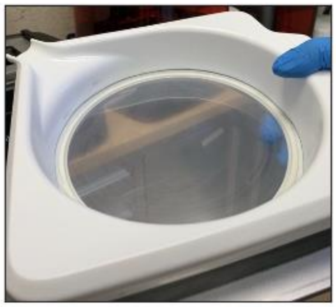
- Manufacture test coupons
  - Failure to demonstrate capabilities
  - Failure to measure features
  - Failure to try different print settings
  - Failure to look at burnout/post-cast
  - Failure to fill out measurement table
- Manufacture student/interesting models
  - Failure to test student models
  - Failure to provide example parts
  - Failure to provide CAD for models
  - Failure to test gating systems
  - Failure to analyze different support structures
- Measure part features (post-print)
  - Failure to fill out measurement table
  - Failure to mention part limitation (in documentation)
  - Failure to discuss curing methods
- Experiment printing settings
  - Failure to try different print settings
  - Failure to fill out measurement table
  - Failure to mention gating systems
  - Failure to analyze different support structures
- Document finishing processes
  - Failure to fill out measurement table
  - Failure to organize document effectively
  - Failures to mention gating systems
  - Failures to mention part limitations
  - Failure to mention finishing processes
  - Failure to discuss curing methods
  - Failure to provide CAD for models
- Measure part features (post-cast)
  - Failure to fill out measurement table
  - Failure to mention part limitation (in documentation)
  - Failure to discuss curing methods
- Quantify success of casts
  - Failure to mention finishing processes
  - Failure to test gating systems (for student parts)
- Document finishing processes
  - Failure to mention finishing processes
- Analyze burnout
  - Failure to look at burnout/post-cast

CAUTION: HAZARDOUS MATERIALS

- Ensure that gloves, masks, goggles, long pants and closed toed shoes are warn in the lab whenever uncured resin is being handled.
- Direct skin contact with the resin should immediately be addressed with soap and water.
- Leave the door open a crack to allow for proper ventilation of the resin fumes.

Setting Up the Printer

1) Examine both the vat and the build surface for cured fragments. If either are found, remove with a plastic scraper or by hand, being careful to avoid damage to either surface.

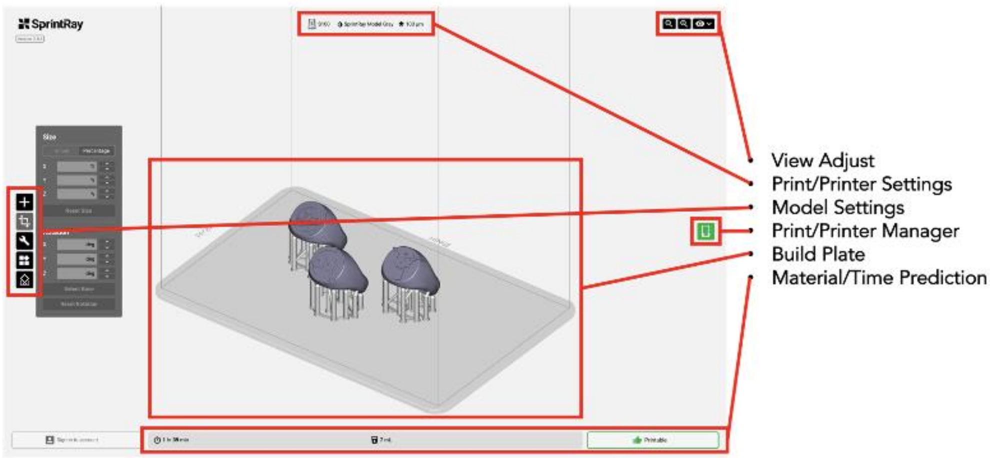


2) Old residue from uncured resin can be sopped up with a paper towel slightly wet with isopropyl alcohol.
3) Make sure that the build surface is fully inserted, and the handle is rotated firmly counterclockwise so that it cannot move.

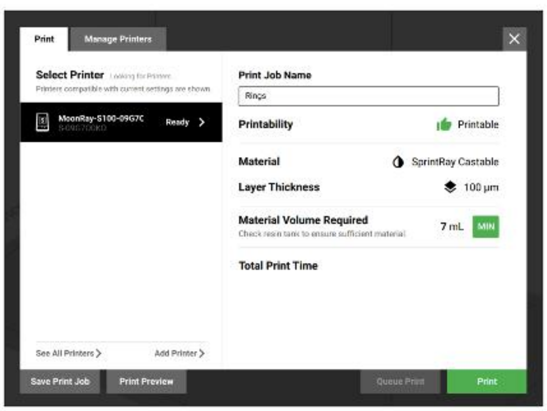
4) Fill the vat with resin ensuring a slow pour and that the level is between the max and min lines.

Using the Slicing Software

1) Start by opening the RayWare software on the desktop and drag and drop or load your model. By selecting the fix option in the pop-up supports will load onto your model. Adjust using the tab options shown below.



2) By selecting the Print/Printer Manager you can view what printers you are connected to and manage the machines that are running. Ensure that you are connected to the right printer by verifying the serial number located on the back left of the printer base.



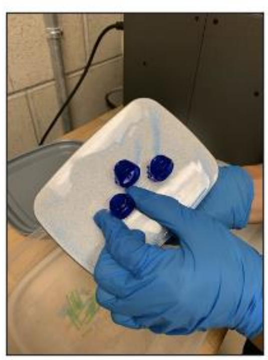
3) Once all the model settings are adjusted and the printer and resin options are selected start the print in the Print/Printer Manager. From there, the print can be paused or halted if need be. The pause button sometimes lags so just hit it once and wait for a little.

Removing the Print

1) Once your print is complete, remove the hood and place it in a safe area.

2) Rotate the build plate handle clockwise to loosen and remove the build plate. Any drips onto the machine should be removed IMMEDIATELY with a paper towel dampened with IPA. NOTE: do NOT get IPA into the resin pool, as it will ruin all excess resin.

3) Over a protected surface, attempt to remove the part from the plate gently by hand or with a plastic scraper.



Finishing the Print

1) Once the print is removed, lightly clean the build plate with IPA and a paper towel, ensuring that there is neither residual resin nor IPA. Replace the surface and tighten the handle.

2) Place your part into an IPA bath and gently stir by hand. Remove and pat dry with a paper towel.

3) Place your part into the curing station and select your cure settings based on your resin. Support removal can be done before or after the cure.

Cleaning Up

1) To clean the vat, CAREFULLY remove it from the printer, making sure not to spill.

2) Place it into the vat drainage mount and allow it to drain back into your bottle through a filter in a funnel. If there is resin to be disposed of ensure an appropriate container and discarded properly.

3) You may also want to remove resin using a rubber spatula to gently scrape it clean.
4) Excess resin can be sopped up with a paper towel. NOTE: Small volume only.
5) Rub down the vat lightly with a paper towel dampened with IPA and replace cover.

APPENDIX L.1

COMPLETED LAB MANUAL

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APPENDIX L.1

COMPLETED LAB MANUAL

1.0 Safety Considerations

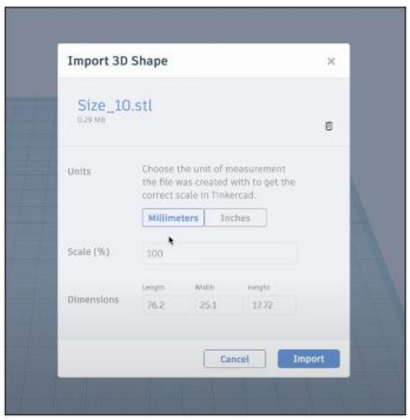
CAUTION: HAZARDOUS MATERIALS

- Ensure that gloves, masks, goggles, long pants and closed toed shoes are warn in the lab whenever uncured resin is being handled.
- Direct skin contact with the resin should immediately be addressed with soap and water.
- Leave door open to allow for ventilation of the resin fumes.
- If resin gets in eyes, wash eyes out with eye-wash bottle for at least 15 minutes and seek medical attention if irritation occurs.
- To find all the information on the resin hazards, please read the SDS sheet provided in the casting lab.

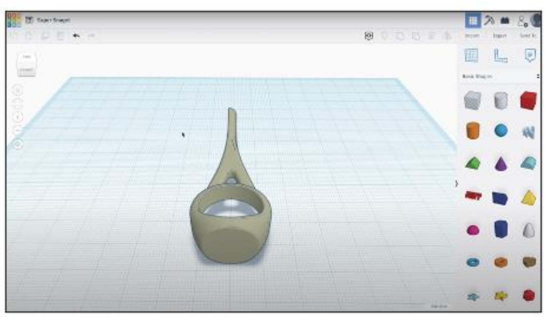
2.0 Customization of Model

NOTE: These are instructions are written for using TinkerCAD for simplicity. If you're proficient with a different CAD software, feel free to use whatever suits you best. The most important aspects to remember are to not scale the part or change the sprue in any way.

1) Go to your course Canvas page and download the desired model to your local computer.
2) Go to https://www.tinkercad.com and create an online account with Autodesk.
3) Click on "Create New Design" and in the upper right corner, click "Import" to load the desired model.
4) Ensure from the next screen that the units are set to **millimeters** and the scale set to **100%**.



5) Use the shape library to add/subtract features to the ring to customize it as you'd like. Make sure that embosses aren't more than 2mm tall.

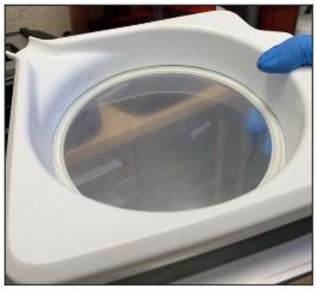


6) Once finished, press the "Export" button in the upper right and export as a .STL file.

2

3.0 Setting Up the Printer

1) Examine both the vat and the build surface for cured fragments. If either are found, remove with a plastic scraper or by hand, being careful to avoid damage to either surface.

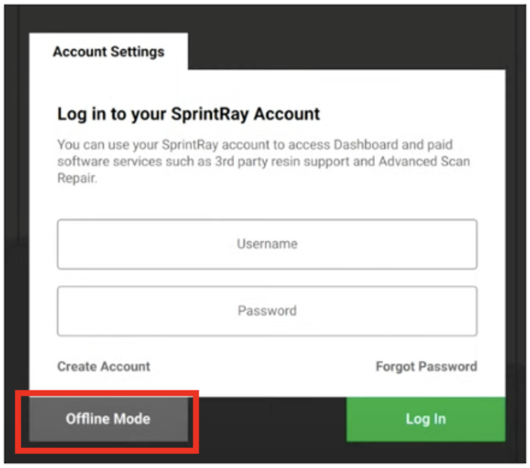


2) Old residue from uncured resin can be wiped away with a paper towel slightly wet with isopropyl alcohol.
3) Make sure that the build surface is fully inserted, and the handle is rotated firmly counterclockwise so that it cannot move.

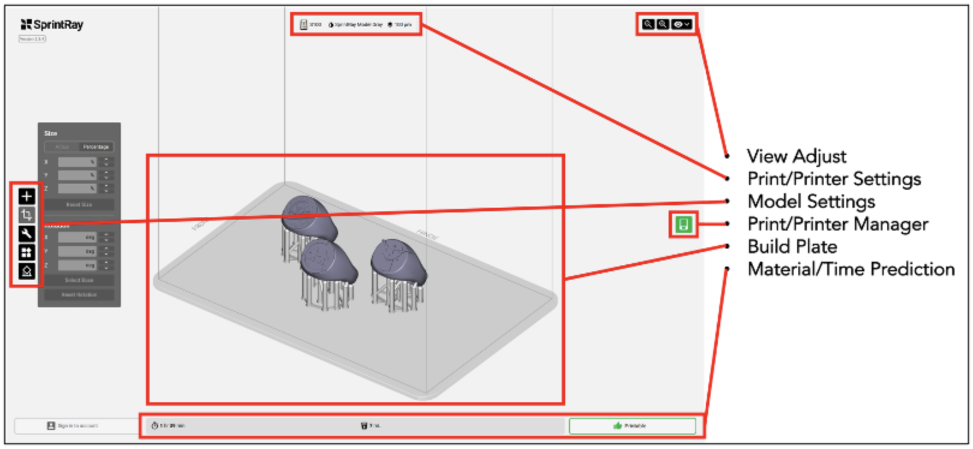
4) Fill the vat with resin ensuring a slow pour and that the level is between the max and min lines. Fill according to the suggested amount in the RayWare software.

4.0 Using the Slicing Software

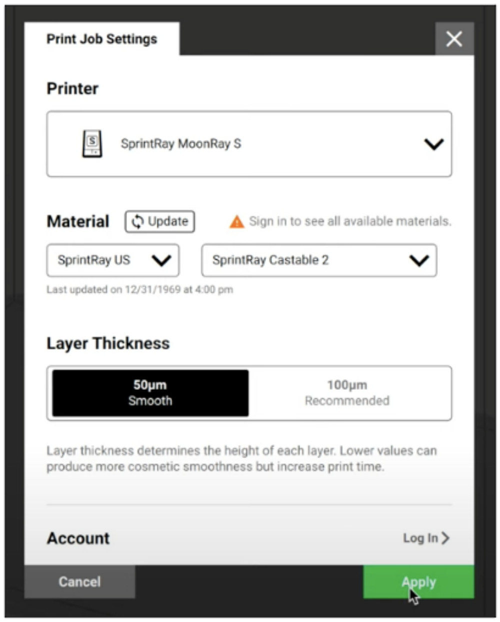
1) When first opening the application, instead of logging in, choose the "Offline Mode."



2) Below is a general layout of the RayWare software:

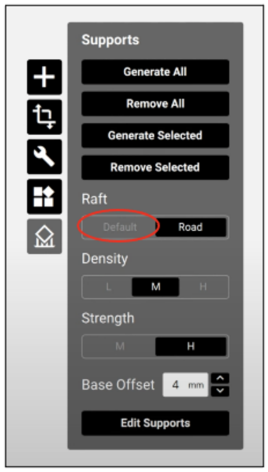


3) Click on the "Print/Printer Settings" and ensure they match the settings shown in the following picture. While 100um layer thickness can be used, the resolution of layers is not as smooth (though much better than filament printers).

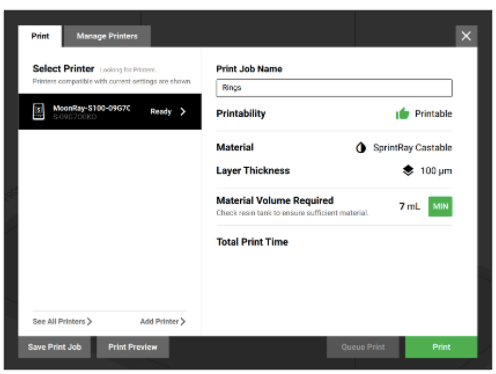


4) Drag and drop your file into the build space or load your model with the import feature. By selecting the "FIX" option in the pop-up, supports will load onto your model and orientation will be improved.

5) Use the "Model Settings" to rotate, move, or scale the part as desired. However, there is no 'undo' button, so be careful with any changes you make to the part's orientation.
6) Once the part is in the desired orientation, go to the 5th tab in the "Model Settings" to set the support structure, as shown in the picture below. Feel free to use the "Edit Supports" to remove any unwanted supports, making sure that the print is still possible with the removed supports. **NOTE:** Use **Default** rafts instead of Road rafts.



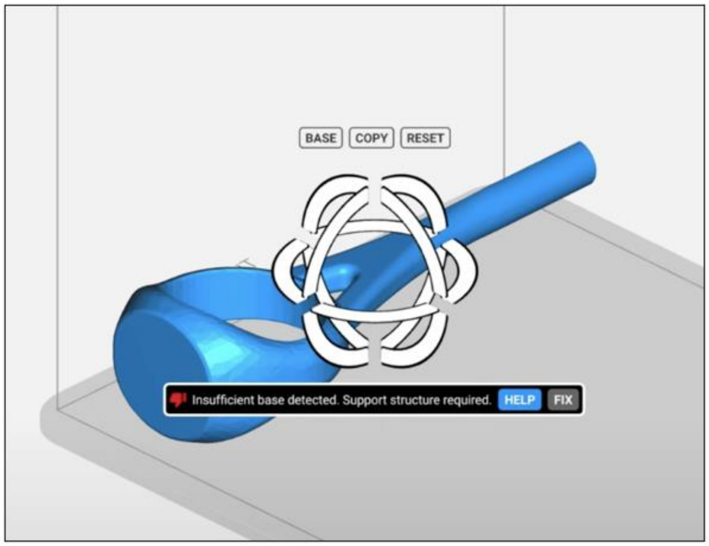
7) When ready, click the green button on the right of the screen to send the information to the printer. By selecting the Print/Printer Manager you can view what printers you are connected to and manage the machines that are running. Ensure that you are connected to the right printer by verifying the serial number located on the back left of the printer base.



8) Once all the model settings are adjusted and the printer and resin options are selected start the print in the Print/Printer Manager. From there, the print can be paused or halted if need be. The pause button sometimes lags so just hit it once and wait for a little.

5.0 Preparing Student Ring Models

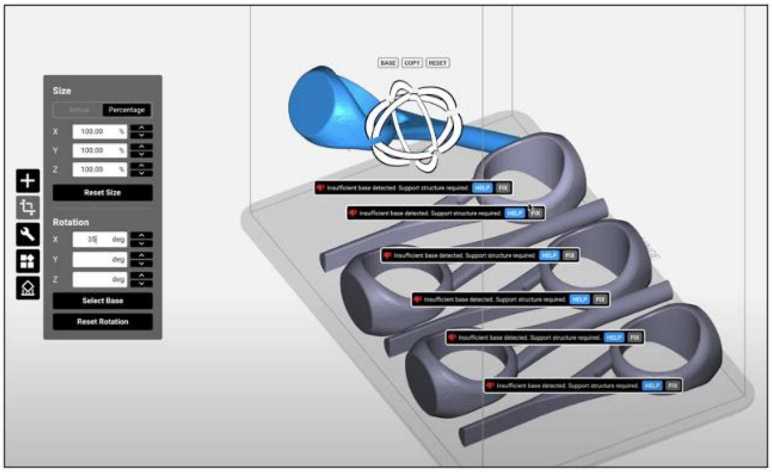
1) Start by importing the rings onto the build plate and orient them as shown:



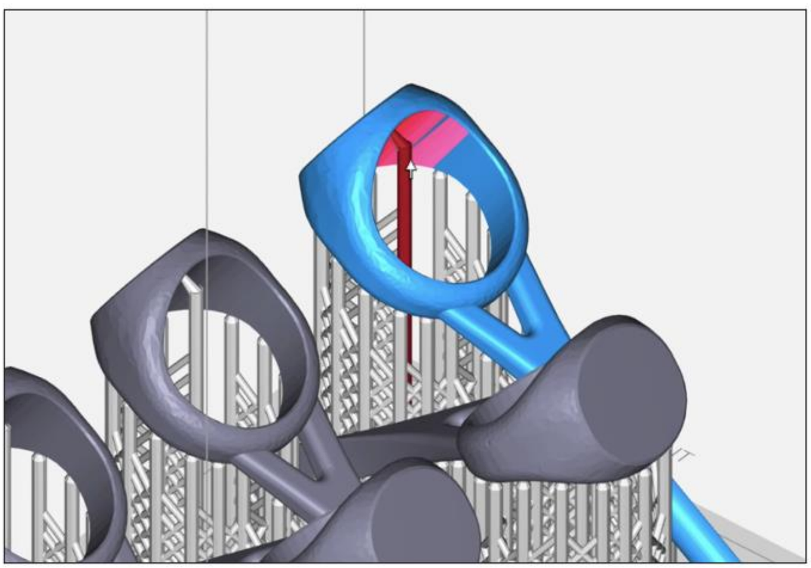
2) Once all 6 models are on the build plate, orient them as such to fit the greatest number of rings onto the build surface:

APPENDIX L.1
COMPLETED LAB MANUAL

3) Next, orient all the parts at a 35˚ angle as this helps prevent print failure. Use the "Size" tab in "Model Settings" to individually angle each ring.

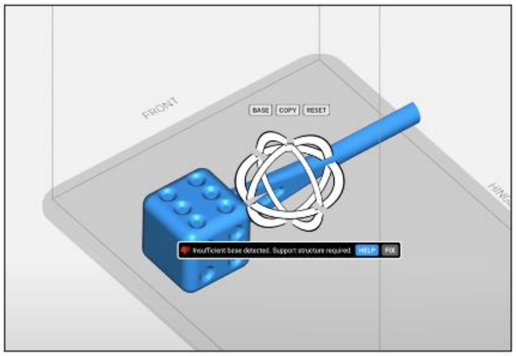


4) Next, add supports by using the **Default** raft type, **Medium** density, **Medium** strength, and a base offset of **4mm**. Click **Generate Selected** to generate supports on all rings.
5) Use the **Edit Supports** to delete any support branches that connect with the inside of the ring. It will highlight them red, and by clicking the mouse, it will remove that support branch. This prevents unnecessary post-processing after casting.

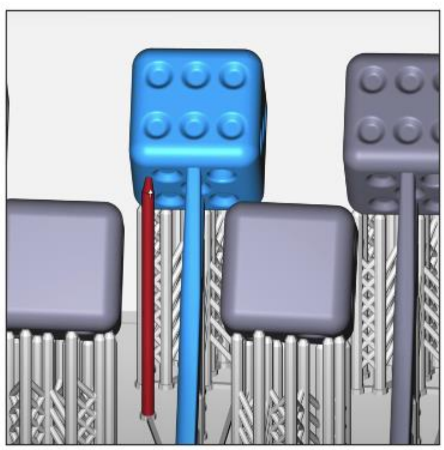


6.0 Preparing Student Dice Models

1) Start by importing the dice onto the build plate and orient them as shown, with the 6-face up:



2) Once all 6 models are on the build plate, orient them the same as the rings shown earlier.
3) Next, orient all the parts at a 35° angle as this helps prevent print failure. Use the "Size" tab in "Model Settings" to individually angle each dice. This is the same as the rings.
4) Next, add supports by using the **Default** raft type, **Medium** density, **Medium** strength, and a base offset of **4mm**. Click **Generate Selected** to generate supports on all rings.
5) Use the **Edit Supports** to delete any support branches that connect with the 5-face of the dice. This prevents unnecessary post-processing after casting.



APPENDIX L.1

COMPLETED LAB MANUAL

7.0 Removing the Print

1) Once your print is complete, remove the hood and place it in a safe area.

2) Rotate the build plate handle counterclockwise to loosen and remove the build plate. Any drips onto the machine should be removed IMMEDIATELY with a paper towel dampened with IPA. NOTE: do NOT get IPA into the resin pool, as it will ruin all excess resin.

3) Over a protected surface, attempt to remove the part from the plate gently by hand or with a plastic scraper.

8.0 Finishing the Print

1) Once the print is removed, lightly clean the build plate with IPA and a paper towel, ensuring that there is neither residual resin nor IPA. Replace the surface and tighten the handle.

2) Place your part into an IPA bath and gently stir by hand. Remove and pat dry with a paper towel.

3) Place your part into the curing station and select your cure settings based on your resin. Support removal can be done before or after the cure. For this lab, select "Castable 2."

9.0 Cleaning Up

1) To clean the vat, CAREFULLY remove it from the printer, making sure not to spill. If you're going to be printing another batch soon, skip the removal and go to Step 2.

2) Place a lid on the vat to protect it from the sun. Put the tray into the toolbox drawer to prevent sun exposure.

12

APPENDIX L.1

COMPLETED LAB MANUAL

10.0 Investment/Casting Process

1) When the parts are done curing, they can be removed (and don't necessarily need to be handled with gloves, as the resin should be cured). Place the sprues of the parts into the investment flask, ensuring they fit snugly.

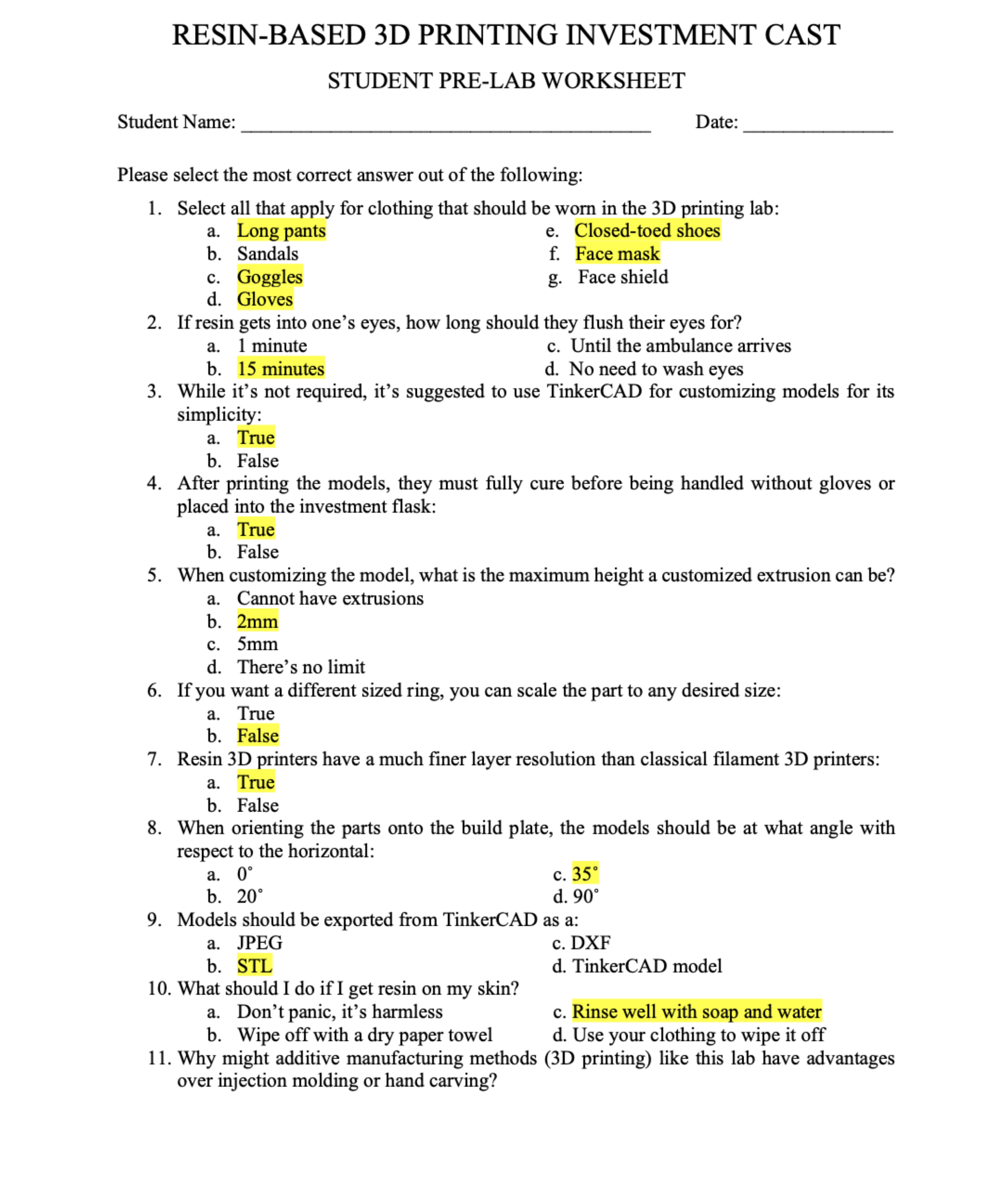
2) Mix the investment material as shown in lab. This includes one full cup of investment material and the proper amount of water (as shown on the water cup). Mix this together until combined and pour into flask. Fill slightly over the brim and use a flat edge to scrape smooth.



3) Let flask sit overnight to ensure full hardening before putting in furnace.
4) Set the flasks in the furnace for the instructors desired time. Likely 7-8 hours at 800°C.
5) When completely burned out, remove flask and cast with aluminum (or metal of your choice). For best results, perform the casting process with a vacuum to ensure the metal fills all crevices of the cavity.
6) When fully hardened, break out cast with arbor press and clean with brushes, hacksaws, and grinders to remove sprues/gating systems.

APPENDIX L.2

PRELAB QUIZ



RESIN-BASED 3D PRINTING INVESTMENT CAST

STUDENT PRE-LAB WORKSHEET

Student Name: ____ Date: _______________

Please select the most correct answer out of the following:

1. Select all that apply for clothing that should be worn in the 3D printing lab:
    a. Long pants
    b. Sandals
    c. Goggles
    d. Gloves
    e. Closed-toed shoes
    f. Face mask
    g. Face shield
2. If resin gets into one's eyes, how long should they flush their eyes for?
    a. 1 minute
    b. 15 minutes
    c. Until the ambulance arrives
    d. No need to wash eyes
3. While it's not required, it's suggested to use TinkerCAD for customizing models for its simplicity:
    a. True
    b. False
4. After printing the models, they must fully cure before being handled without gloves or placed into the investment flask:
    a. True
    b. False
5. When customizing the model, what is the maximum height a customized extrusion can be?
    a. Cannot have extrusions
    b. 2mm
    c. 5mm
    d. There's no limit
6. If you want a different sized ring, you can scale the part to any desired size:
    a. True
    b. False
7. Resin 3D printers have a much finer layer resolution than classical filament 3D printers:
    a. True
    b. False
8. When orienting the parts onto the build plate, the models should be at what angle with respect to the horizontal:
    a. 0˚
    b. 20˚
    c. 35˚
    d. 90˚
9. Models should be exported from TinkerCAD as a:
    a. JPEG
    b. STL
    c. DXF
    d. TinkerCAD model
10. What should I do if I get resin on my skin?
    a. Don't panic, it's harmless
    b. Wipe off with a dry paper towel
    c. Rinse well with soap and water
    d. Use your clothing to wipe it off
11. Why might additive manufacturing methods (3D printing) like this lab have advantages over injection molding or hand carving?

APPENDIX L.3

LINKS TO COMPLETED LAB VIDEO TUTORIALS

Below are the links to access the student videos:

- Customization of Models: https://www.youtube.com/watch?v=zEBS78VUYkQ
- How to Use RayWare: https://www.youtube.com/watch?v=mrVNPfA6b7E
- RayWare for Printing: https://www.youtube.com/watch?v=2PeWu45zZV8
- Lab Setup: https://www.youtube.com/watch?v=5o1KrIcicFs

APPENDIX M.1

TENTATIVE VIDEO STORYBOARD

Title: LAB VIDEO — Page: 1

Scene No. 1 — Shot No. 1

LAB#:
CREATING INVESTMENT CASTING PATTERNS USING RESIN 3D PRINTING

INTRO / TITLE FRAME

Scene No. 1 — Shot No. 2

- SHOW EXAMPLE PARTS
- INTRODUCE CONCEPTS

Scene No. 2 — Shot No. 1

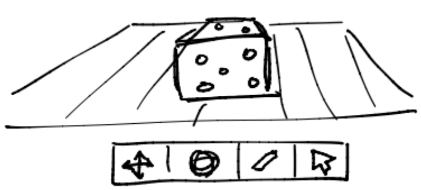
3D MODELING

- 3D MODEL INTRO

Scene No. 2 — Shot No. 2

- TINKERCAD

Scene No. 2 — Shot No. 3



- SCREEN RECORD
- HOW TO IMPORT + MODIFY SAMPLES

Scene No. 3 — Shot No. 1

PRINTING AND CURING

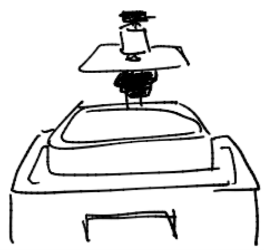
- PRINT + CURE INTRO

APPENDIX M.1

TENTATIVE VIDEO STORYBOARD

Title: LAB VIDEO | Page: 2

Scene No. 3 | Shot No. 2

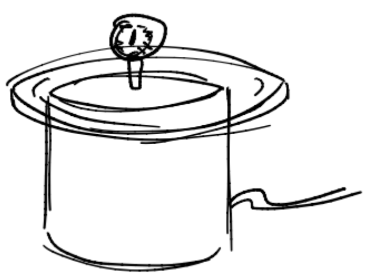


- 3D PRINT TIMELAPSE

Scene No. 3 | Shot No. 3

- PART CLEAN UP

Scene No. 3 | Shot No. 4



- CURING PROCEDURE

Scene No. 4 | Shot No. 1

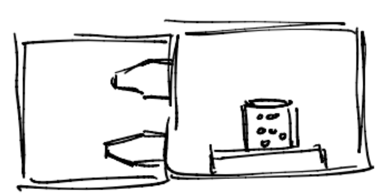
CASTING

- CASTING INTRO

Scene No. 4 | Shot No. 2

- MAKING THE MOLD

Scene No. 4 | Shot No. 3



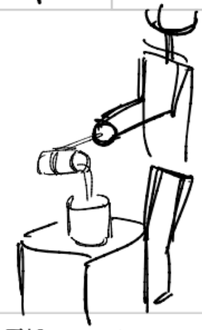
- HOW BURNOUT WORKS

APPENDIX M.1

TENTATIVE VIDEO STORYBOARD

Title: LAB VIDEO — Page: 3

Scene No.	4	Shot No.	4



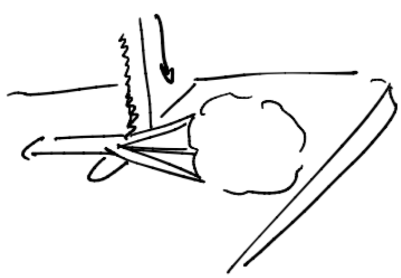
- CASTING THE METAL

Scene No.	5	Shot No.	1

FINISHING

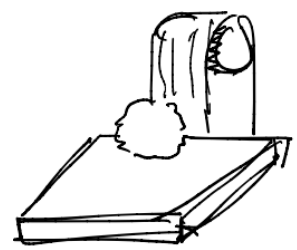
- INTRO TO PART FINISHING

Scene No.	5	Shot No.	2



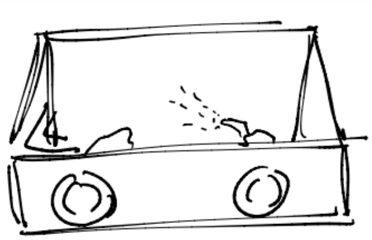
- SAWING OFF GATING

Scene No.	5	Shot No.	3



- GRINDING WHEEL

Scene No.	5	Shot No.	4



- SAND BLAST

Scene No.	5	Shot No.	5

THANK YOU

- OUTRO

APPENDIX N.1

EXAMPLE OF STUDENT-FILLED SATISFACTION SURVEY

PROCESS SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME Joshua Pratt **DATE** 02/05/22

MAJOR Mechanical Engineering **GRADE** 4th Year

GENERAL QUESTIONS:

(Y) N I'VE TAKEN THE IME 141/471 COURSE PRIOR TO TODAY
(Y) N I'VE KNOW HOW TO USE CAD SOFTWARE SYSTEMS
Y (N) I'VE CAST METAL BEFORE (OUTSIDE IME 141/471)
(Y) N I'VE USED A 3D PRINTER BEFORE
Y (N) I'VE USED A RESIN 3D PRINTER BEFORE

PRINTING PROCESS (1 FOR EASY, 5 FOR HARD):

(1) 2 3 4 5 DIFFICULY TO SET PRINT PARAMETERS OUTLINED IN MANUAL
(1) 2 3 4 5 DIFFICULTY TO OPERATE THE ISOPROPYL CLEANING BATH
(1) 2 3 4 5 DIFFICULTY TO SETUP CURING SETTINGS
(1) 2 3 4 5 DIFFICULTY UNDERSTANDING SAFETY PRECAUTIONS
N/A MINUTES TIME SPEND CLEANING PART

COMMENTS FOR PRINTING PROCESS:

CASTING PROCESS (1 FOR EASY, 5 FOR HARD):

(1) 2 3 4 5 DIFFICULY OF MIXING THE INVESTMENT CASTING PLASTER
(1) 2 3 4 5 DIFFICULTY OF POURING INVESTMENT INTO FLASK
1 (2) 3 4 5 DIFFICULTY OF INSERTING 3D PRINTED PATTERN INTO FLASK
1 (2) 3 4 5 DIFFICULTY CASTING PART
1 (2) 3 4 5 DIFFICULTY REMOVING GATING SYSTEM
N/A MINUTES TIME SPEND CLEANING PART

COMMENTS FOR CASTING PROCESS:

OVERALL SATISFACTION IN LAB PROCESS: 100 %

APPENDIX N.1

EXAMPLE OF STUDENT-FILLED SATISFACTION SURVEY

MODEL CUSTOMIZATION SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME Joshua Pratt **DATE** 02/05/22

MAJOR Mechanical Engineering **GRADE** 4th Year

GENERAL QUESTIONS:

Y N I'VE KNOW HOW TO USE CAD SOFTWARE SYSTEMS
Y N I'VE TAKEN A CAD MODELLING CLASS AT CAL POLY
Y N I'M CONFIDENT IN EXTRUDING/SKETCHING/TEXT

SOFTWARE PROCESS (1 FOR EASY, 5 FOR HARD):

1 2 3 4 5 DIFFICULTY FINDING THE SOFTWARE/STARTING IT UP
1 **2** 3 4 5 DIFFICULTY LOADING MODEL INTO PROGRAM
1 **2** 3 4 5 DIFFICULTY OPERATING THE CAD SOFTWARE START UP
1 2 3 4 5 DIFFICULTY EXTRUDING
1 **2** 3 4 5 DIFFICULTY PANNING/ROTATING MODEL
1 **2** 3 4 5 DIFFICULTY INSERTING TEXT
1 2 3 4 5 DIFFICULTY COMING UP WITH A DESIGN
1 2 3 4 5 DIFFICULTY EXPORTING MODEL ONCE FINISHED
1 **2** 3 4 5 DIFFICULTY CUSTOMIZING MODEL (OVERALL)
30 MINUTES TIME SPEND ADDING CUSTOMIZATION TO MODEL

COMMENTS FOR CUSTOMIZATION PROCESS:

OVERALL CUSTOMIZATION SATISFACTION: 100 %

APPENDIX N.1

EXAMPLE OF STUDENT-FILLED SATISFACTION SURVEY

CURRICULUM SATISFACTION SURVEY

RESIN-BASED 3D PRINTED INVESTMENT CASTING

NAME Joshua Pratt **DATE** 02/05/22

MAJOR Mechanical Engineering **GRADE** 4th Year

GENERAL QUESTIONS:

(Y)	N	I'VE ALREADY TAKEN THE IME 141/471 COURSE
(Y)	N	I'VE TAKEN OTHER LAB COURSES WITH LAB MANUALS
(Y)	N	I'VE TAKEN OTHER LAB COURSES WITH VIDEO TUTORIALS

CURRICULUM QUESTIONNAIRE (1 FOR BAD, 5 FOR GOOD):

VIDEO	MANUAL	
1 2 3 4 (5)	1 2 3 4 (5)	PROVIDED NECESSARY BACKGROUND INFO
1 2 3 (4) 5	1 2 3 (4) 5	DETAILED PROCESS OF MODEL CUSTOMIZATION
1 2 3 (4) 5	1 2 3 (4) 5	DETAILED PROCESS OF SENDING MODEL TO PRINTER
1 2 3 4 (5)	1 2 3 4 (5)	DETAILED CLEANING MODEL POST-PRINT
1 2 3 4 (5)	1 2 3 4 (5)	DETAILED CURING METHODOLOGY AND SPECS
1 2 3 4 (5)	1 2 3 4 (5)	DOCUMENTATION OF INVESTMENT PLASTER MIXING
1 2 3 (4) 5	1 2 3 (4) 5	POST-PROCESSING METHODS DESCRIBED
1 2 3 4 (5)	1 2 3 4 (5)	CONCISE AND GRAMMATICALLY CORRECT
1 2 3 4 (5)	1 2 3 4 (5)	VISUALS ARE ADEQUATE
1 2 3 4 (5)	1 2 3 4 (5)	SAFETY MEASURES WERE OUTLINED
______	X	PREFERED MODE OF LEARNING (CHECK ONE)

GENERAL QUESTIONS:

(Y)	N	THE CURRICULUM WAS EDUCATIONALLY BENEFICIAL
(Y)	N	THE CURRICULUM WOULD BE A GOOD ADDITION TO IME 471
(Y)	N	THE CURRICULUM FACILITATES STUDENT LEARNING
Y	(N)	THE CURRICULUM WAS BORING
(Y)	N	THE CURRICULUM WAS EASY TO FOLLOW

COMMENTS FOR CURRICULUM:

OVERALL CURRICULUM SATISFACTION: 95 %

APPENDIX O.1

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON A

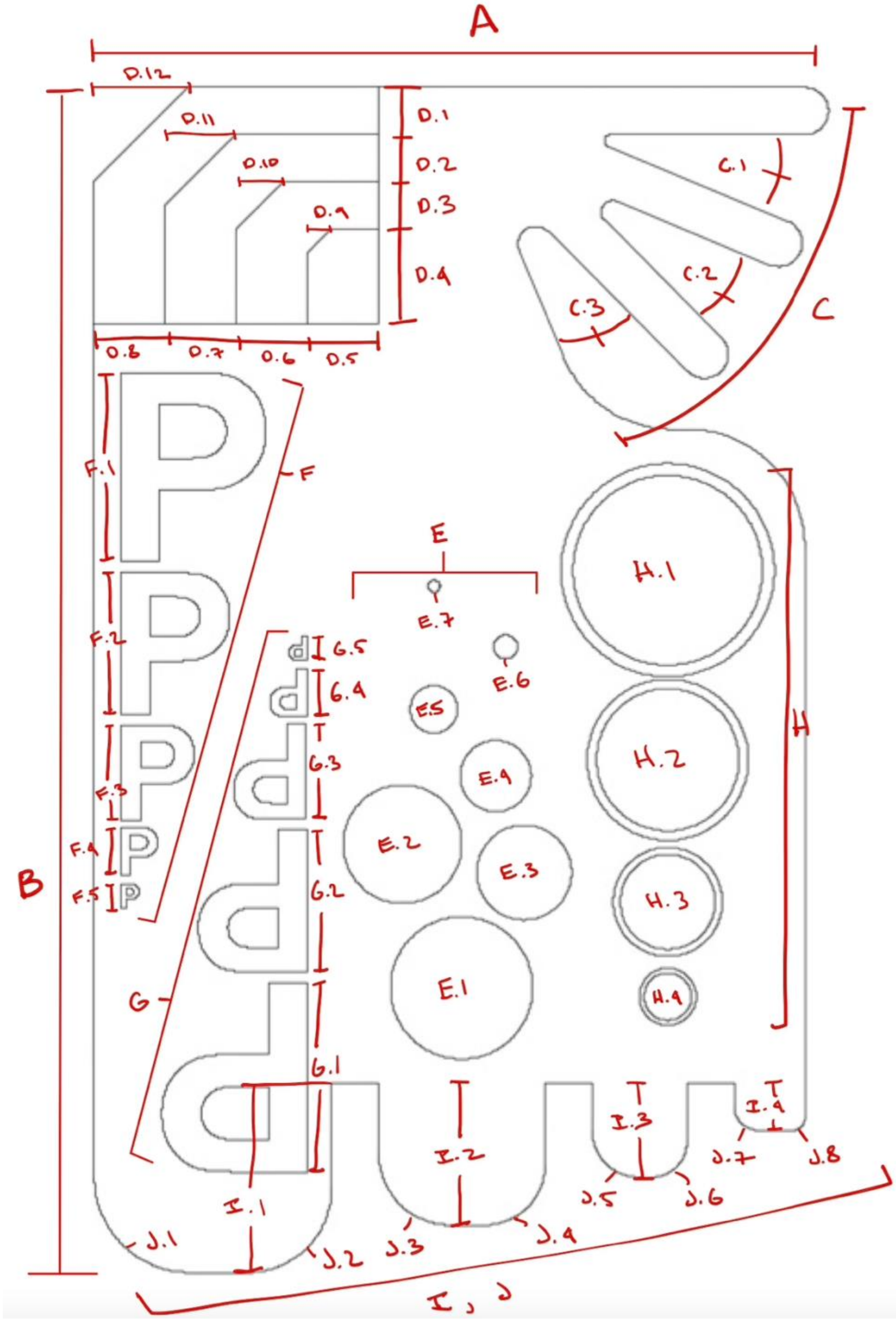


Figure 47. Labelled model of test coupon #1 for use in measuring features.

APPENDIX O.1

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON A

TESTING LAB PROCEDURE & MEASUREMENT LOG

RESIN-BASED 3D PRINTED INVESTMENT CASTING

LAB TECHNICIAN(S) ________________________________ **DATE** ____________

OPTION 6

PROCESS PARAMETERS:

CURING METHOD: ________ SUPPORT DENSITY: ________

PRINT ANGLE: ______ PRINT SPEED: ________ INFILL DENSITY: ________

QUANTITATIVE MEASUREMENTS:

Feature		Nominal Dimension (from CAD) [mm]	Measured Dimension		
			Post-Print	Post-Cure	Post-Cast
A		50			
B		90			
C	1	22.5°			
	2	22.5°			
	3	22.5°			
D	1	2			
	2	2			
	3	2			
	4	2			
	5	3			
	6	3			
	7	3			
	8	3			
	9	0.2			
	10	0.3			
	11	0.4			
	12	0.5			
E	1	6			
	2	5			
	3	4			
	4	3			
	5	2			
	6	1			
	7	0.5			

APPENDIX O.1

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON A (CONT'D)

F	1	8			
	2	6			
	3	4			
	4	2			
	5	1			
G	1	8			
	2	6			
	3	4			
	4	2			
	5	1			
H	1	8			
	2	6			
	3	4			
	4	2			
I	1	8			
	2	6			
	3	4			
	4	2			
J	1	4.5			
	2	4			
	3	3.5			
	4	3			
	5	2			
	6	1.5			
	7	1			
	8	0.5			

QUALITATIVE MEASUREMENTS:

SURFACE FINISH:

NUMBER OF VOIDS/INCLUSION DEFECTS:

OVERALL SUCCESS OF CAST:

GENERAL NOTES:

Appendix O.2

Tentative Test Plan & Measurement Log for Test Coupon B

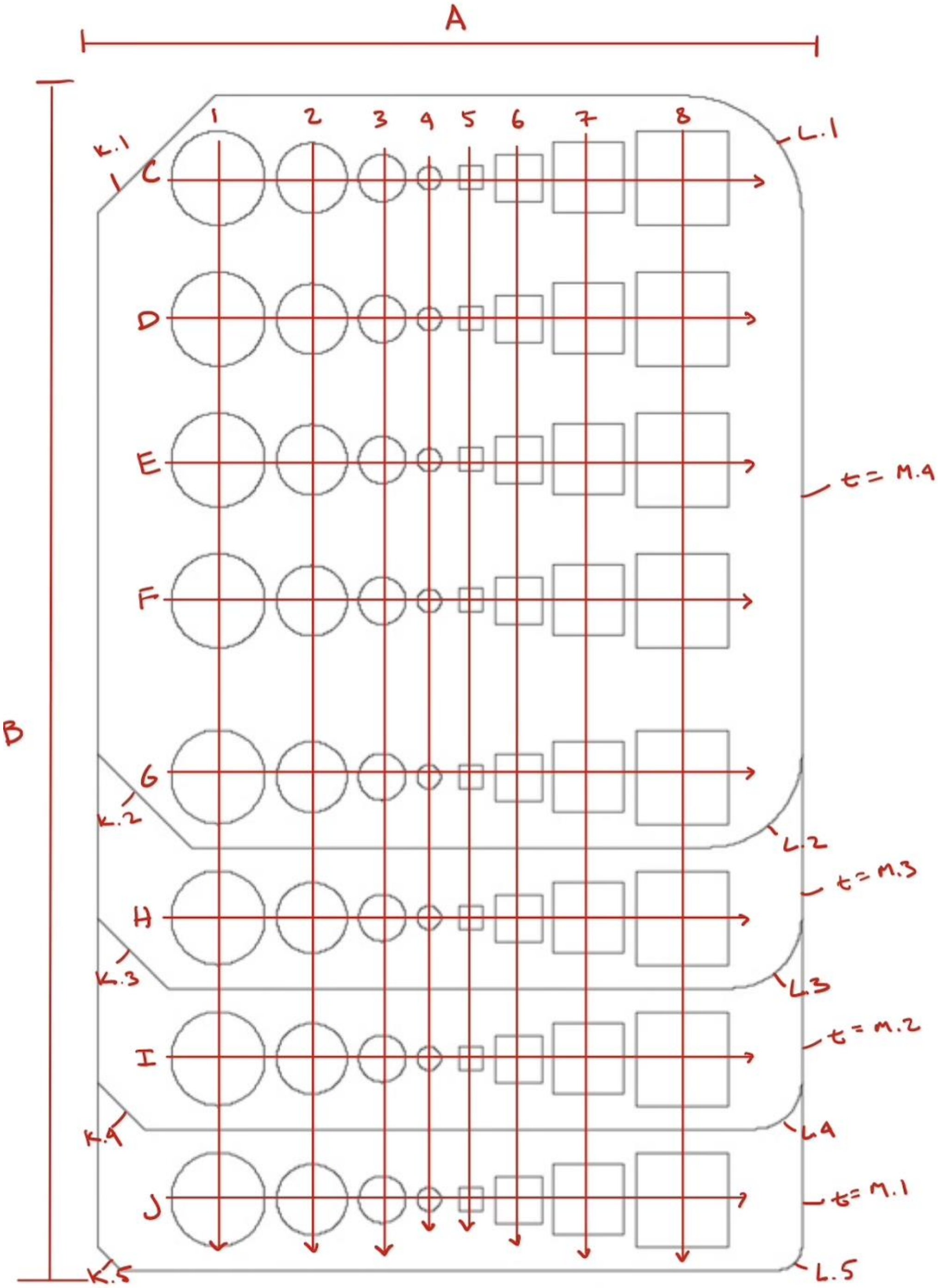


Figure 48. Labelled model of test coupon #2 for use in measuring features.

APPENDIX O.2

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON B

TESTING LAB PROCEDURE & MEASUREMENT LOG

RESIN-BASED 3D PRINTED INVESTMENT CASTING

LAB TECHNICIAN(S) ______________________________ **DATE** __________

OPTION 11

PROCESS PARAMETERS:

CURING METHOD: ________ SUPPORT DENSITY: ________

PRINT ANGLE: ______ PRINT SPEED: ________ INFILL DENSITY: ________

QUANTITATIVE MEASUREMENTS:

Feature		Nominal Dimension (from CAD)	Measured Dimension		
			Post-Print	Post-Cure	Post-Cast
A		50			
B		90			
C	1	4, h = 4			
	2	3, h = 4			
	3	2, h = 4			
	4	1, h = 4			
	5	1, h = 4			
	6	2, h = 4			
	7	3, h = 4			
	8	4, h = 4			
D	1	4, h = 3			
	2	3, h = 3			
	3	2, h = 3			
	4	1, h = 3			
	5	1, h = 3			
	6	2, h = 3			
	7	3, h = 3			
	8	4, h = 3			
E	1	4, h = 2			
	2	3, h = 2			
	3	2, h = 2			
	4	1, h = 2			
	5	1, h = 2			
	6	2, h = 2			
	7	3, h = 2			
	8	4, h = 2			

APPENDIX O.2

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON B (CONT'D)

F	1	4, h = 1			
	2	3, h = 1			
	3	2, h = 1			
	4	1, h = 1			
	5	1, h = 1			
	6	2, h = 1			
	7	3, h = 1			
	8	4, h = 1			
G	1	4			
	2	3			
	3	2			
	4	1			
	5	1			
	6	2			
	7	3			
	8	4			
H	1	4			
	2	3			
	3	2			
	4	1			
	5	1			
	6	2			
	7	3			
	8	4			
I	1	4			
	2	3			
	3	2			
	4	1			
	5	1			
	6	2			
	7	3			
	8	4			
J	1	4			
	2	3			
	3	2			
	4	1			
	5	1			
	6	2			
	7	3			
	8	4			
K	1	5			
	2	4			
	3	3			
	4	2			
	5	1			
L	1	5			
	2	4			
	3	3			
	4	2			

APPENDIX O.2

TENTATIVE TEST PLAN & MEASUREMENT LOG FOR TEST COUPON B (CONT'D)

	5	1			
M	1	1			
	2	2			
	3	3			
	4	4			

QUALITATIVE MEASUREMENTS:

SURFACE FINISH:

NUMBER OF VOIDS/INCLUSION DEFECTS:

OVERALL SUCCESS OF CAST:

GENERAL NOTES:

APPENDIX O.3

EXCEL SPREADSHEET FOR STATISTICAL ANALYSIS OF TEST COUPON C

Feature	Nominal	Measurements from Test Coupons -- Post Cast											
		1	2	3	4	5	6	7	8	9	10	11	12
Overall Length	30.00	29.72	29.70	29.60	29.59	29.62	29.77	29.69	29.70	29.50	29.48	29.79	29.84
Square Extrusion Length	10.00	9.93	9.97	9.93	9.97	9.94	10.00	9.99	10.04	9.87	9.84	9.97	9.98
Square Intrusion Length	10.00	9.71	9.72	9.63	9.62	9.72	9.65	9.66	9.63	9.71	9.72	9.63	9.63
Circle Extrusion Diameter	10.00	10.13	9.89	9.91	9.87	9.94	9.90	9.93	9.91	9.90	9.86	9.95	9.94
Circle Intrusion Diameter	10.00	9.62	9.60	9.65	9.61	9.67	9.70	9.69	9.67	9.68	9.68	9.62	9.64

Feature	Nominal	Deviations from Nominal													
		1	2	3	4	5	6	7	8	9	10	11	12	AVG [mm]	AVG %
Overall Length	30.00	0.28	0.30	0.40	0.41	0.38	0.23	0.31	0.30	0.50	0.52	0.21	0.16	0.33	1.1
Square Extrusion Length	10.00	0.07	0.03	0.07	0.03	0.06	0.00	0.01	-0.04	0.13	0.16	0.03	0.02	0.05	0.5
Square Intrusion Length	10.00	0.29	0.28	0.37	0.38	0.28	0.35	0.34	0.37	0.29	0.28	0.37	0.37	0.33	3.3
Circle Extrusion Diameter	10.00	-0.13	0.11	0.09	0.13	0.06	0.10	0.07	0.09	0.10	0.14	0.05	0.06	0.07	0.7
Circle Intrusion Diameter	10.00	0.38	0.40	0.35	0.39	0.33	0.30	0.31	0.33	0.32	0.32	0.38	0.36	0.35	3.5

Feature	*n*	$(x_i - x_{AVG})^2$													
		1	2	3	4	5	6	7	8	9	10	11	12	SUM	*s*
Overall Length	12	0.0028	0.0011	0.0044	0.0059	0.0022	0.0107	0.0005	0.0011	0.0278	0.0348	0.0152	0.0300	0.1367	0.1067
Square Extrusion Length	12	0.0005	0.0003	0.0005	0.0003	0.0002	0.0023	0.0014	0.0077	0.0068	0.0127	0.0003	0.0008	0.0336	0.0529
Square Intrusion Length	12	0.0017	0.0026	0.0015	0.0024	0.0026	0.0004	0.0001	0.0015	0.0017	0.0026	0.0015	0.0015	0.0201	0.0409
Circle Extrusion Diameter	12	0.0410	0.0014	0.0003	0.0033	0.0002	0.0008	0.0000	0.0003	0.0008	0.0046	0.0005	0.0002	0.0532	0.0666
Circle Intrusion Diameter	12	0.0011	0.0028	0.0000	0.0018	0.0003	0.0023	0.0014	0.0003	0.0008	0.0008	0.0011	0.0002	0.0126	0.0324

Feature	Average Shrinkage	Uncertainty	Upper Limit	Lower Limit
Overall Length	0.33	0.11	0.44	0.23
Square Extrusion Length	0.05	0.05	0.10	-0.01
Square Intrusion Length	0.33	0.04	0.37	0.29
Circle Extrusion Diameter	0.07	0.07	0.14	0.01
Circle Intrusion Diameter	0.35	0.03	0.38	0.32

Appendix P.1

Risk Assessment

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-6	adult first use / test	heat / temperature : severe heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-1-7	adult first use / test	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-1-8	adult first use / test	fluid / pressure : vacuum A vacuum is used to get air bubbles out of cast. Use care with pressured vesicles.	Moderate Unlikely	Low	Have instructor set up the vacuum chamber. Follow manual guidelines	Moderate Remote	Negligible	Complete [11/1/2021] Dr. Carter
1-1-9	adult first use / test	wastes (Lean) : moving material / transport Moving the molton aluminum should be done carefully.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-2-1	adult normal use	mechanical : crushing An arbor press is used to break out plaster.	Moderate Unlikely	Low	Slowly break out investment. Use handle for smoother control.	Moderate Unlikely	Low	On-going [Daily] Dr. Carter
1-2-2	adult normal use	mechanical : cutting / severing When removing gating, the hacksaw is sharp.	Moderate Unlikely	Low	Hold part in vice, saw with control.	Moderate Unlikely	Low	On-going [Daily] Dr. Carter
1-2-3	adult normal use	fire and explosions : hot surfaces The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter

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Risk Assessment

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-4	adult normal use	heat / temperature : burns / scalds The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-2-5	adult normal use	heat / temperature : radiant heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-2-6	adult normal use	heat / temperature : severe heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-2-7	adult normal use	chemical : reaction to / with irritant chemicals The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-2-8	adult normal use	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-2-9	adult normal use	fluid / pressure : vacuum A vacuum is used to get air bubbles out of cast. Use care with pressured vesicles.	Moderate Unlikely	Low	Have instructor set up the vacuum chamber. Follow manual guidelines	Moderate Remote	Negligible	On-going [Daily] Dr. Carter
1-2-10	adult normal use	wastes (Lean) : moving material / transport Moving the molton aluminum should be done carefully.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter

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Risk Assessment

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-3-1	adult maintenance / lubrication	ventilation / confined space : confined space The 3D printing room is small.	Minor Remote	Negligible	Don't overcrowd the room or get too close to the exposed resin if not wearing proctective gear	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-3-2	adult maintenance / lubrication	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-3-3	adult maintenance / lubrication	fluid / pressure : vacuum A vacuum is used to get air bubbles out of cast. Use care with pressured vesicles.	Moderate Unlikely	Low	Have instructor set up the vacuum chamber. Follow manual guidelines	Moderate Remote	Negligible	On-going [Daily] Dr. Carter
1-4	adult trouble-shooting / problem solving	<None>						
1-5-1	adult cleaning	mechanical : crushing An arbor press is used to break out plaster.	Moderate Unlikely	Low	Slowly break out investment. Use handle for smoother control.	Moderate Unlikely	Low	On-going [Daily] Dr. Carter
1-5-2	adult cleaning	mechanical : cutting / severing When removing gating, the hacksaw is sharp.	Moderate Unlikely	Low	Hold part in vice, saw with control.	Moderate Unlikely	Low	On-going [Daily] Dr. Carter
1-5-3	adult cleaning	ventilation / confined space : confined space The 3D printing room is small.	Minor Remote	Negligible	Don't overcrowd the room or get too close to the exposed resin if not wearing proctective gear	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-5-4	adult cleaning	chemical : reaction to / with irritant chemicals The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah

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RISK ASSESSMENT

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-5-5	adult cleaning	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
1-6-1	adult misuse	heat / temperature : burns / scalds The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-6-2	adult misuse	heat / temperature : radiant heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-6-3	adult misuse	heat / temperature : severe heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
1-6-4	adult misuse	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
2-1-1	passer-by / non-user walk near	heat / temperature : burns / scalds The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
2-1-2	passer-by / non-user walk near	heat / temperature : radiant heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter

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Risk Assessment

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-3	passer-by / non-user walk near	heat / temperature : severe heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
2-1-4	passer-by / non-user walk near	chemical : reaction to / with irritant chemicals The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
2-1-5	passer-by / non-user walk near	chemical : skin exposed to toxic chemical The resin should not touch skin.	Minor Unlikely	Negligible	Wear protective gear. Wash hands if resin gets on it.	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah
2-2-1	passer-by / non-user observe / watch	heat / temperature : radiant heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
2-2-2	passer-by / non-user observe / watch	heat / temperature : severe heat The molten AL is hot before/after casting.	Serious Unlikely	Medium	Wear provided protective gear, move slowly. Wear gloves until part is fully quenced.	Serious Unlikely	Medium	On-going [Daily] Dr. Carter
2-2-3	passer-by / non-user observe / watch	ventilation / confined space : lack of fresh air The 3D printing room doesn't have any ventilation for resin fumes.	Minor Remote	Negligible	Don't overcrowd the room or get too close to the exposed resin if not wearing proctective gear	Minor Remote	Negligible	Complete [11/1/2021] Matthew/Isaiah

APPENDIX Q.1

DESIGN VERIFICATION PLAN & REPORT DVP&R

DVP&R - Design Verification Plan (& Report)

Project: 3D Printings/Casting | Sponsor: Dr. Xuan Wang | Edit Date: 3/8/22

	TEST PLAN									TEST RESULTS		
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing	Success?
1	Library of successful models	Currently have all the CAD models, but must try casting each of them and modifying gating structure until all of them are successful. Success is defined as filling the entire cavity with metal to provide the intended shape.	Visual inspection to ensure model is fully cast. # of successful models.	Pass/Fail >5 successful models	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Castable 2 Resin, Investment material, Aluminum 356	Isaiah	10/25/21	3/2/22	6 models are currently in the library	All of them have high reliability which is great!	Y
2	Library of student-ready models	Based on Test #1, this test will be similar in that we will count the number of successful models. The student-ready models are the dice, ring, and Kirby (possibility of skull based on complexity).	Visual inspection to ensure model is fully cast. # of successful models.	Pass/Fail >3 student models	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Castable 2 Resin, Investment material, Aluminum 356	Isaiah	11/8/21	12/1/21	3 models are currently ready for students	The dice, rings, and Kirby die casting are all great learning opportunities for students	Y
3	Process satisfaction survey	Get a group of >5 students to test out the process. This will include printing models, curing, investing, burnout, and casting. This will likely go over several days since each process can take some time. The students will follow the instruction manual/video and use us for assistance.	Satisfaction survey (provided in CDR report) with some general questions and ratings	75% satisfaction	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Castable 2 Resin, Investment material, Aluminum 356	Mattthew	1/24/22	2/9/22	N/A	The students weren't able to get into the lab and pour their investments, so this was skipped (at the instructors request)	Y
4	Customization satisfaction survey	Satisfaction surveys for customizing the provided models. A group of >5 students will be expected to load the model in Fusion 360 and add their own personal touch. A video tutorial will be provided that they will follow as general guidance, but ultimately the design is up to them.	Satisfaction survey (provided in CDR report) with some general questions and ratings	75% satisfaction	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Castable 2 Resin, Investment material, Aluminum 356	Mattthew	1/24/22	2/9/22	About a 100% score was achieved based on student feedback	Nothing major to fix!	Y
5	Curriculum satisfaction survey	Throughout Tests #3 and #4, the lab manual, video tutorial, and example models will be shown to guide them through the process. This satisfaction survey will evaulate these materials and their appropriateness/completeness for implementing into the IME curriculum.	Satisfaction survey (provided in CDR report) with some general questions and ratings	75% satisfaction	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Castable 2 Resin, Investment material, Aluminum 356	Mattthew	1/24/22	2/9/22	About a 100% score was achieved based on student feedback	Nothing major to fix!	Y
6	Time to clean/post-process	Average the time needed to clean the parts, remove supports/gating structure, and sand down the model to improve surface finish. Will record time on each part manufactured.	Time	<15 minutes for post-printing, <15 minutes for post-cast	Snips, grinding wheel (in IME lab), files, sand paper, paper towels, stop watch	Student models (dice, rings, Kirby)	Isaiah	11/8/21	12/1/22	Approximately 1 minute between printing and casting, and then on average 10 minutes for post-cast	Dependent on how much the student wants to clean up their finished product, but 10 minutes is aboout average	Y
7	Time for respective process (print vs cast)	Average time for the student models to print/cure, as well as the burnout schedule and investment-making process.	Time	<8 hours for 3D printing/curing, <12 hours for burnout schedule	Moonray printers, curing station, oven, stop watch	Student models (dice, rings, Kirby)	Matthew	11/8/21	3/1/22	about 4 hours per 12 parts if both printers are funning, and burnout is 8 hours	Nothing to do to speed this up, but it's within reason	Y
8	Reliability	Test a large quantity of models to make sure they are generally going to work (for student success in the lab).	# of models passed/fails	Pass/Fail on individual models. 90% success in total	IME casting lab, MoonRay printers, curing chamber, oven, investment flasks	Student models (dice, rings, Kirby)	Matthew	1/24/22	3/1/22	90% (49 made throughout the quarter, 44 successes)	Improving reliability would come from a vacuum pump for the investment to remove all air bubbles	Y
9	Quantifiable features	For the test coupons, we want to make sure that there are enough features to quantify/measure to inspect the shrinkage throughout the process. Each test coupon will have several quantifiable features measured post-print, post-cure, and post-cast. The number of quantifiable features are determined from the CAD files.	Counting number of possible measurements that can be taken from the models	>5 measureable features	Fusion 360	N/A. Just CAD files of the test coupons.	Isaiah	5/25/21	5/31/21	Each coupon has over 50 measureable features.	N/A. Documented in the Appendix of the CDR report.	Y
10	Volume	For budgetary purposes, the student models can't be too large. Additionally, they must fit within the investment flasks. Volume will be decided from the Fusion 360 files and ensured to be as low as possible.	Volume (in^3)	<$1in^3$	Fusion 360	N/A. Just CAD files of the test coupons.	Isaiah	11/8/21	5/31/21	The largest ring (and sprue) is $0.34in^3$ and the dice (and sprue) is $0.54in^3$	Well within the acceptable range, so the parts are also within budget	Y
11	Video length	Ensure the video is a reasonable length (we don't wantt o bore students). However, it still needs to be descriptive enough to ensure high student success. The test will come from clipping down the video to a reasonable length and using feedback from Test #5 to see if it's an appropriate length.	Time	<15 minutes	Stop watch	Video tutorial	Matthew	1/24/22	2/9/22	The total video length (across all 4 videos) is about 10 minutes	Seems appropriate according to the test subjects	Y

Appendix R.1

Gantt Chart