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Raytheon -- Design of Boat Hull Segments Using Additive Manufacturing

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Final Design Report

Team 12: 3DPB
Design of Boat Hull Segments Using Additive Manufacturing

Raytheon

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Abstract

The purpose of this project was to assess the effectiveness of designing and producing a boat hull in segments, using additive manufacturing. The group accomplished this, by completing an in-depth research into additive manufacturing processes and 3 Dimensional (3D) printing techniques. The design was to be dimensionally stable, and have a process that strives for easy repeatability and reproducibility. Evaluated was the V-Bottom, Round Bottom and Flat Bottom style. Through the use of modeling the different hull styles in SolidWorks it was determined the Flat bottom was more stable and reproducible. The hull was broken into four segments and used finger joints to align and join the segments. The 3D printer used was capable of printing Acrylonitrile styrene acrylate (ASA), Polyethylene Terephthalate (PETG), Acrylonitrile Butadiene Styrene (ABS), Nylon, Carbon Fiber and Polycarbonate. After printing with all these materials it was determined ASA would be the best fit for additive manufacturing of a boat hull. After the segments were printed and joined together with adhesives a waterproof coating was applied. The assembled hull was subjected to a series of strength tests to determine its effectiveness in this application. The finished product rode smoothly in water, was weather resistant, safe, buoyant, and reliable to manufacture.

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List of Acronyms

1. 3D 3 Dimensional
2. ABS Acrylonitrile Butadiene Styrene
3. ASA Acrylonitrile Styrene Acrylate
4. CAD Computer Aided Design
5. CDR Critical Design Review
6. DEM Department of Environmental Management
7. OSHA Occupational Safety and Health Administration
8. PETG Polyethylene Terephthalate
9. PLA Polylactic Acid
10. POC Proof of Concept
11. PVA Polyvinyl Acetate
12. QFD Quality Function Deployment
13. RP Rapid Prototyping
14. SLA Stereolithography
15. USPTO United States Patent and Trademark Office
16. BAAM Big Area Additive Manufacturing
17. FEA Finite Element Analysis
18. CFD Computational Fluid Dynamics
19. CEL Coupled Eulerian-Lagrangian

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Introduction

This report is focused on designing a boat hull in segments that can be created using additive manufacturing. Many factors go into this design such as the material being printed, the hull shape, the number of segments, and how the segments will be adhered together. At the moment, there is no 3D printed boats on the market, so these will be the first documented tests on this idea. Outlined in the report below is how it is planned to accomplish the creation of this boat hull using additive manufacturing technology.

Although the origins of additive manufacturing can be traced back to a patent created in 1986 by Charles Hull as stated by Flynt [1], it has only become relevant to the public within the past 10-15 years. Stereolithography (SLA), or Rapid Prototyping (RP) as it was initially called, was not very popular or reliable in its early stages. The first ever 3D printer was made in 1986, and like any other skill, it is an art that requires much repetition and exposure to perfect. Each 3D print job can be unique, depending on factors such as geometry and material being used, that will affect what is required from the printer. This innovative process was first used for inexpensive and fast prototyping but has developed into a reliable process with endless possibilities in thousands of different applications.

Additive manufacturing can be used as a cost-effective technique of developing prototypes before the final products are sent to the production lines. In today's world it has become quite advanced, and with it coming into the focus of the public eye, improvements keep coming which have led to the technology being made available to everyone, not just industry. The price of 3D printers has also gone down by the thousands, which makes the service available to a broader audience. The printers are generally user friendly, and thanks to free software programs, it is much easier to design 3D models and have them printed.

Today, anyone can produce prints with a wide variety of materials that are not explicitly plastic, such as wood, metal, and even carbon fiber. Although these special filaments are plastic based, their respective particles are mixed into a plastic, generally Polylactic Acid (PLA), to provide the finished product with exquisite characteristics both material and aesthetic, that cannot be obtained from a regular plastic. The possibilities of what can be printed nowadays keeps innovators pushing the envelope with this technology. Now things such as musical instruments, household items, and jewelry can be printed. Where does the technology go from here? Well, in the near future inventors are looking to 3D print homes, drones, vehicles, and even prosthetic body parts in the medical industry.

Patent Searches & Literature Searches

Additive Manufacturing for Archaeological Reconstruction of a Medieval Ship [2]

Abstract- The purpose of this paper is to examine the suitability of additive manufacturing technologies in the reconstruction of archaeological discoveries as illustrative models. The processes of reverse engineering and part fabrication are discussed in detail, with particular emphasis placed on the difficulties of managing scaling and material characteristics for the manufacturing process. Design/methodology/approach - Through a case-based approach, this paper examines the reconstruction of a fifteenth-century ship recovered from the River Usk in South Wales, UK. Using interviews and process data, the paper identifies challenges for both archaeologists and manufacturers in the application of additive manufacturing technologies for archaeological reconstruction applications. Findings - This paper illustrates both the suitability of additive manufacturing in archaeological restoration, but also the challenges which result from this approach. It demonstrates the practical considerations of scaling process and materials, whilst also highlighting the techniques to improve accuracy and mechanical properties of the model. Originality/value - Whilst the technologies of additive manufacturing have previously been applied to model making, little scholarly research has considered the practical techniques of design elicitation and manufacturing for archaeological applications. Using an in-depth case study, this paper highlights the principal considerations for these applications, and provides guidance in the mitigation of manufacturing issues.

Relevance- This article is about additive manufacturing of a ship display which gives an example of what is trying to be achieved. This situation in a way is related to the project of designing boat hull segments through the use of additive manufacturing. This article proves that additive manufacturing has the capability to print a complex design, such as a ship.

Scientists Develop 3D Printed, Self-Driving Boats [3]

Abstract- Researchers from the Massachusetts Institute of Technology's (MIT) Computer Science and Artificial Intelligence Laboratory (CSAIL) and the Senseable City Lab in the Department of Urban Studies and Planning (DUSP) have developed an autonomous boat that combines high maneuverability with precise control and can be rapidly printed using only a low-cost 3D printer. For precise positioning, the researchers incorporated an indoor ultrasound beacon system and outdoor real-time kinematic GPS modules, which allow for centimeter-level localization, as well as an inertial measurement unit (IMU) module that monitors the boat's yaw and angular velocity, among other metrics. To improve the control of the boats, the team also developed a method that enables the boat to track its position and orientation more quickly and accurately with a more efficient version of a nonlinear model predictive control algorithm that is used to control and navigate robots within various constraints.

Relevance- This article about how scientists used a low-cost 3D printer to develop an autonomous boat that supports the goal of designing a boat hull using additive manufacturing. This situation in a way is related to the project of designing boat hull segments through the use of additive manufacturing and printed waterproof materials. This article proves that a 3d printer has the capability to print a complex design, such as a boat along with that product having the ability to be used in a body of water.

Additive Manufacturing for Marine Tooling [4]

Abstract- A 3D-printed boat hull pattern has been completed using a near-net shape additive manufacturing process, and a production-capable fiberglass mold has been successfully pulled from the pattern, in a collaborative proof-of- concept joint evaluation program conducted by Thermwood Corp (Dale IN, US), Techmer PM (Clinton TN, US) and Marine Concepts (Cape Coral FL, US). On display at the AM2017 Additive Manufacturing Conference, held Oct 10-12, 2017 in Knoxville TN, US, the pattern was 3D printed slightly oversized, over a period of approximately 30 hours, and subsequently trimmed to final net size and shape, using Thermwood's trademarked Large-Scale Additive Manufacturing (LSAM) system. The printed material was Techmer's trademarked Electrafil ABS LT1 3DP, which reportedly has proven suitable for marine tooling applications when processed using LSAM print technology. The Thermwood machine used for the demonstration program has a 10-ft-by-20-ft (3.05m-by-6.1m) worktable, but Thermwood says it also offers larger machines.

Relevance- This article is how a boat hull pattern can be created from a 3D printer used to create production capable fiberglass mold. This situation in a way is related to the project of designing boat hull segments through waterproofing materials. This article proves that a waterproof material can be 3d printed and used within a body of water.

Conducting a patent search is an essential piece of the research process when coming up with a new design. Knowing what is currently on the market is the first step when trying to come up with an original design. Designing something that has already been established is a waste of time, resources, and money. Finding patents related to the design idea can be building blocks to what the final design could look like. For example, flaws can be found in old patents that can be improved upon or new ideas can be generated by comparing different previously patented designs. Shown below are relevant patent searches.

Patent Number 7,752,986 for Boat hull design [5]

Abstract - A shallow draft boat has a flat bottom that extends along a substantial length of the boat hull. The port and starboard sides of the boat that extend beyond the bows are slightly inwardly inclined toward the center longitudinal plane of the boat to provide a tumblehome configuration. The hull progressively increases in width from the bows toward the stern and has a maximum width within the rear 15% waterline length of the hull. Compressed air nozzles, in association with venturi nozzles, controllably generate an air cushion under the bottom of the hull for selectively reducing drag on the hull. Fore and aft steering rotors are provided on the bottom of the hull for maintaining the boat accurately along its true heading. The boat also comprises retractable trim surfaces at the stern for adjusting the attitude and the speed of the hull.

Relevance - This patent is for a shallow draft boat with a flat bottom that extends along a substantial length of the boat hull. The patent gave great insight into how the hull may be designed to optimize buoyancy and maintain a balance in weight throughout the boat.

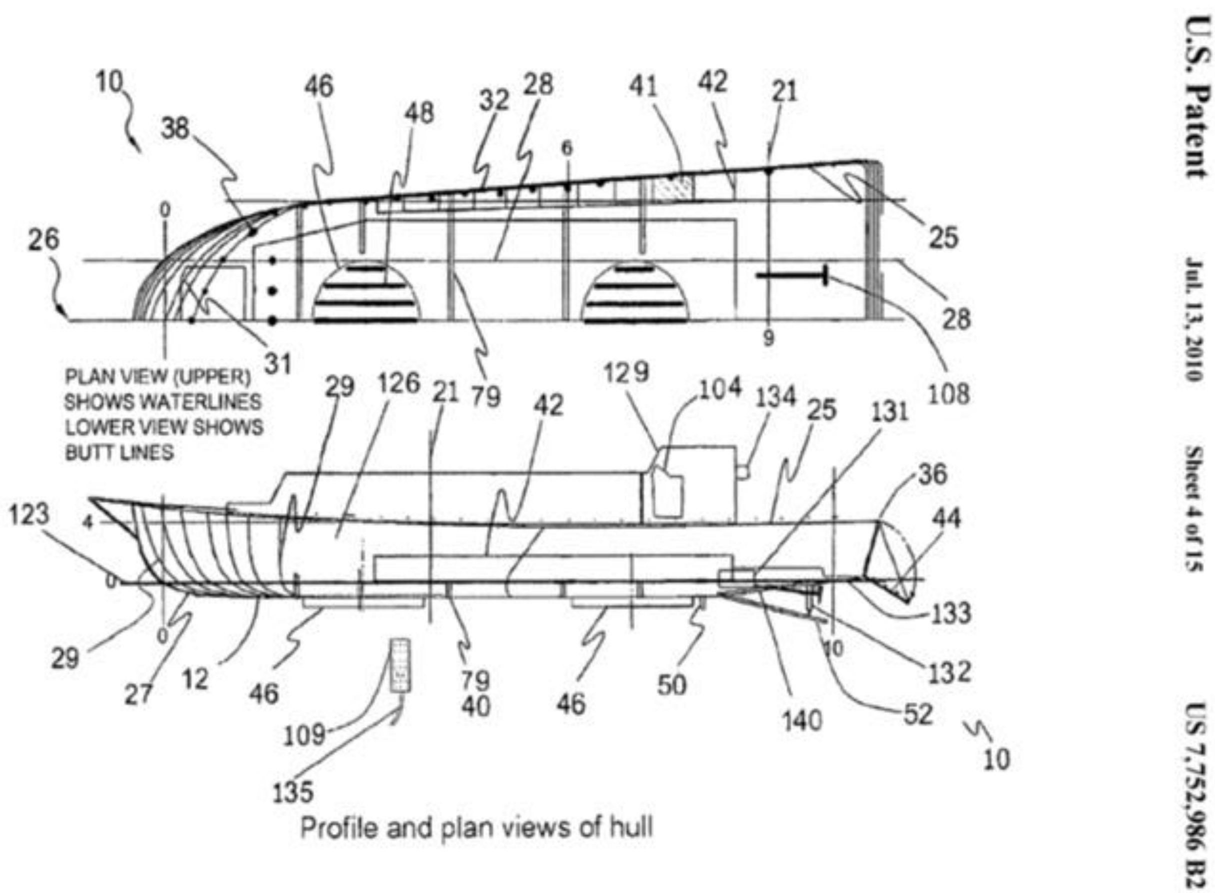

Figure 1: Hull Design Pate

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The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is best defined by the appended claims.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

In order that the invention may be more fully understood, it will now be described, by way of example, with reference to the accompanying figures in which:

FIG. **1** is an illustrative view of the prior art;

FIG. **2** is a view of the present invention;

FIG. **3** is a front view of the present invention;

FIG. **4** is a plan and profile view of the present invention;

FIG. **5** is an orthographic view of the present invention;

FIG. **6** is a cross sectional view of the rotor disk of the present invention;

FIG. **7** is a plan view of the rotor disk assembly of the present invention;

FIG. **8** is a graphic cross section of a venturi system of the present invention;

FIG. **9** is an illustrative side view of the present invention;

FIG. **10** is an illustrative side view of the present invention;

FIG. **11** is a diagram of a sailing pattern of the present invention.

FIG. **12** is a cross-sectional view in FIG. **4** of ballast bucket **41** of the present invention.

FIG. **13** is a sketch of an inside weld to be used in welding the sides and bottom of the hull

FIG. **14** is a sketch showing a metal sheet that resist marine growth clad to the underwater portion of the hull and the extent of the cladding of metal sheet beyond the waterline.

FIG. **15** shows how pressurized air nozzles and venturis can reduce wetted surface of present-day commercial and navel bottoms.

DESCRIPTION OF THE REFERENCED NUMERALS

Turning now descriptively to the drawings, in which similar reference characters denote similar elements throughout the several views, the figures illustrate the Improved Boat Hull Design of the present invention. With regard to the reference numerals used, the following numbering is used throughout the various drawing figures.

10 Boat Hull Design of the present invention
12 hull
14 spring-loaded hinge
16 expanded metal grating
18 stern area
19 swing door
20 enclosed patio railing structure
21 station line
22 scupper
24 station cross sections
25 sheer line
26 center plane
27 wetted surface (area of outer hull surface of the floating hull in direct contact with the surrounding water)
28 main butt planes
29 butt lines (curved)
30 diagonal planes
31 curved water lines
32 straight side
36 stem
38 compressed air nozzle
40 venturi

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41 water ballast bucket
42 a whole side of ballast buckets
44 boarding ramp
46 steering rotor
48 rotor fin
50 speed brake
52 trim surface
54 angle of heel
56 sheet of air
58 rotor bearing
59 thrust bearing
60 fastener
62 rotor shaft
64 rotor shaft housing
66 seal
68 wood bearing block
70 rotor plate
72 reinforcing rib
74 hull ring reinforcement
75 rotor reinforcement ring
76 rotor disc bearing surface
78 venturi slot
79 venturi channel
80 venturi air intake
82 air inflow control
83 air manifold
84 air flow
86 water flow
88 water surface
90 ocean swell
92 swell direction
94 course of the craft
96 wind direction
98 course of hurricane
100 swell pattern
101 rudder
102 keel
103 permanent ballast
104 integrated pilot house navigation, radio and equipment control center
105 stem, most forward part of hull
106 starboard bow
107 port bow
108 propeller
109 remote control unit for diverse equipment
111 sail-driven power
112 deck
113 deck hatch
114 grating
116 ballast water redistribution system
118 ballast bucket door
119 bucket door activator mechanism
120 rainwater drain from ballast bucket to fresh water tank
121 isolator valve
122 fresh water tank
123 designed, or static water line
124 ballast bucket vent
125 inside weld
126 manifold-controlled output-source of compressed air
127 bonding agent
128 bonded to hull anti-marine growth metal sheet
129 wheel house
130 metal strip
131 propulsion motors and sources of electrical, hydraulic and pneumatic resources mentioned in the specifications and in the claims
132 trim surface control

Figure 2: Patent 7,752,986 Description

133 displacement-type stern
134 winch to launch and retrieve water skiers
135 interconnecting cable
139 roller
140 trim surface recess
141 self-furling sails equipment

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The following discussion describes in detail one embodiment of the invention. This discussion should not be construed, however, as limiting the invention to this particular embodiment. Practitioners skilled in the art will recognize numerous other embodiments as well. For definition of the complete scope of the invention, the reader is directed to appended claims.

Referring to FIG. **1**, shown is the prior art state of the design of a blue water, one-class, racing sailboat. This hull was specifically designed according to the Storm Trysail Transpac 65 Rule. This vessel is now in full use. It is said to be a long term competitor in this specific class. It is expected to be able to attain 40+ knots under certain conditions.

The things to note are the massive ballast **103** at the end of a 16 ft long, high aspect ratio keel **102**, the sharp, water plow shape of the bows, **106** and **107**, and the deep high aspect-ratio rudder **101**. Item **105**, the most forward part of the hull is referred to as the stem.

Another thing to note is the relatively low reserve buoyancy of the forward and the aft sections of the hull. Operating vessels in storms necessitates ample reserve buoyancy in the bows and the stern of said vessels. In my experience as shipmate in the service of the merchant marine in crossing the very turbulent North Atlantic Ocean as much as 15 times per year such buoyancy is essential in all-weather cruising and racing vessels. The hull shown in FIG. **1** is not an all-weather sailing craft.

On modern sailing vessels the angle of the bow surfaces with the lengthwise center plane of the boat is sharp, so that the bows **106** and **107**, at speeds below planing, push the water to the side to create a gully through which the hull can pass. This continuous pushing aside of massive amounts of water reduces the speed of the hull. Modern hull designs incorporate a rather shallowly curved bottom into the hull so that when the boat speeds up sufficiently, the bows will be raised above the waterline as the boat assumes a planing attitude. At lower speed ranges, the entire hull remains immersed up to the waterline. In this situation the plow effect of the hull to push water out of the way is considered the best way to move the slow moving hull through the water.

Referring to FIG. **2**, shown is a view of the present invention **10**. The solidly enclosed patio area **18** has one foot high or so flattened metal grated scuppers **22** upward from the patio deck **18** at the base of the enclosed patio railing structure **20** that have top hinged spring **14** loaded swing doors **19** on their outside so that when a swell rises above the scuppers **22** the doors **19** are in closed position due to the spring load **14** on them; but when the patio area **18** is flooded the doors **19** swing open by the pressure of the water that has flooded the patio area **18** allowing the water to quickly drain overboard. The swing doors **19** do not cover the entire metal grated area **16** but leave about a ½ to ¼ inch gap at the bottom through which the last remaining water in the patio area **18** can drain away. Extra buoyancy is only needed for a few seconds or so in a situation of emergency. This scupper design allows for such momentary extra buoyancy.

Referring to FIGS. **3** and **4**, shown are the hull lines in front view, plan view and profile view of the hull **12** of the present invention **10**. The plan view in FIG. **4** identifies curved water lines **31**, the projection of the sheer line **25** and the straight, numbered main station lines **21**. Auxiliary station lines, not shown, were necessary to identify the correct shape and correctness of the main cross section curves. FIGS. **3** and **4** show miscellaneous shape identifying lines to keep the drawings uncluttered and still show the proper shape of the hull. The front view shows some station cross section curves **24** to identify shape progression of the hull **12** from bow to stern. The profile view shows curved butt curves/longitudinal cross sections **29**. The equally spaced 'station' lines **21** start with '**0**' station placed at the waterline at the stem **105** and station '**10**' placed at the waterline at the stern **36**, and butt cross sectional curved lines **29** to show the progression of the shape of the hull **12** from centerline toward the sides. For a hull **12** of, for example, a water line length of 50 feet it is about 12 ft shorter at the waterline than the STP 65 shown in FIG. **1**, yet the bows, **106** and **107**, and stern **36** sections of the hull **12** in FIGS. **3** and **4** have many times the reserve buoyancy. As can be seen from the station cross section curves **24** in the front view of FIG. **3**, the hull **12** will allow plow action at very low speed, but very quickly will force the upcoming water under the hull **12**. This hull design **12** causes the bottom surface to rise slowly from station '**2**' to the waterline at station '**0**; that at higher speed ranges causes low-energy spray to be emitted rather than big, energy-consuming, bow waves.

This hull **12** has many unique and advantageous features; a very important one is that the entire underwater surface is clad with a thin sheet of marine-growth resisting material such as copper; making the hull **12** virtually maintenance free. In order to plane and surf this hull design the bottom must remain smooth and free from biological growth. Over the long haul cladding the surface with a permanent, anti-marine growth material is the best and, overall, the cheapest way to accomplish this.

To get the hull **12** to plane compressed air emitted from nozzles **38** introduce a sheet of air under the hull **12**, and sail force **111**, the kinetic energy of a swell **90** or forward motor power **108** brings the hull **12** into a planing position. The nozzles **38**, along the straight sides are placed so that when the hull **12** is heeled some nozzles **38** spray air to the sides of the hull **12** and the alternating nozzles **38** release air underneath the hull **12**. This is the best arrangement for a sailing hull **12** to reduce wetted surface **27**. Once the hull **12** glides on a sheet of air supplied by the crosswise running venturis **79**, the nozzles' **38** flow of air **84** can be reset or shut off. In a sailing race these things can be accomplished before the hull **12** passes the starting line.

Looking at the plan view one can see an array of copper or monel, compressed air nozzles **38**, represented by black dots that when turned on help the hull **12** to attain a planing attitude by increasing speed at a sharply reduced drag factor. The hull's speed will then increase sharply, causing the venturis **79**, also seen in FIG. **4**, to activate. From then on the boat glides forward on a cushion of air, and the airflow from the compressed air nozzles **38** can be shut off or set to a reduced flow. This hull **12**, when used as a sailing craft, will plane at any angle to the wind as long as the angle of heel does not exceed 4° or so. The heeling angle can be kept under control by judicious use of ballast water sail. The judicious use of water ballast in the rear sections of the water ballast buckets **41** can also aid the hull **12** in maintaining a proper planing or surfing attitude.

The straight, angled, sides of the hull **12** have several purposes and advantages:

Figure 3: Patent 7,752,986 Description cont.

Patent Number 10,145,073 for Watercraft docking structure [6]

Abstract- A structure includes a bracket and a vertical member. The vertical member includes a vertical member top end and a vertical member bottom end. The vertical member is affixed to the bracket. The structure further includes at least one bumper. The at least one bumper is affixed to the vertical member bottom end via a bumper connecting structure. The structure further includes an arm member. The arm member includes an arm member first end and an arm member second end. The arm member second end is affixed to the vertical member top end. In another aspect, a structure includes a support, and affixed to the support, a bracket. The structure further includes, affixed to the support via a bumper connecting structure, at least one bumper. The structure further includes, affixed to the support, an arm member.

Relevance- This patent is for a watercraft docking structure. This situation in a way is related to the project of designing boat hull segments through buoyant and waterproof 3D printed materials. This patent proves that 3D printed materials can float within a body of water and are used with relation to boats.

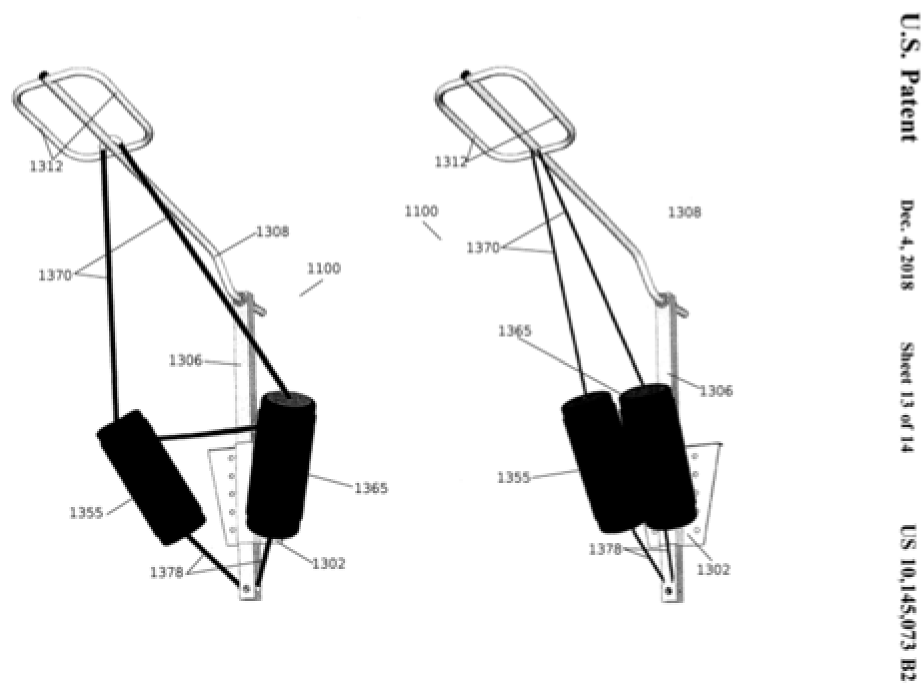

Figure 4: Docking station 1

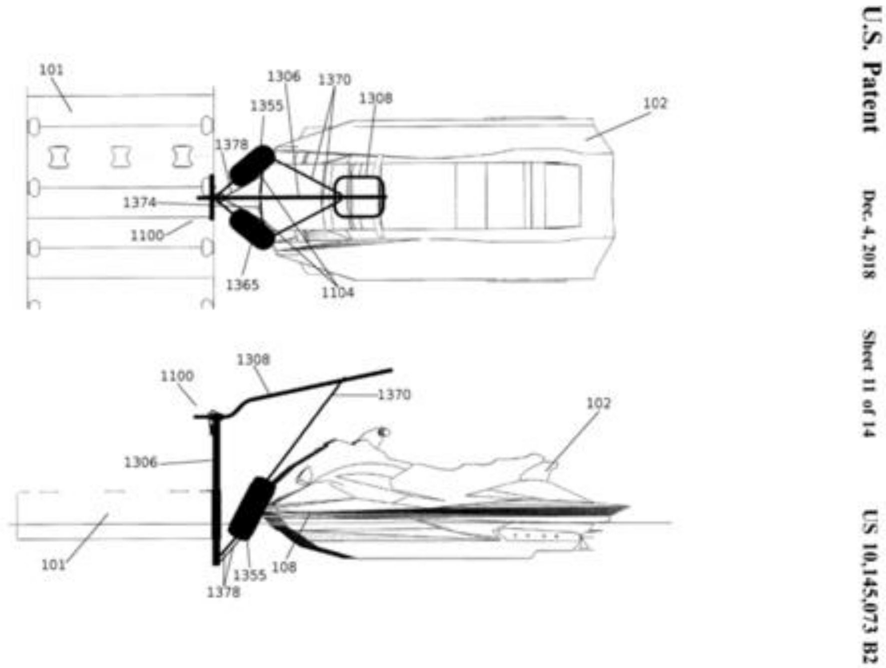

Figure 5: Docking Station 2

Evaluation of Competition

Additive manufacturing is a rapidly growing field and seems to have no restrictions on what can be accomplished. One of the next big ideas that innovators are working on, is designing vehicles that can be 3D printed. Right now, there are many designs available for 3D printed cars and some may be available to be purchased by consumers as soon as next year. Although 3D printed cars could be the next big thing, there is no record of attempts made for production 3D printed boat hulls for sale to the public.

In order to optimize the boat hull design, a target consumer had to be decided on. At the moment, it is not planned for the boat hull design to be massed produced, meaning that the only consumer will be Raytheon as they are the sponsoring company. Once the customer was determined, it was possible to determine the necessary requirements and how the design met these requirements. This was implemented through a Quality Function Deployment (QFD). QFD is a focused methodology for carefully listening to the needs of the customer and then effectively responding to those needs and expectations through a well-organized chart. This chart includes a house of quality with a column for customer requirements, how the design will meet these requirements, how these requirements relate to each other and other similar designs. Below is the team's QFD analysis.

Despite the shape and size, all boat hulls are designed to do one of only two things: either displace water, or ride on top of it, which is called planing. The hull types evaluated are as follows [7]:

- Flat-Bottomed Hulls - Boats with "flat-bottomed" hulls are very stable, great for fishing and other uses on calm, small bodies of water.
- Round-Bottomed Hulls - "Round-bottomed" hulls are typically displacement hulls and are designed to move smoothly through the water with little effort. An example of a round-bottomed hull is that found on a canoe. One drawback to the round-bottomed design is that it's less stable in the water and can capsize more easily. So, extra care needs to be taken when entering, exiting and loading these types of boats.
- V-Shaped Hulls - "V-shaped" hulls are planing hulls and are the most common type of hull for powerboats. Deep v-shaped boats are designed to plane on top of the water at higher speeds and provide a smoother ride through choppy water. These boats are usually equipped with a larger engine than flat or round-bottomed boats.
- Multi-Hulled - Finally, let's look at "multi-hulled" boats. These boats can have either planing or displacement hulls depending on the shape of hull and size of engine. Multi-hulled boats are some of the most stable on the water. They also require more room to steer and turn. Examples of common multi-hulled boats are catamarans and pontoon boats.

The Flat-Bottomed Hull is the most stable hull and cost effective to produce. Flat-Bottomed hulls can be marketed not only in local retail stores such as Wal-Mart, Dicks Sporting Goods, Bass Pro Shops, Cabelas, Modells, along with other smaller private retailers which will allow for reach a large consumer base.

Specifications Definition

Raytheon requirements for the design of a boat hull were to use additive manufacturing and bond multiple structures together. In order to optimize the design, the hull need to be broken up into 4 structures and bonded together. In order to fit and align the structures finger joints were required. Bonding material was required to join the structures together and waterproofing applied to seal the structures for a watertight hull.

The team was asked to create a boat hull in segments using additive manufacturing. Other than this simple project definition no other specifications were given to us from our sponsor. This gave freedom to take the project in any direction while also having the option to be creative. The basic functions of the design are to be able float high on the water to allow for more weight and be as light as possible while being able to withstand the forces of water at high speeds when moving on water. The hull had to be split in segments and also withstand the forces of water on the hull at high speeds. The team had to abide by all safety guidelines for Occupational Safety and Health Association (OSHA) and the Coast Guard.

Table 1: Design Specifications

Boat Hull Dimensions	
Full Scale	*Test Scale*
Width - 5.56 ft	Width - 0.397 ft (4.76 in)
Length - 13.79 ft	Length - 0.989 ft (11.87 in)
Height - 2.548 ft	Height - 0.181 ft (2.17 in)
Boat Hull Weight	
Full Scale	*Test Scale*
Weight - 743.45 lbs	Weight - 0.3 lbs
Infill Percentage	
Full Scale	*Test Scale*
5%	15%
Shell Thickness	
Full Scale	*Test Scale*
0.4 in	0.02 in
Environmental	
OSHA Standard 1926.106a-d (boating safety); **Respiratory** - OSHA respirator regulations 29 CFR 1910.134 and European Standards EN 141, 143 and 371; **Eye safety** - Safety glasses with side shields per OSHA eye- and face-protection regulations 29 CFR 1910.133 and European Standard EN166(XTC-3D safety regulations); United States Code, Chapter 43, Sections 4301-4311.	

Conceptual Design

Matt Lebel's Concepts

Evaluation of Concepts

1. **Number of segments-** The boat hull was required to be split into segments. The concepts created for this were hulls split into either 2, 3, or 4 segments. The idea behind the number of segments was to reduce the complexity of each separate part.
    a. The 2 or 3 segment design allowed for easier creation in SolidWorks but didn't fully support the project definition. Since, in large scale, boat

hulls will be made up of many smaller sections it was decided that the 4-segment design would fit best.

2. **Deadrise angle-** The deadrise angle is the angle between the hull bottom and the horizontal plane tangent to the bottom the concepts chosen for the deadrise angle were 30, 45, and 50 degrees.
3. **Material-** The materials that were planned were PETG, nylon, carbon fiber filled and ABS.

. All concepts involving ABS and nylon were discarded. This is due to that fact that they are not water resistant [8]. This means that some sort of water-resistant coating would be necessary to use. On the other hand, PETG is naturally water resistant meaning no extra cost for waterproofing our design.

List of concepts

With all of these aspects in mind, the following 32 concepts were created.

The first set of designs were based around using a 45-degree deadrise angle. A 45-degree deadrise angle will be used in rough waters where the boat will be traveling at lower speeds.

PETG as a plastic is water resistant and may not need any further waterproofing. It is a durable material that can withstand use in rough waters.

ABS is a plastic that is easily printable compared to most other plastics. Using ABS as the hull material will require the use of a waterproofing seal.

Carbon Fiber as a printing material is a very strong, durable, material that can withstand use in rough waters. This design will require a waterproof coating.

Nylon is a material that is strong and flexible allowing it to withstand forces from the water at many different angles. This design will require further waterproofing.

1. 2 Segment Boat Hull (PETG Plastic) (45-degree deadrise angle)
2. 2 Segment Boat Hull (ABS Plastic) (45-degree deadrise angle)
3. 2 Segment Boat Hull (Carbon fiber filled) (45-degree deadrise angle)
4. 2 Segment Boat Hull (Nylon with coating) (45-degree deadrise angle)
5. 3 Segment Boat Hull (PETG Plastic) (45-degree deadrise angle)
6. 3 Segment Boat Hull (ABS Plastic) (45-degree deadrise angle)
7. 3 Segment Boat Hull (Carbon fiber filled) (45-degree deadrise angle)
8. 3 Segment Boat Hull (Nylon with coating) (45-degree deadrise angle)
9. 4 Segment Boat Hull (PETG Plastic) (45-degree deadrise angle)
10. 4 Segment Boat Hull (ABS Plastic) (45-degree deadrise angle)
11. 4 Segment Boat Hull (Carbon fiber filled) (45-degree deadrise angle)
12. 4 Segment Boat Hull (Nylon with coating) (45-degree deadrise angle)

For these next few designs, the deadrise angle of the hull was increased to 50 degrees. Increasing the deadrise angle will allow for the boat to travel in rougher waters and at higher speed.

PETG is a good material to use for this due to its inherent strength and durability, allowing it to withstand larger forces and higher pressure.

For usage at high speeds, ABS will be a good material. Along with it being easily printable, ABS also has high durability.

Carbon fiber filled, will not be very useful for rougher waters and higher speeds. Out of the 4 materials picked, it has the lowest strength and durability. Using carbon fiber filled will cause the maximum pressure, that the hull can handle, to decrease.

Nylon, on the other hand, is the best material to use for this situation in terms of strength and durability. While it has very high strength and durability, it is also flexible. This means that at higher speeds that pressure against the hull with cause it to flex rather than break. While the is true, flexibility can also have a negative effect on the hull. If the hull is too flexible, it is susceptible to high torsional stress and could cause the boat to flip.

13. 2 Segment Boat Hull (PETG Plastic) (50-degree deadrise angle)
14. 2 Segment Boat Hull (ABS Plastic) (50-degree deadrise angle)
15. 2 Segment Boat Hull (Carbon fiber filled) (50-degree deadrise angle)
16. 2 Segment Boat Hull (Nylon with coating) (50-degree deadrise angle)
17. 3 Segment Boat Hull (PETG Plastic) (50-degree deadrise angle)
18. 3 Segment Boat Hull (ABS Plastic) (50-degree deadrise angle)
19. 3 Segment Boat Hull (Carbon fiber filled) (50-degree deadrise angle)
20. 3 Segment Boat Hull (Nylon with coating) (50-degree deadrise angle)
21. 4 Segment Boat Hull (PETG Plastic) (50-degree deadrise angle)
22. 4 Segment Boat Hull (ABS Plastic) (50-degree deadrise angle)
23. 4 Segment Boat Hull (Carbon fiber filled) (50-degree deadrise angle)
24. 4 Segment Boat Hull (Nylon with coating) (50-degree deadrise angle)

For the final designs, the deadrise angle of the hull will be at 30 degrees. The designs using a 30 degrees deadrise angle will be used for calm waters at low speeds.

At low speeds, PETG will be a useful material for this design. It is also waterproof and will save money on production.

ABS will be a good material to use on calm waters as it is durable, cheap and has high printability.

With the low durability of carbon fiber filled, it can still find its uses with this design. Alough, it has low printability and will require expenses towards waterproofing.

Nylon is a material that is strong and flexible allowing it to withstand forces from the water at many different angles. This design will require further expenses towards waterproofing.

25. 2 Segment Boat Hull (PETG Plastic) (30-degree deadrise angle)
26. 2 Segment Boat Hull (ABS Plastic) (30-degree deadrise angle)
27. 2 Segment Boat Hull (Carbon fiber filled) (30-degree deadrise angle)
28. 2 Segment Boat Hull (Nylon with coating) (30-degree deadrise angle)
29. 3 Segment Boat Hull (PETG Plastic) (30-degree deadrise angle)
30. 3 Segment Boat Hull (ABS Plastic) (30-degree deadrise angle)
31. 3 Segment Boat Hull (Carbon fiber filled) (30-degree deadrise angle)
32. 3 Segment Boat Hull (Nylon with coating) (30-degree deadrise angle)

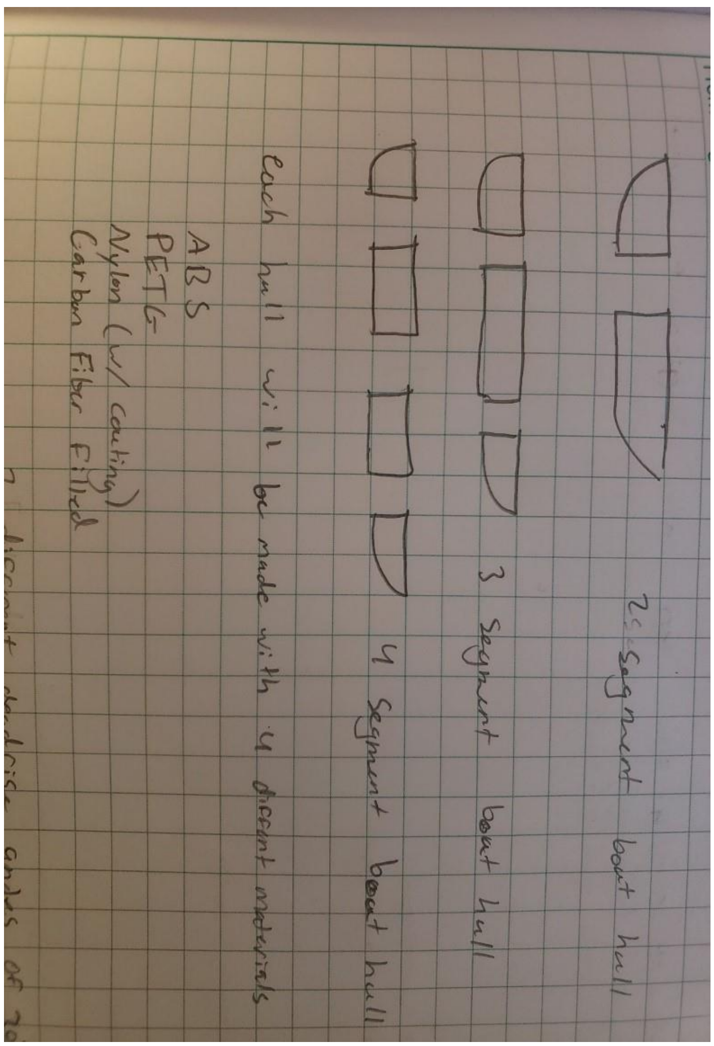

Figure 6: Segment Number and Material Concepts

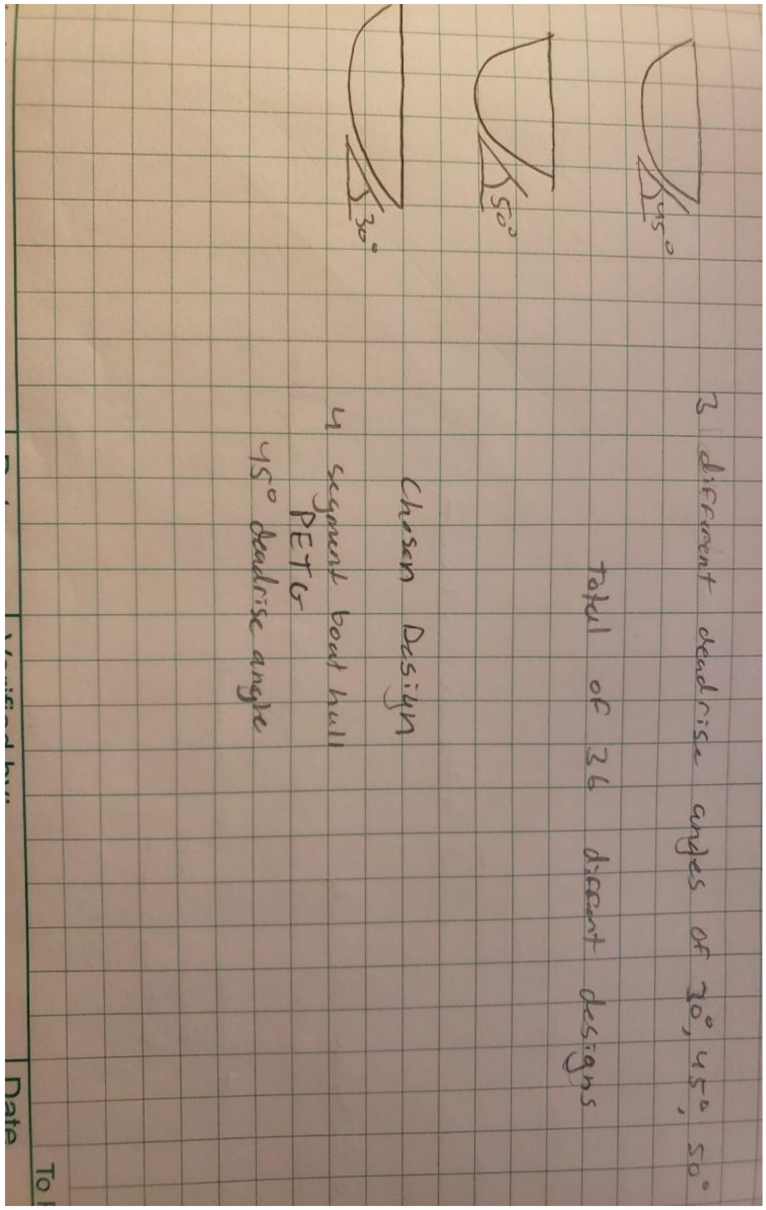

Figure 7: Deadrise Angle for Concept Generation

James Stead's Concepts

Evaluation of Concepts

1. **Hull Style (Shape)** Flat Bottom, Round Bottom, V-Bottom, Chine Bottom, and Catamaran Bottom: There were five different hull bottom types which could be used for different types of applications. The Flat Bottom hull is a small and lightweight hull that is used in freshwater and laminar bodies of water. The round bottom is a big, bulky, and heavy hull that is used with ship applications in open ocean to power through the water. The v-bottom is a

recreational high-speed hull used for gliding on the surface of the water as the boat gains speed in ocean environment. The Chine Bottom is a multi-hull bottom that is used in rough mater for more stability. The catamaran bottom is a wide two hull that is used in sailing applications for stability.

2. **Materials** ABS, PETG, Nylon, PLA, Polyvinyl Acetate (PVA), and Carbon Fiber: There are six different materials that can be used for additive manufacturing. ABS is an impact and heat resistant filament used in durable applications. PETG is a water resistant, chemical resistant, and fatigue resistant filament used in durable applications. Nylon is a flexible, impact, heat, and fatigue resistant filament used in very durable applications. PLA is a rather weak and non-applicable filament. PVA is flexible, soft, dissolvable, and fatigue resistant filament used in relatively durable applications. Carbon Fiber is a lightweight composite filament that cannot be used in durable applications.

List of Concepts

Once these circumstances were considered, these 30 design concepts were then created.

1. Flat Bottom- ABS
    - The Flat Bottom hull made out of ABS provides for a stable and lightweight combinations when used in a laminar environment. The ABS will allow for the laminar product to be impact and heat resistant giving it a full advantage during impact with rocks and debris in the laminar environment.
2. Round Bottom-ABS
    - The Round Bottom paired with ABS allows for a rather large vessel with sturdy structure used in deep sea applications. Deep sea applications with many weather and temperature ranges apply to material properties.
3. V-Bottom-ABS
    - The V-Bottom made out of ABS plastic will provide an all-around benefits with many applications. The V-Bottom is a very stable hull that can be used in both fresh and saltwater applications. The ABS with the V-Bottom gives leeway for any impact and collision protection with rocks or other substances.
4. Chine Bottom-ABS
    - The Chine Bottom hull allows for extra stability in rough water. This concept provides an advantage in a hot and turbulent environment.
5. Catamaran Bottom-ABS
    - The Catamaran Bottom hull made out of ABS allows for stable and impact resistant sailing applications. The ABS properties allow for the Catamaran Bottom to resistant high heat and turbulence.
6. Flat Bottom-PETG

- The Flat Bottom Hull made out of PETG allows for water resistant, chemical resistant, and fatigue resistant applications in a freshwater environment. Doesn't need to be waterproofed because material is resistant to water.

7. Round Bottom-PETG
    - The Round Bottom Hull paired with PETG plastic opens up for a water resistant, chemical resistant, and fatigue resistance in the deep sea. Good for large ship applications. Doesn't need to be waterproofed because material is resistant to water.
8. V-Bottom-PETG
    - The V-Bottom made out of PETG plastic will provide benefits with both freshwater and saltwater applications. The PETG with the V-Bottom gives water resistant, chemical resistant, and fatigue resistant abilities in saltwater environment. Doesn't need to be waterproofed because material is resistant to water.
9. Chine Bottom-PETG
    - A Chine Bottom hull paired with PETG plastic gives a wide range of possible applications. Since PETG plastic is water resistant, chemical resistant, and fatigue resistant, it can be used in turbulent saltwater applications. Doesn't need to be waterproofed because material is resistant to water.
10. Catamaran Bottom-PETG
    - The Catamaran Bottom hull made out of PETG allows for water resistant, chemical resistant, and fatigue resistant sailing applications in rough water. Doesn't need to be waterproofed because material is resistant to water.
11. Flat Bottom-Nylon
    - A Flat Bottom hull made with Nylon could be used for a variety of uses within a laminar environment. Due to Nylon being flexible, impact, heat, and fatigue resistant, that allows for easy maneuverability, long lasting life, and resistance to all forms of weather.

12. Round Bottom-Nylon
    - The Round Bottom hull made with a Nylon material can be used with a large amount of shipping applications. A large boat or ship would have an increased amount of maneuverability, long life, and resistance to weather since the Nylon is flexible, impact, heat, and fatigue resistant.

13. V-Bottom-Nylon

    - The V-Bottom paired with Nylon plastic provides an all-around advantage to more maneuverability, more life, and more resistance to weather. Good for both freshwater and saltwater environments.

14. Chine Bottom-Nylon

    - A Chine Bottom hull made out of Nylon plastic would apply to a boat in a high traffic, weather, and turbulent. Since the material is flexible, impact, heat, and fatigue resistant, it will give the boat more advantage in fast paced, rough, and saltwater environments.

15. Catamaran Bottom-Nylon
    - For a Catamaran Bottom made out of Nylon, it will fit mostly in high demand sailing applications that require a lot of maneuverability, impact, and high tension.
16. Flat Bottom-PLA
    - A Flat Bottom hull made out of PLA plastic would be good for exhibit and toy applications due to the rather weak material properties.
17. Round Bottom-PLA
    - A Round Bottom hull made out of PLA plastic would provide for large boat or ship examples in exhibit and toy applications due to the rather weak material properties.
18. V-Bottom-PLA
    - A V-Bottom hull paired with PLA plastic wouldn't be applied to any real-world applications because of the rather weak material properties. This would be good for exhibit and toy applications.
19. Chine Bottom-PLA
    - A Chine Bottom hull made with PLA plastic wouldn't satisfy any real-world situations except serving as a display or exhibit of its shape. The material properties of the PLA plastic are weak in every aspect.
20. Catamaran Bottom-PLA
    - The Catamaran Bottom hull made out PLA plastic wouldn't allow for any benefits because of the PLA being an all-around weak material.
21. Flat Bottom-PVA
    - A Flat Bottom hull made with PVA plastic would apply to a small speedboat used in freshwater streams, rivers, lakes, and ponds. The soft, flexible, and fatigue resistant properties of PVA will allow for easy and safe maneuverability in shallow and crowded areas. Must be waterproofed to prevent dissolving in water.
22. Round Bottom-PVA
    - A Round Bottom hull made out of PVA plastic would apply to a large boat or ship that requires a lot of maneuverability through crowded zones. The PVA will give the large boat or ship a more flexibility in bays and harbors. Must be waterproofed to prevent dissolving in water.
23. V-Bottom-PVA
    - The V-Bottom hull made out of PVA gives flexible, soft, and fatigue resistance. Best used for easy maneuverability in high traffic areas. Must be waterproofed to prevent dissolving in water.

24. Chine Bottom-PVA
    - The Chine Bottom made out of PVA plastic will give the boat a more flexible, soft, and fatigue resistant structure when performing in rough water. Must be waterproofed to prevent dissolving in water.
25. Catamaran Bottom-PVA
    - The Catamaran Bottom hull made out PVA plastic gives a flexible, soft, dissolvable, and fatigue resistant properties in saltwater sailing applications. Must be waterproofed to prevent dissolving in water.
26. Flat Bottom-Carbon Fiber
    - A Flat Bottom hull made out of a carbon fiber material would apply to high speed performances within laminar environments because of the material being a lightweight composite. Good for use in freshwater lakes and ponds.
27. Round Bottom-Carbon Fiber
    - A Round Bottom hull made out of carbon fiber plastic would apply to a large boat or ship that requires a lot of speed and performance. The carbon fiber will give the large boat or ship a more speed in bays, harbors, and relatively calm ocean. Good for uses in high speed ferry and cargo applications.
28. V-Bottom-Carbon Fiber
    - A V-Bottom hull made out of a carbon fiber material would apply to high speed performances within turbulent environments because of the material being a lightweight composite. Good for use in freshwater and saltwater coves and bays.
29. Chine Bottom-Carbon Fiber
    - A Chine Bottom hull made out of carbon fiber plastic would apply to a high-speed boat traveling through rough water. Since the material is composite and lightweight, it will give the boat more buoyancy in environments such as fast currents, jetties, and choppy surf.

30. Catamaran Bottom-Carbon Fiber
    - A Catamaran Bottom hull made out of carbon fiber material will provide benefits is high speed sailing applications. The composite and lightweight properties of the carbon fiber will allow for quick and more buoyancy in performance sailing.

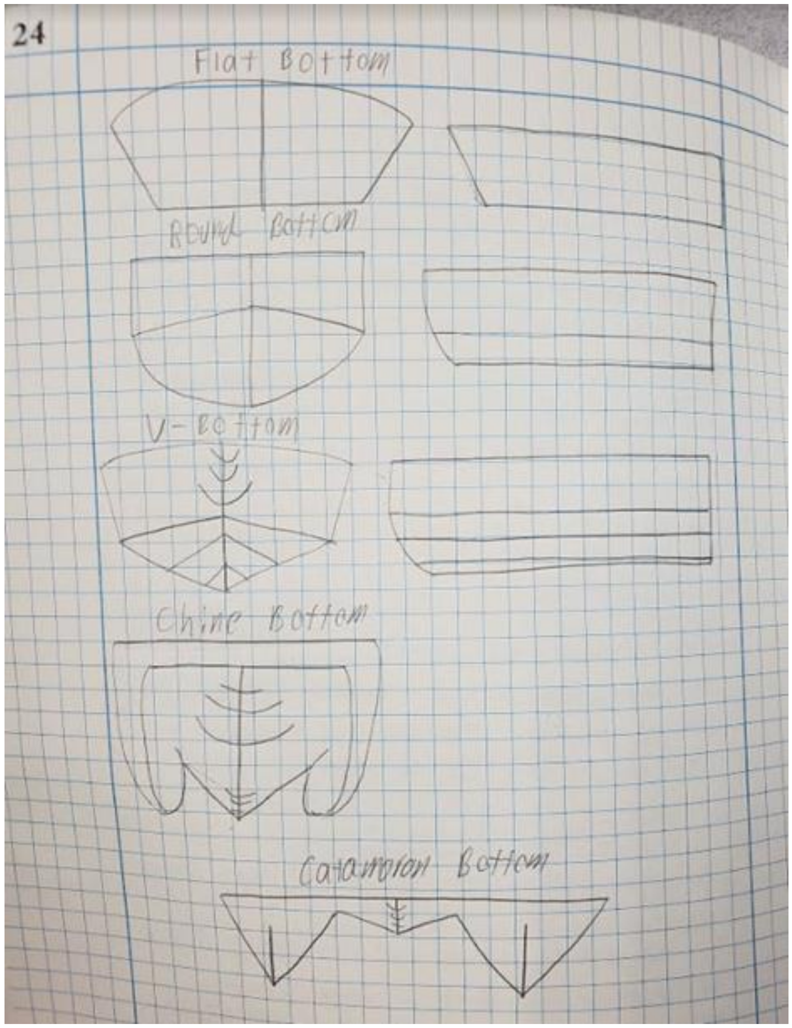

Figure 8: Hull Concept Designs

David Guevara's Concepts

Evaluation of Concepts

1. **Material:** PETG, ABS, Nylon, Carbon Fiber Filled
    1. As previously stated, PETG and Carbon Fiber Filled filaments were decided on for materials for the design. PETG being water-resistant made it the obvious choice, whereas a Carbon Fiber reinforced filament will be a more durable material that can be useful in situations where the boat may rub up against foreign objects in shallow waters.
2. **Boat Type:** Kayak-style, Skiff
    1. These boat styles were chosen because they are very common boat styles used for leisure activities in calm waters. Rough waters (i.e. ocean, white water) do not seem ideal for a boat hull that is manufactured in segments, therefore the designs concentrated on what can be used in lakes, ponds, rivers

3. **Joint Type:** Finger joint, Butt-Lap joint
    1. The choice of a finger joint was inspired by the woodworking technique. It is the strongest joint used in woodworking [9]. The butt-lap joint would only be used with an adhesive. This joint is another common practice in woodworking but was discarded because it is only to be used when the material is thick enough that it can maintain its structural integrity at the point of contact with the other joint.

List of concepts

After these three components of the design were considered, the following list and drawings of possible concepts was generated:

1. 3 Segment Kayak, Lap Joint, PETG boat
2. 3 Segment Kayak, Lap Joint, ABS boat
3. 3 Segment Kayak, Lap Joint, Carbon-Fiber boat
4. 3 Segment Kayak, Lap Joint, Nylon boat
5. 3 Segment Kayak, Finger Joint, PETG boat
6. 3 Segment Kayak, Finger Joint, ABS boat
7. 3 Segment Kayak, Finger Joint, Carbon-Fiber boat
8. 3 Segment Kayak, Finger Joint, Nylon boat
9. 3 Segment Skiff, Lap Joint, PETG boat
10. 3 Segment Skiff, Lap Joint, ABS boat
11. 3 Segment Skiff, Lap Joint, Carbon-Fiber boat
12. 3 Segment Skiff, Lap Joint, Nylon boat
13. 3 Segment Skiff, Finger Joint, PETG boat
14. 3 Segment Skiff, Finger Joint, ABS boat
15. 3 Segment Skiff, Finger Joint, Carbon-Fiber boat
16. 3 Segment Skiff, Finger Joint, Nylon boat
17. 2 Segment Skiff, Lap Joint, PETG boat
18. 2 Segment Skiff, Lap Joint, ABS boat
19. 2 Segment Skiff, Lap Joint, Carbon-Fiber boat
20. 2 Segment Skiff, Lap Joint, Nylon boat
21. 2 Segment Skiff, Finger Joint, PETG boat
22. 2 Segment Skiff, Finger Joint, ABS boat
23. 2 Segment Skiff, Finger Joint, Carbon-Fiber boat
24. 2 Segment Skiff, Finger Joint, Nylon boat
25. 2 Segment Skiff Extended Hull, Lap Joint, PETG boat
26. 2 Segment Skiff Extended Hull, Lap Joint, ABS boat
27. 2 Segment Skiff Extended Hull, Lap Joint, Carbon-Fiber boat
28. 2 Segment Skiff Extended Hull, Lap Joint, Nylon boat
29. 2 Segment Skiff Extended Hull, Finger Joint, PETG boat
30. 2 Segment Skiff Extended Hull, Finger Joint, ABS boat
31. 2 Segment Skiff Extended Hull, Finger Joint, Carbon-Fiber boat
32. 2 Segment Skiff Extended Hull, Finger Joint, Nylon boat

33. 3 Segment Skiff Multi-Chine Hull, Lap Joint, PETG boat
34. 3 Segment Skiff Multi-Chine Hull, Lap Joint, ABS boat
35. 3 Segment Skiff Multi-Chine Hull, Lap Joint, Carbon-Fiber boat
36. 3 Segment Skiff Multi-Chine Hull, Lap Joint, Nylon boat
37. 3 Segment Skiff Multi-Chine Hull, Finger Joint, PETG boat
38. 3 Segment Skiff Multi-Chine Hull, Finger Joint, ABS boat
39. 3 Segment Skiff Multi-Chine Hull, Finger Joint, Carbon-Fiber boat
40. 3 Segment Skiff Multi-Chine Hull, Finger Joint, Nylon boat

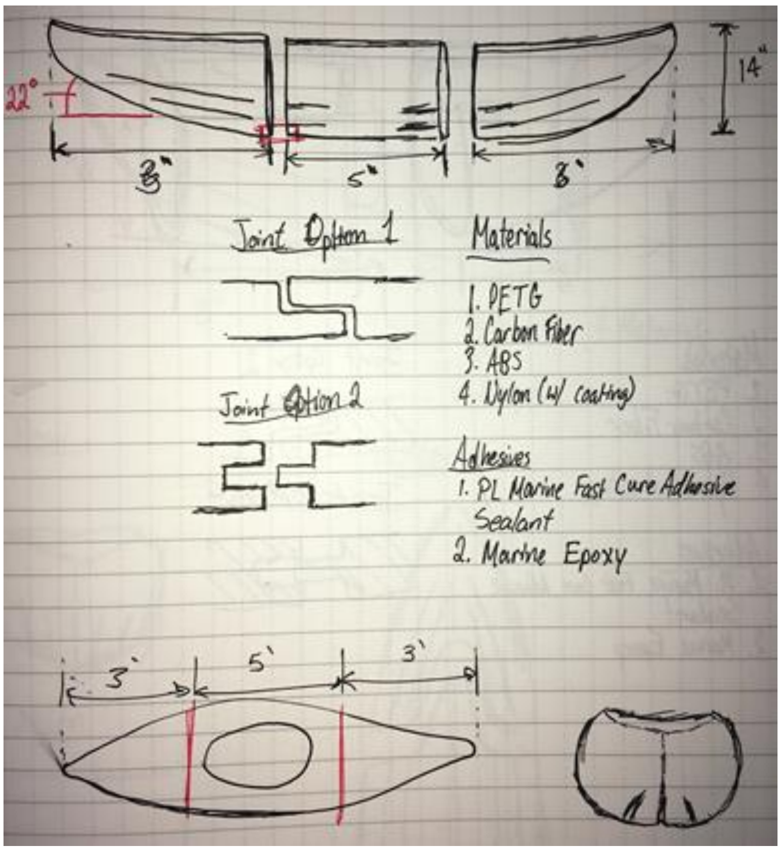

Figure 9: 3 segment kayak hull design

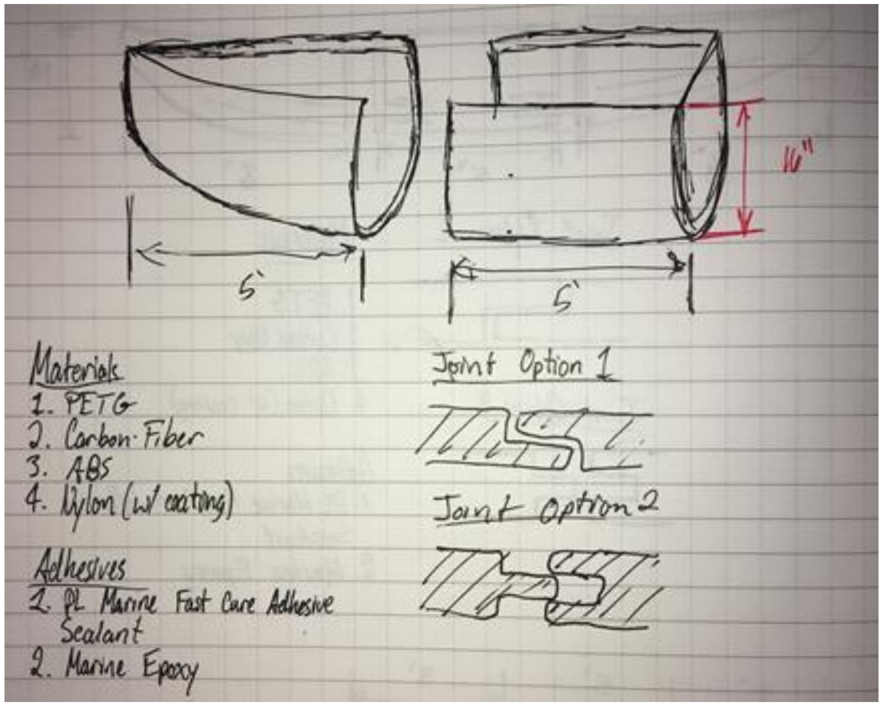

Figure 10: 2 Segment Skiff with Joint and Adhesive Options

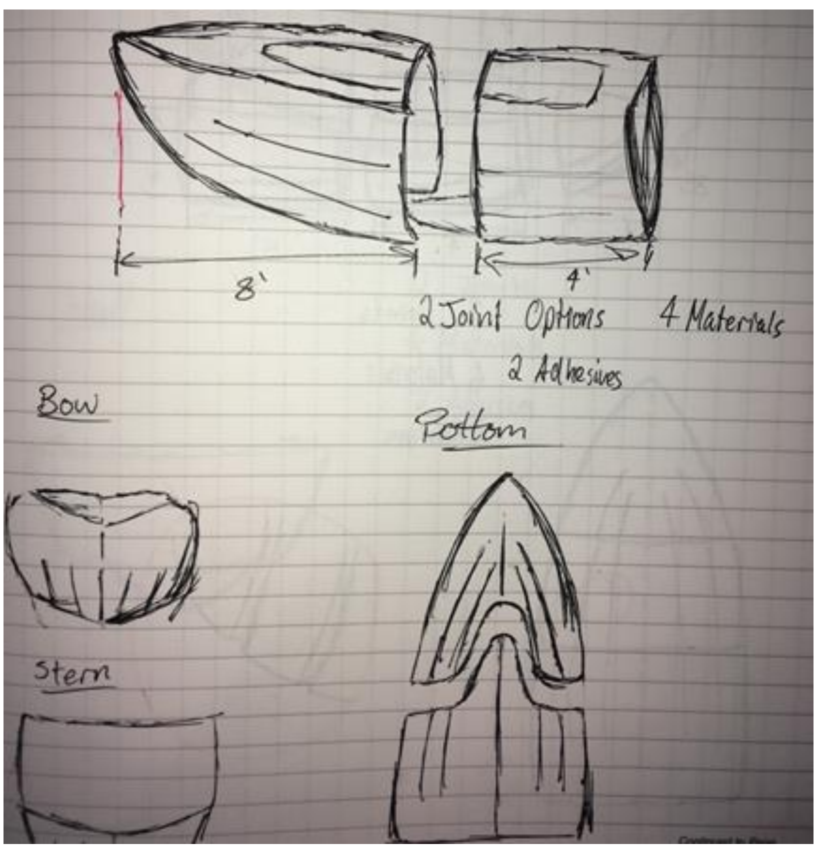

Figure 11: 2 Segment Skiff with Extended Hull

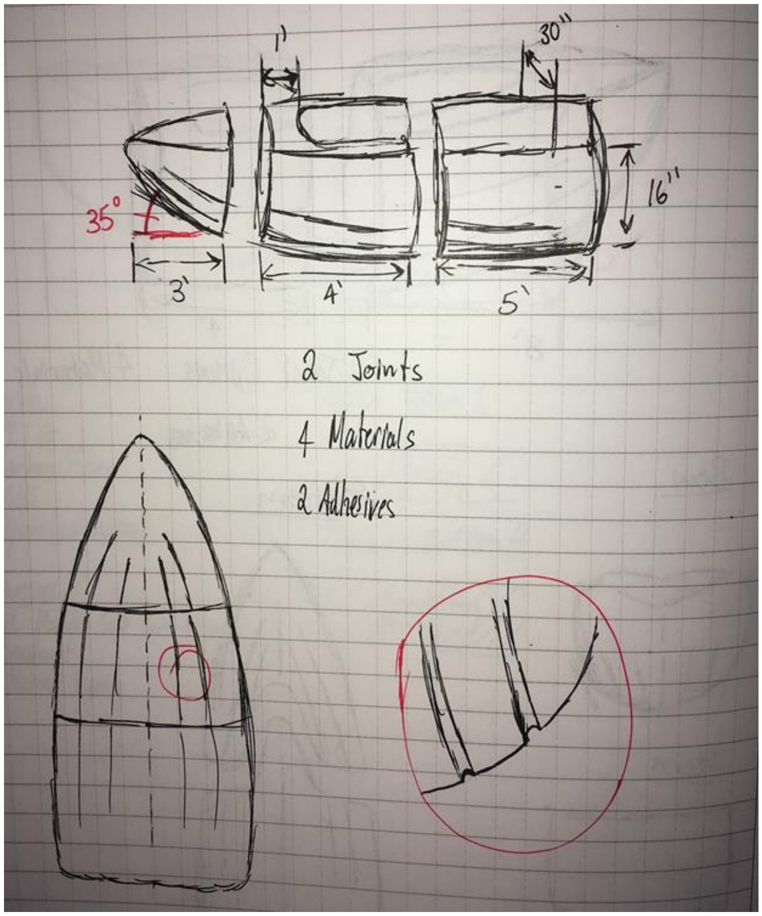

Figure 12: Segment Skiff

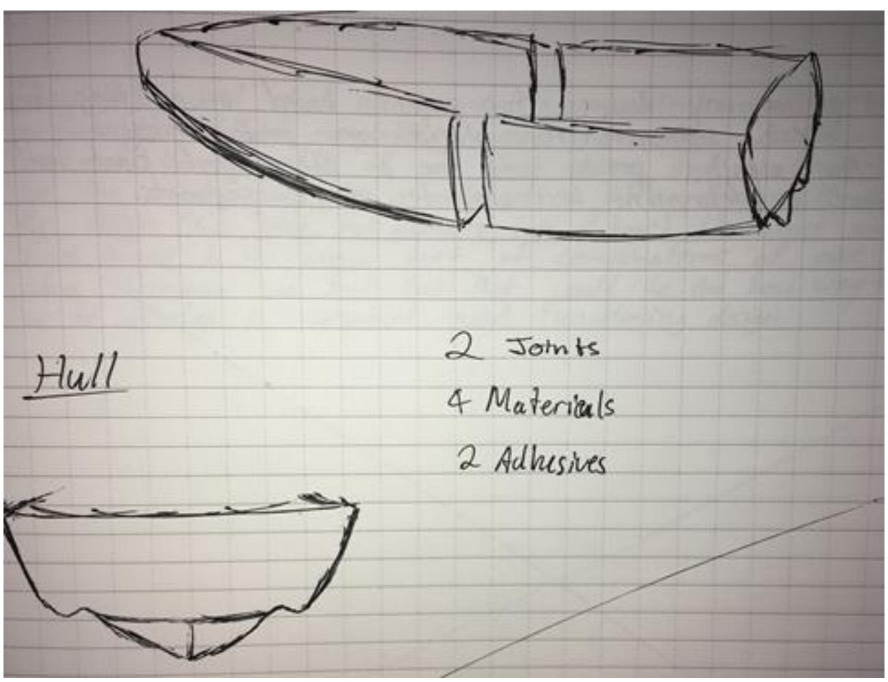

Figure 13: 2 Segment Multi-Chine Skiff

Connor Mullen's Concepts

Evaluation of Concepts

1. **Hull Type:** Four hull types were chosen based on the engineering requirements that were established. A Flat bottom hull was chosen based on the simplicity, easy printability, and stability in freshwater. The deep v design was then created for easy boating in ocean waters. A round bottom was chosen based on simplicity and stable movement on calm waters at slow speeds. Lastly, a modified v was chosen because of its versatility to be able to perform on ocean water and freshwater.
2. **Material:** Three materials were chosen based on their durability, strength, printability, cost, and weather resistance. PETG was chosen for its great durability, resistance to water, and easy printability. ABS was chosen based on its strength, relatively easy printable, and low cost. Nylon was chosen because of tremendous durability, relatively easy printability, and resistance to fatigue.
3. **Strakes and Chine:** A strake is part of the shell of the hull of a boat which, in conjunction with the other strakes, keeps the vessel watertight and moving comfortably on a given body of water. Most ocean dwelling boats have large strakes for smooth cruising through rough waters while lake dwelling boats require small strakes for calm waters. Strakes were added to some of the designs below for smoother movement on water. Not all designs will contain these strakes due to possible complications with future prints. A chine in boating refers to a sharp change in angle in the cross section of a hull. A hull without chines has a gradually curving cross section known as a round bottom hull. The angle of a chine is important when trying to design a boat hull. Steep chines coincide with ocean dwelling boats that ride in rough waters while most shallow chines apply to smaller freshwater boats.

List of Concepts

With these three factors in mind the thirty designs below were generated.

1. Flat Bottom made with ABS plastic. This design is for a lake dwelling boat made with ABS plastic which is generally easy to print with and will have to be waterproofed. This design is the easiest to reproduce.

2. Flat Bottom made with PETG plastic. This design is made for a boat moving in calm waters and is easily reproduced do to the simple hull design. PETG is a water resistant plastic and might not need to be waterproofed depending on if it passes testing and will save money on production due to not having to be waterproofed.

3. Flat Bottom made with Nylon with water resistant coating. This design can be easily printed and easily reproduced because of simple hull design. Nylon is extremely strong but slightly flexible to allow the hull to take all of the different forces from water at different angles. This design will have to be waterproofed which will cost more money.

4. Deep V made with ABS plastic. A deep v design allows a hull to travel smoothly on rough waters but will be much more difficult to print. ABS will be the easiest plastic to print this complicated design.

5. Deep V made with PETG plastic. This design is a complicated hull that travels on rough waters but by using PETG can be waterproof and will save money during production.

6. Deep V made with Nylon with water resistant coating. This design can glide smoothly on rough ocean waters but will be difficult to reproduce. Nylon will provide great strength with flexibility to withstand rough waters and will need to be waterproofed.

7. Round Bottom made with ABS plastic. Round bottom hulls are relatively simple compared to deep v hulls and should not be tough to print. ABS will help make this design more easily reproducible.

8. Round Bottom made with PETG plastic. This design is relatively simple and can't withstand rough waters but will be stable with water that is a little choppy. The PETG should save money in production without having to waterproof the boat.

9. Round Bottom made with Nylon with water resistant coating. This design is simple and strong and can handle choppy water on a windy day. Nylon is strong but is questionable when it comes to printability.

10. Modified V made with ABS plastic. Modified v hulls are very popular as they aren't as steep as deep v's and can be more easily printed. A lot of fishing boats use this design and using ABS plastic should help to make this design easier to print.

11. Modified V made with PETG plastic. A shallower version of a deep v hull that glides well on all waters and should be moderate in printing difficulty. PETG is water resistant and will save money on waterproofing costs.

12. Modified V made with Nylon with water resistant coating. This design will work well on all waters and strong by printing with nylon. Nylon does not work well with water and will need to be coated to waterproof.

13. Modified V with strakes made with ABS plastic. The modified v hull is the most versatile hull and adding strakes will help the boat glide better on water.

14. Modified V with strakes made with PETG plastic. With strakes added to the modified v hull the boat will glide much cleaner and will not have to be waterproofed if printed with PETG.

15. Modified V with strakes made with Nylon with water resistant coating. Strakes are added to modified v hull for smoother boating and will gain more strength using nylon to print.

16. Deep V with strakes made with ABS plastic. Deep v hulls will glide smoothly on very rough waters and even more so when large strakes are added. ABS will help make printing the boat much easier.

17. Deep V with strakes made with PETG plastic. Large strakes are added to the deep V hull for smoothing movement through water and PETG will save money in production by eliminating waterproofing.
18. Deep V with strakes made with Nylon with water resistant coating. Large strakes will help with smoother movement and will strengthen hull when printed with nylon.

19. Modified V with strakes and steep chine made with ABS plastic. Strakes added to the modified v will help with movement in rough waters and can be easier to produce when printed with ABS.

20. Modified V with strakes and steep chine made with PETG plastic. Strakes added to the modified v will help with movement in rough waters and will be already waterproofed if printed with PETG.

21. Modified V with strakes and steep chine made with Nylon with water resistant coating. Strakes and a steep chine added to the modified v will help with movement in rough waters and will be extremely strong being printed with nylon.

22. Modified V with strakes and shallow chine made with ABS plastic. Strakes and a shallow chine added to the modified v will help with movement in calm waters and can be easily printed using ABS plastic.

23. Modified V with strakes and shallow chine made with PETG plastic. Strakes and a shallow chine added to the modified v will help with movement in calm waters and will be waterproof when printed with PETG.

24. Modified V with strakes and shallow chine made with Nylon with water resistant coating. Strakes and a shallow chine added to the modified v will help with movement in calm waters and will be able to withstand forces at high speeds when printed with nylon.

25. Deep V with strakes and steep chine made with ABS plastic. Strakes and a steep chine added to the deep v will help with movement in rough waters and can be more easily printed using ABS plastic.

26. Deep V with strakes and steep chine made with PETG plastic. Strakes and a steep chine added to the deep v will help with movement in rough waters and will not need to be waterproofed when printed with PETG.

27. Deep V with strakes and steep chine made with Nylon with water resistant coating. Strakes and a steep chine added to the deep v will help with movement in rough waters and will allow for high stresses when printed with nylon.

28. Deep V with strakes and shallow chine made with ABS plastic. Strakes and a shallow chine added to the deep v will help with movement in calmer waters and will be more easily printed.

29. Deep V with strakes and shallow chine made with PETG plastic. Strakes and a shallow chine added to the deep v will help with movement in calmer waters and will not have to be waterproofed when printed with PETG.

30. Deep V with strakes and shallow chine made with Nylon with water resistant coating. Strakes and a shallow chine added to the deep v will help with movement in calmer waters and can withstand high stresses when printed with nylon.

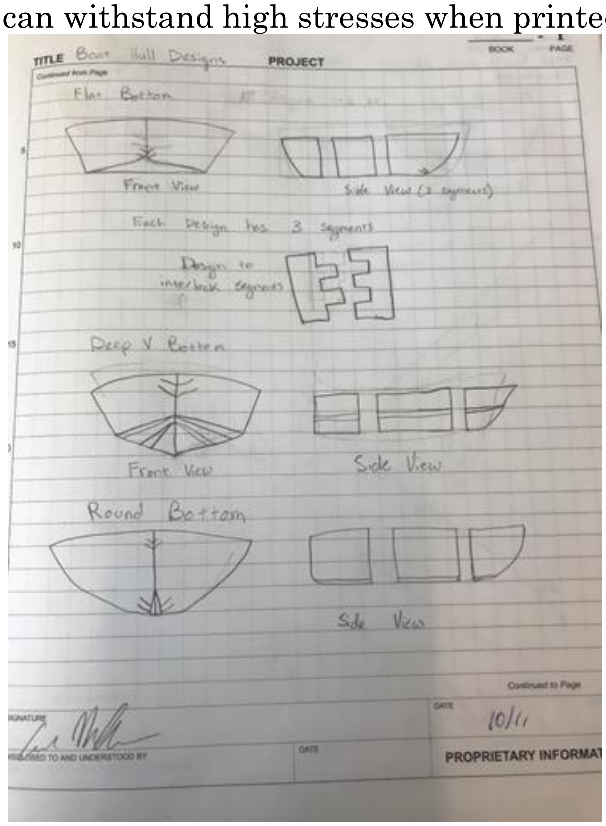

Figure 14: Boat Hull Designs

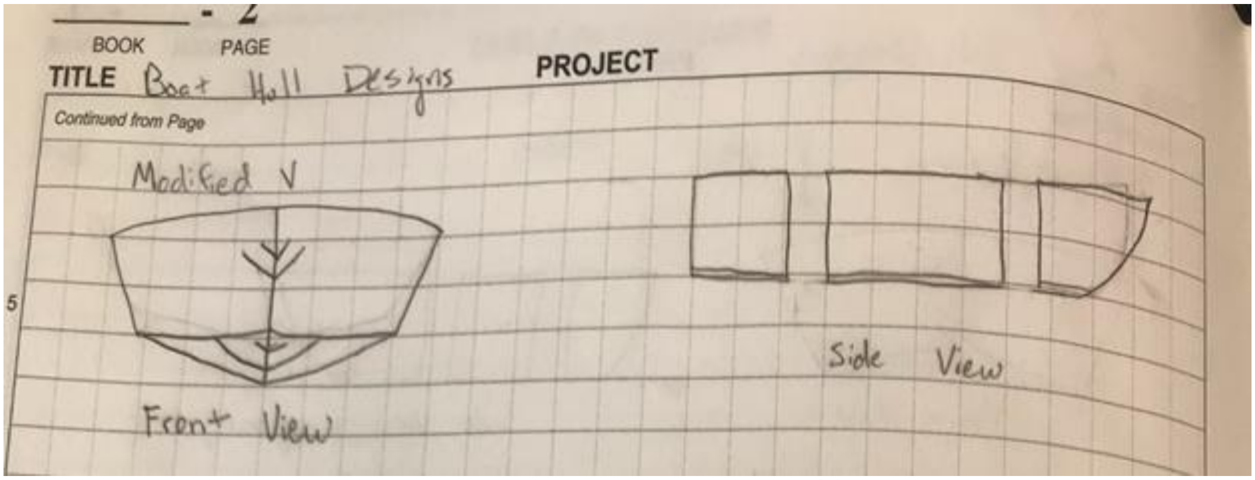

Figure 15: Boat Hull Designs (2)

QFD

Additive manufacturing is a rapidly growing field and seems to have no restrictions on what can be accomplished. One of the next big ideas that innovators are working on, is designing vehicles that can be 3D printed. Right now, there are many designs available for 3D printed cars and some may be available to be purchased by consumers as soon as next year. Although 3D printed cars could be the next big thing, there is no record of attempts made for production 3D printed boat hulls for sale to the public.

In order to optimize the boat hull design, a target consumer had to be decided on. At the moment, it is not planned for the boat hull design to be massed produced, meaning that the only consumer will be Raytheon as they are the sponsoring company. Once the customer was determined, it was possible to determine the necessary requirements and how the design met these requirements. This was implemented through a QFD. QFD is a focused methodology for carefully listening to the needs of the customer and then effectively responding to those needs and expectations through a well-organized chart. This chart includes a house of quality with a column for customer requirements, how the design will meet these requirements, how these requirements relate to each other and other similar designs. Below is the team's QFD analysis.

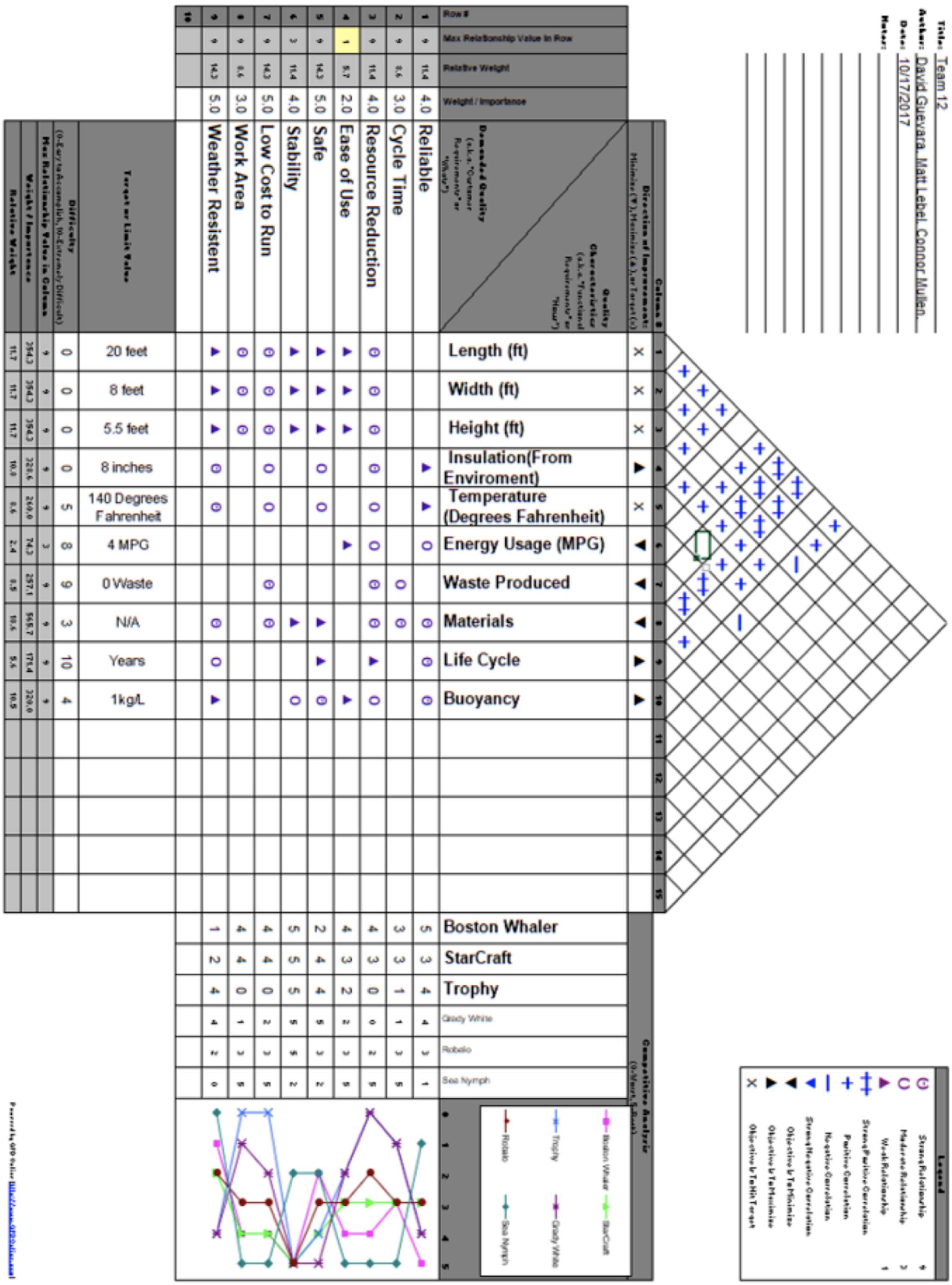

Figure 16: QFD Analysis Chart

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Figure 17: QFD Legend

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	x	▲	x	▼	▼	▼	▲	▲					
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Length (ft)	Width (ft)	Height (ft)	Insulation(From Enviroment)	Temperature (Degrees Fahrenheit)	Energy Usage (MPG)	Waste Produced	Materials	Life Cycle	Buoyancy					
1	9	11.4	4.0	Reliable				▲	▲	O		Θ	Θ	Θ					
2	9	8.6	3.0	Cycle Time							O	Θ							
3	9	11.4	4.0	Resource Reduction	Θ	Θ	Θ	Θ	O	O	Θ	Θ	▲	O					
4	1	5.7	2.0	Ease of Use	▲	▲	▲			▲				▲					
5	9	14.3	5.0	Safe	▲	▲	▲	O	O			▲	▲	Θ					
6	3	11.4	4.0	Stability	▲	▲	▲					▲		O					
7	9	14.3	5.0	Low Cost to Run	Θ	Θ	Θ	O	O		Θ	Θ							
8	9	8.6	3.0	Work Area	Θ	Θ	Θ												
9	9	14.3	5.0	Weather Resistent	▲	▲	▲	Θ	Θ			Θ	O	▲					
10																			
				Target or Limit Value	20 feet	8 feet	5.5 feet	8 inches	140 Degrees Fahrenheit	4 MPG	0 Waste	N/A	Years	1kg/L					
				Difficulty (0=Easy to Accomplish, 10=Extremely	0	0	0	0	5	8	9	3	10	4					
				Max Relationship Value in Column	9	9	9	9	9	3	9	9	9	9					
				Weight / Importance	354.3	354.3	354.3	328.6	260.0	74.3	257.1	565.7	171.4	320.0					
				Relative Weight	11.7	11.7	11.7	10.8	8.6	2.4	8.5	18.6	5.6	10.5					

Figure 18: QFD Requirements and Characteristic Correlation

Each demanded quality or customer requirement was categorized by its importance. The most important qualities included safety, weather resistant, low cost of production, and reliability. These requirements are followed by resource reduction and stability as shown above.

The quality characteristics or functional requirements were then established and listed along the top as shown above in Figure 17. These quality characteristics establish how the design plans to accomplish the customer requirements. Then it was determined whether these characteristics would need to reach the target, be maximized or minimized as shown at the top row above named "Direction of Improvement".

The quality characteristics are then compared to the customer requirements and a correlation is determined between the two. These correlations are assigned a rating of 1, 3, or 9. This number coincides with the correct symbol shown in Figure 16. The higher the number the stronger the correlation is between the two requirements. Below the plot containing the correlation between customer requirements and quality characteristics, lies the target value of each quality characteristic. These target values are then ranked from 1 to 10 in terms of difficulty to achieve as shown at the bottom of Figure 17.

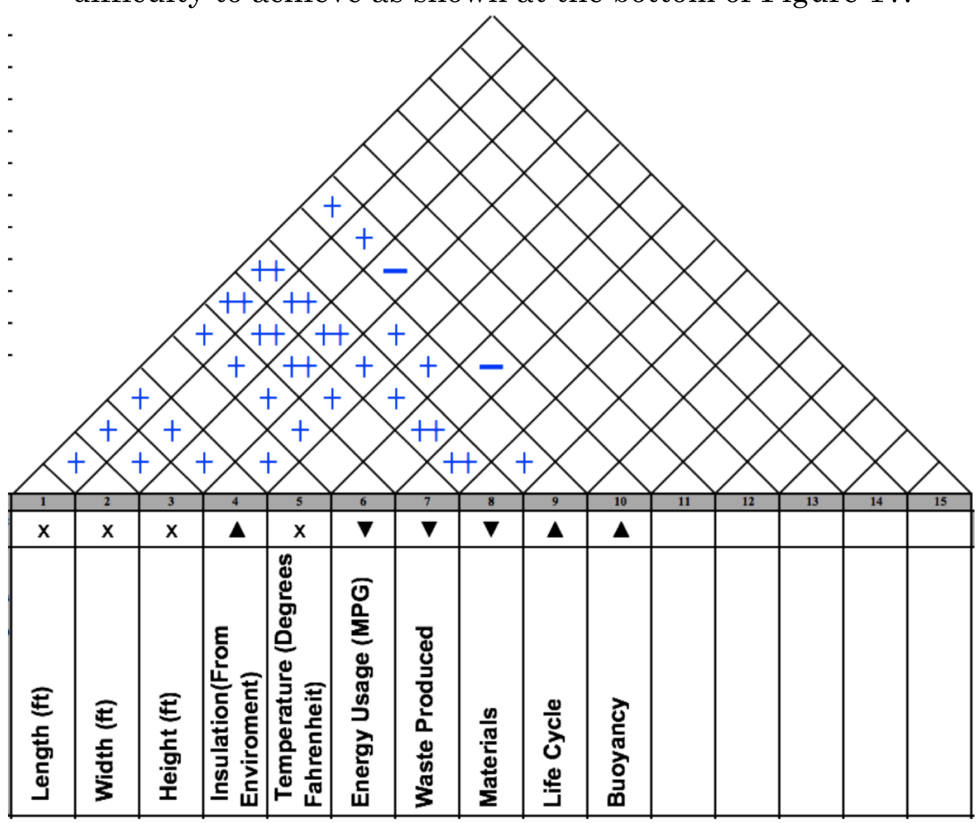

Figure 19: QFD Correlation of Quality Characteristics

At the very top of the QFD is the house of quality. The house of quality identifies the importance of quality characteristics and defines a correlation between each one as shown above. By looking at Figure 18, the quality characteristics can be related by a strong positive correlation, positive correlation, strong negative correlation, or a negative correlation.

Competitive Analysis
(0=Worst, 5=Best)

Boston Whaler	StarCraft	Trophy	Grady White	Robalo	Sea Nymph
5	3	4	4	3	1
3	3	1	1	3	5
4	3	0	0	2	5
4	3	2	2	3	5
2	4	4	5	3	2
5	5	5	5	5	2
4	4	0	2	3	5
4	4	0	1	3	5
1	2	4	4	2	0

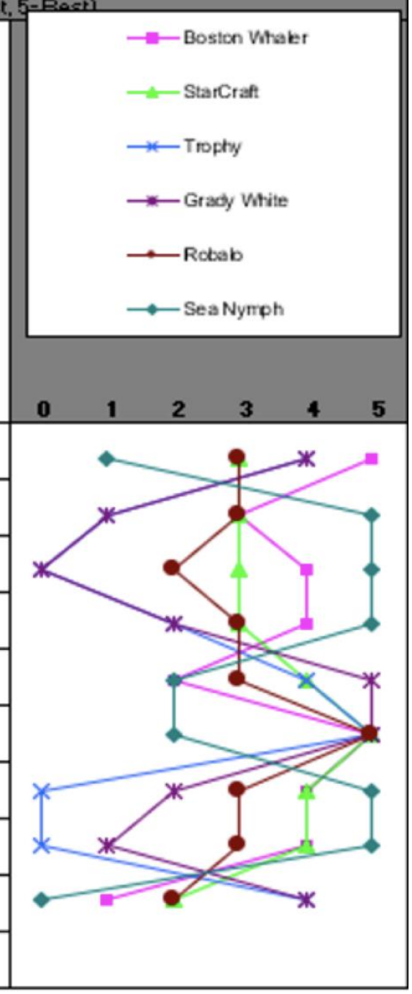

Figure 20: Competitive Analysis

Another important part of the QFD analysis includes the comparison of competitors designs to the one created above. Since there are no known competitors at the moment, six major boat manufacturing companies were chosen to represent possible future competition as shown above in Figure 19.

Design for X

The Flat-Bottom design was easily broken up into 4 structures. With 4 structures and interlocking finger joints the hull can be mass produced with high efficiency and repeatability. The shapes of the structures are manufactured so they can easily be moved around and assembled with consistency and minimal waste.

When designing the boat hull four major factors were carefully considered: safety, cost, manufacturability, and the environment.

Safety

When designing the boat hull, the safety of customers using the product was a major area of concern. The most important safety factor is to have the boat be able to handle the stresses of water at high speeds with an applied load. To ensure this, the material in which the boat would be made of was strength tested at the correct infill density. The other major safety concern was to make sure the boat would not break apart at the joints at high stresses. To ensure the strength of the joints and the adhesive used to join them a tensile test was conducted which confirmed the strength of the joints was actually stronger the rigid material the boat was made from which was a pleasant surprise.

Cost

Although safety was the biggest concern for our design cost was a significant factor. Infill density was to be as small as possible without compromising the strength of the boat. This was determined to be 15% for our small-scale model and 5% for the large scale. The change in infill density to the large-scale model was due to the increase in the width of the walls of the boat otherwise known as the "shell". Since the walls were much thicker for the large scale it increased greatly in strength and the infill was able to be lowered further to save on cost of printing material. In order to waterproof our boat XTC-3D was used and two layers were applied to the small-scale model. After careful consideration and research of this material it was decided that only one layer was needed for the large-scale model as XTC-3D is extremely durable.

Manufacturability

To make manufacturing and assembly easier, a flat bottom hull was chosen as it has a simple geometry which will help greatly when printing the hull. A modified v hull was the original choice but after a few prints it was decided that this would be extremely hard to replicate without constant errors. The joints of the boat were designed so that each piece could be printed straight up without a need for supports which would be a waste of material. The joints were designed with a perfect tolerance so that each segment clicks in place very easily. For the full-scale boat, only a small amount of adhesive needs to be applied because each piece fits together so well. This is due to the simple but very effective design of the finger joints for each segment. All angles less than forty-five degrees were taken off of our hull to ensure that the 3D printer will have no issues when printing every segment.

Environment

While designing the boat hull, all steps necessary were taken to minimize the effect our product has on the environment. The first thing looked at was material selection. Acrylonitrile Styrene Acrylate (ASA) is used on many outdoor products because of its chemical and UV resistance. ASA will only slightly seep into water over time once placed in it. To account for this XTC-3D was coated over the ASA to ensure the safety of the environment. XTC-3D has no special environmental precautions as noted in the XTC-3D material safety data sheet. The design of our boat hull has an extremely small carbon footprint as nothing is burned to complete our design and no materials are wasted and need special treatment to dispose of.

Project Specific Details and analysis

Assigned with designing a segmented boat hull using additive manufacturing, the team set out to come with engineering requirements of this design. This task included taking the requirements of the system and assigning numerical values and measurements. The table of these specifications is as follows:

Table 2: customer & Engineering Requirements

Customer Requirements	Engineering Requirements
Boat Hull Dimensions (Test Scale)	0.397 ft. x 0.989 ft. x 0.181 ft.
Boat Hull Weight (Test Scale)	0.3 lbs.
Current Budget Used	$347.70
Budget	$500 - $1000
Environmental Conditions	• Freshwater • 32-95 Degrees Fahrenheit • Low turbulence

Safety and Environmental Restrictions	OSHA Standard 1926.106a-d (boating safety); Respiratory - OSHA respirator regulations 29 CFR 1910.134 and European Standards EN 141, 143 and 371; Eye safety - Safety glasses with side shields per OSHA eye- and face-protection regulations 29 CFR 1910.133 and European Standard EN166(XTC-3D safety regulations); United States Code, Chapter 43, Sections 4301-4311.

The project at hand targets the studies of testing the possibilities of additive manufactured boats. Since the project focuses on the idea of a boat, some criteria and standards must be achieved. The boat is to be operating in an outdoor environment which means that environmental and federal guidelines are to be followed. The Department of Environmental Management (DEM) aims for a safe and non-hazardous approach towards the preservation of the environment. Wildlife, vegetation, and ecosystems are protected and managed under DEM protection. The Coast Guard's intent is to enforce federal laws against vessel and personal safety standards. Vessel dimensions, specifications, and extra implemented equipment are all focused on by the Coast Guard. OSHA improves workplace safety and health regulations for workers.

Throughout the project development, all regulations, rules, and realistic standards must be considered in order for a legal product. Since the point of the project is to explore the possibilities of making additive manufactured boats, there isn't much known about the future purposes and uses of the product after completion.

Detailed Product Design

The first step in designing the project was to come up with a list of boat hull designs. A few examples of designs that were choses were the flat bottom hull, the deep V hull, and the modified V hull. After analyzing the customer requirements for the project, the flat bottom design was chosen (Figure 41 Appendix). The flat bottom design was chosen due to its simplicity. A simplistic design was chosen because 3D printed boat hulls are not very common. Due to the idea being new, a simple design was chosen as a way to test the waters, so to speak. The team figured that if the idea failed for a simple design then testing a more complex would not be worth it. With the hull design chosen, the next step was to choose a material to 3D print with. A small list of three materials was created, PETG, nylon, and carbon fiber filament. After extensive research of those materials, it was decided that PETG would be the best to use. It was chosen to do to it having high durability and it being naturally water resistant. As the second semester came around, the hull design had a few changes to it. The first major change was that the hull was to now be made using ASA. ASA was chosen as the material for the final design due to its similarities to ABS. Along with these similarities, ASA is also more chemical and UV resistant that ABS. This was important for our design because it allowed for easy printability and greater durability than the original PETG idea. Thus determining the final material for the hull to be ASA. The next and final step of creating the design was to determine a way to connect the segments together. It was decided that the best joint to use is the finger joint (Figure 22 Below). Due to the shape of the finger joint, the segments will have a much easier time locking in place. The finger joints were fitted with a tolerance of 0.02 inches in length and 0.05 inches in width. With all of this decided, the boat design was finalized. The full design is a flat bottom boat, split in four segments, made from ASA. Each segment then has a finger joint on opposite sides running along the curve of the hull.

As stated above, the hull dimensions for the test scale are 0.397 ft. x 0.989 ft. x 0.181 ft., with a total weight of 0.28 lbs. The front segment of the hull was designed to be at an angle of 30 degrees to allow for a smoother flow of water around the hull (Appendix Figure 34). The back segment of the hull was designed with a 45-degree angle leading from the base to the rear side (Appendix Figure 37). This was designed to allow for easy printing of the hull piece. The 45-degree angle created a smooth surface finish which is required on a hull. Any malformations on the hull can cause unwanted turbulence in the surrounding water. Finally, the hull was made to be slightly front heavy, while placed in water, the boat will tip forward slightly. This is to counteract the weight of the added motor on the back of the hull. All of these considerations made while designing the hull, lead to the final product (Appendix Figure 38).

Engineering Analysis

Hull Shape

Prior to printing and possibly wasting material on a design that would not work, it was imperative that the preliminary design be analyzed in a way to ensure that it would work. For the boat specifically, this was done by making sure that it would float. To determine this, the mass and volume of the boat had to be calculated. The value of the mass was provided by SolidWorks, whereas the value of the volume of the water displaced was calculated by simplifying the buoyant force equation [10] which was derived from Archimedes' Principle and states that if an object is floating on a fluid, then the weight of the fluid being displaced, is equal to that of the object which is displacing it. The mass of the boat was given as m=1.42 lbm and the value used for the density of water was provided as ρ=62.4 lbf/(ft^3) [11] and was converted to English Imperial units to ρ_{H2O}=0.03613 lbm/(in^3). The calculation is shown as follows:

$$W_{H2O}=W_{boat}$$

$$\rho_{H2O} * V * g = m_{boat} * g \quad (1)$$

$$V = m_{boat} / \rho_{H2O}$$

Substituting for ρ_{H2O} and m_{boat}, equation (1) becomes:

V=(1.42 lbm)(0.03613 lbm/(in^3))

V=39.305 in^3

This calculated value gives the volume of the displaced water. Now using the value provided by SolidWorks for the surface area of the boat which is given as SA=196.86 in^2, it is possible to calculate the draft that the boat will have. Draft is the name given to height of the boat that is submerged in the water. This is a very important feature in every boat because every different type of hull has a different purpose which will require a different draft. In the case of a flat bottom boat hull, a small draft is desirable because the boat is meant for leisurely use in shallow waters such as lakes and ponds. These bodies of water tend to have rocks or greenery that are not to far from the surface, so avoiding contact with these objects is optimal. The draft can be calculated using the surface area of the boat, and the calculated volume:

D=VS*A (2)

Substituting the values into equation (2), the calculated value of the draft will be:

D=(39.305 in^3)/(196.86 in^2)

D=0.1996 in

When scaled up to the full size of the boat (14 ft.) this would come to a value of ~ 4 in., which for a flat bottom boat is desirable. This does not take into account infill density, or added weight being carried by the boat.

The next step in the team's engineering analysis was material testing. For this process, the team printed out a total of eight dog-bone shapes from ASA plastic to conduct tensile tests and determine the tensile strength of the material that was being used. The first four tests were conducted using uncured dog bones using an Instron 5582 machine.

The second half of the dog-bone test were conducted using dog-bones that were submerged in water for one week, at 38°F. The reasoning behind this was to determine how the material will be affected by this environment. ASA plastic is advertised as a weather resistant material [12], so instead of assuming it to be true, the team wanted to verify this statement. Before testing, the dog-bones were allowed to warm up to room temperature.

To determine the strength of the material being used, the team conducted tensile tests to obtain the true and engineering stresses that the dog-bones were subjected to. When an object is subject to a force, it strains. Strain describes quantitatively the deformation of the body in question [13]. This force is then considered in terms of the cross section onto which it is being exerted. The engineering stress is calculated as follows:

$$\sigma = F/A_o \quad (3)$$

Where F is the applied load and A_o is the original cross-sectional area of the gage length. This method however, will have its flaws when analyzing large strains, and particularly used in cases with smaller strains, because the variance in the cross-sectional area is negligible. Instead, true stress is used to determine the state of stress of the dog-bones. True stress is defined as:

$$\sigma_T = \sigma(1+\varepsilon) \quad (4)$$

Where σ is the engineering stress determined in equation (3), and ε is the strain.

Build/Manufacture

The prototype designed for this project utilized a flat bottom boat hull split into four segments. Each segment was 3D printed using ASA. Two segments of the hull were printed simultaneously in an effort to minimize the print time required. Once all pieces were printed, J.B. Weld adhesive was applied to the joints to secure the hull together. After the J.B. Weld completely dried, XTC-3D was applied to the hull using two layers to ensure appropriate waterproofing.

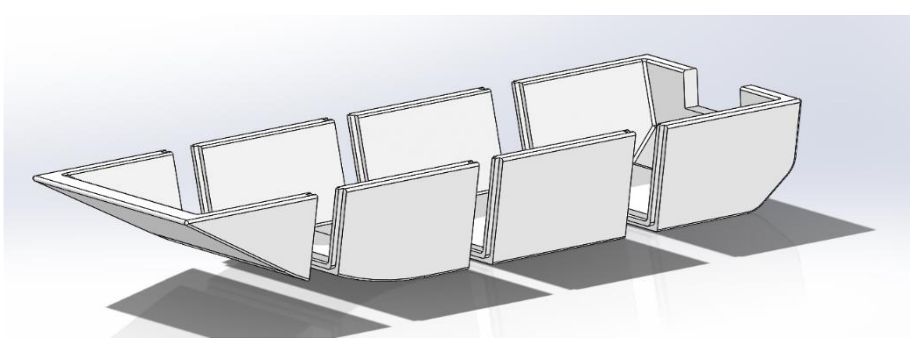

Figure 21: Flat Bottom Boat Sub-Assembly

Testing on this prototype was completed simply by placing it into a tub of water to determine whether it floated. This simple test was done because the design is still on a small scale. The design was able to float above the water and the pieces lock into place as desired. When compared to the other ideas for hull designs, deep V and modified V, the flat bottom was the best choice. The flat bottom hull is a much simpler design than the others and does not require as many intricacies that may cause more problems for the 3D printers.

Designs like the deep or modified V have a much more complex geometry due to the nature of their usage. Specifically, the angle of each section of the hull. These different hull types are designed to sit deeper in the water so that they can tackle turbulent waters more easily. The boat will float more sturdily if the hull sits deeper in the water. The flat bottom hull design can also be more stable compared to the other designs. The simplicity of the flat bottom hull design leads to a smaller chance of deformities occurring, making it the best hull design to test in 3D printing because it is a newer process.

Mass production of this product would not be easily accessible currently. It would require the use of multiple industrial 3D printers running simultaneously just to print a single hull. Matched with the time it would take to print a single piece, mass production does not seem feasible at this moment. At this time 10 boats could be manufactured in the first year and increasing to 15 the second year as manufacturing efficiencies are realized.

Testing

The testing below performed on the hull showed the boat hull floats 0.0 inches below was and can hold 4.5 times its weight of ~192 grams (Fully assembled test-scale) The J.B. Weld is stronger than ASA plastic so when tensile tested, the plastic, not the J.B. Weld, gave way.

Table 9, seen in the appendix, provides a list of the engineering tests completed, and the parameters used to determine the success of the test.

Material Test

To test the strength of the material, the team printed out a total of eight dog-bone shapes from ASA plastic to conduct tensile tests and determine the tensile strength of the material that was being used. The first four tests were conducted using uncured dog bones using an Instron 5582 machine.

The second half of the dog-bone test were conducted using dog-bones that were submerged in water for one week, at 38°F. The reasoning behind this was to determine how the material will be affected by this environment. ASA plastic is advertised as a weather resistant material [12], so instead of assuming it to be true, the team wanted to verify this statement. Before testing, the dog-bones were allowed to warm up to room temperature.

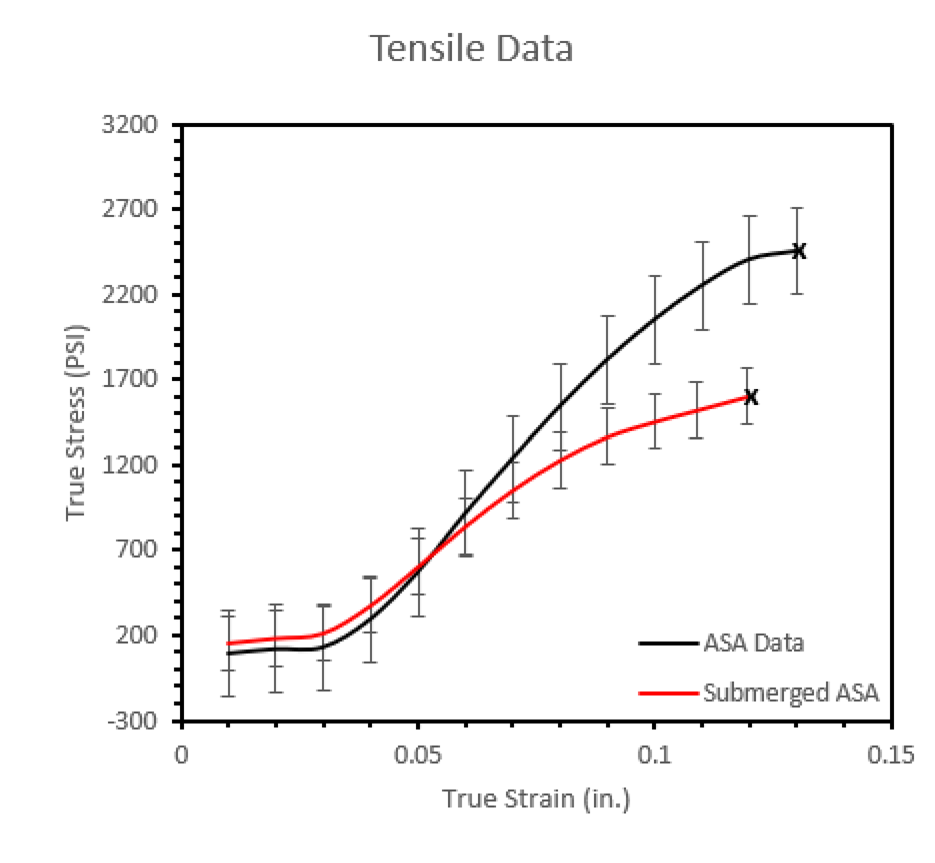

Figure 22: Tensile Test True Stress-True Strain

Through testing, the data shown in Figure 24 was obtained. From this plot it is visible that the "submerged" dog-bone lost strength. These dog-bones were also found to be waterlogged, which may have contributed to the loss in strength. This justifies the decision to use the XTC-3D coating.

Dimension and Structural (Float) Tests

Through the testing stated in the test matrix, it was determined that the boat hull floats 0.2 inches below was and can hold 4.5 times its weight of ~192 grams (Fully assembled test-scale). This was determined by placing the hull in a bucket filled with water, then adding a known amount of weight into the hull, until it begin to take on water.

Joint Test

To test the joint structure, multiple joint geometries were printed and assembled to simulate the behavior of the joints under tensile stresses. These tests were conducted in the same manner as the previously mentioned tensile tests, to determine where they would fail. After conducting the test, it was determined through observation that the joints failed at the base of the prong joint.

Figure 23: Joint Assembly

Redesign

______The first redesign of our product introduced a change in the material. As the second semester began, the group noticed that PETG had multiple consecutive misprints. Upon experiencing this, it was decided to conduct a new material search. After an extensive search, a material called Acrylonitrile Styrene Acrylate, or ASA, was discovered. ASA, being a material based around ABS, was described to have similar printability. A major difference from ABS, however, was that ASA is considerably more chemical and UV resistant. This meaning, that any deterioration due to water, or other waterborne substances will take longer. These resistances will also keep deterioration due to the ozone effect to a minimum as well. With all of these benefits, it was decided that ASA will be the new material for our design.

For the team, the main scope of the redesign is to allow for easier printability of the boat hull and ensure strength. Tensile tests on ASA dog bones and joints were conducted to obtain data for the strength of our hull material and gave guidance on the adjustments that needed to be made. A compression test was also conducted to help determine the strength of the material being printed. From the testing it was decided that the material was definitely strong enough to handle the overall stresses from water on the hull with the fifteen percent infill at which our parts were to be printed. Once this was discovered the infill density was changed to five percent on the large-scale model in order to cut some material costs but still maintain enough strength. After getting results from the joint tests it was concluded that the joints could be made slimmer and a small gap could be made which would be filled by the J.B. Weld adhesive.

Another major problem that the team was having was being able to have successful prints frequently. Sometimes prints would stop for no apparent reason, the nozzle would clog, the material would not stick to the heated bed, or pieces would become warped. Repeatability is a major factor if this boat hull is ever going to be mass produced using additive manufacturing. To try and fix these issues we made a couple redesigns. The rear segment of the hull was adjusted so that the bottom fillet was not under forty-five degrees. A rule when 3D printing an object is nothing can be angled lower than forty-five degrees without supports. Using supports would have been easier but to cut costs on material the team decided to use the forty-five-degree rule instead. To fix other printing issues the joints were reversed so that the front segment of the hull could be printed straight up without supports also following this forty-five-degree rule. As for the warping and problems with sticking to the bed, the heated bed temperature was raised, and printing speed was lowered to allow each layer to cool and avoid warping.

Project Planning

In order organize this design project and be able to track certain tasks to be completed at certain times, Gantt charts were created using Microsoft Project. These charts include the start and end dates for every specific task assigned to each team member every week.

Fall 2018

Project planning is the procedural stage in managing the time of a project. The use of project planning helped in keeping track of due dates and upcoming tasks. A project planning program was used in helping in managing this project.

The software used was Microsoft Project. This software was used to log tasks, dates, and times. The software generated a Gantt chart that displays progress bars and labels for each task input within the program. Below is the Gantt chart of the project that gives a visual representation of the plan and deadlines. The project planning stage helped in keeping the group on track and gave the group a heads up of upcoming assignments.

Throughout the semester, the group had to submit progress reports biweekly. The progress reports included a summary of the group's progress along with summaries of each individual group member. Problems and issues were explained if they were to appear during that report period. Plans for the next reporting period, which was usually scheduled to be completed by the next reporting period talked about what the group intends to accomplish during the next week along with any updates or changes that were to take place. The progress reports gave the instructor some insight on what has been accomplished and what the group has in mind moving forward in the semester.

The first portion of the project was the research stage. The research stage involved conducting research on the internet about the project topic. The assignments that were assigned for the research stage were the patent and literature search. The first of the two assignments that was completed by the group was the patent search. The patent search was an assignment that involved each individual group member using the United States Patent and Trademark Office (USPTO) database to search for any relevant patents that could show any examples of previously completed products. These previously completed products would eventually aid the group in helping decide on a final concept for the design. The next research assignment that was completed by each individual group member, was the literature search. The literature search was an assignment that involved each individual group member using the University of Rhode Island library database to search for any relevant articles that could give the group any examples of any previously made products. These articles explained reasons, scientific methods, ideas, and product explanations about the researched topics. Once the research stage was completed, it was now time for the concept stage.

The second portion of the project was the concept stage. The concept stage involved writing up design ideas that could possibly be a good fit for the project. The assignments that were assigned for the concept stage were the PDS first draft, 30 Design Concept and Analysis, QFD assignment, and Critical Design Review (CDR) Presentation. The first of five assignments that was by the group was the PDS first draft. The PDS first draft was an assignment that involved documenting the initial product design specifications. The design specifications involved product identifications, key project deadlines, physical descriptions, financial requirements, and manufacturing requirements. This assignment gave a possible assumption and set goals to aim for when the design stage begun. The next assignment was the 30 Design Concept and Analysis. The 30 Design Concept and

Analysis assignment involved each individual group member coming up with at least 30 design possibilities that would be good fits for the design problem. Along with the 30 design concepts, each group member chose one of their 30 designs to serve as their best fit for the project. Once the best out of the 30 was chosen, it was then implemented in a Pugh chart to compare positives and negatives with the engineering criteria against the other 29 concepts. This assignment gave possible viewings on the positives and negatives that the design concept might face. The third assignment was the QFD analysis. The QFD analysis was an assignment that structured the customer requirements of the product and organized them into specific comparison plans to help meet the needs of the engineering criteria. For this assignment, the group created a chart that labeled customer needs, quality characteristics, design targets, and a competitive analysis and then compared each section by relationship and correlations. The final part of the concept stage was the CDR presentation. The CDR presentation is a detailed technical review presented to the class to ensure that the system under review can proceed into system fabrication, demonstration, and test. During the presentation, the group provided a brief restatement of the problem to orient the audience, a description of work to date, and detail design, along with analysis and explanation. Overall, the concept stage gave the group the ability to come up and choose the desired design based off the engineering criteria and other requirements. Once the concept stage was completed, it was now time for the design stage.

The third portion of the project was the design stage. The design stage involved drawing up the design for the chosen concept, modeling the concept within a 3D modeling program, printing out the 3D model as a prototype, and assembling the printed prototype. The first part of the design stage was drawing out the desired drawing on paper. The drawing involved dimensioning the product relative to the desired scaled down version of the realistic object. The group would then use the drawing to model the product within SolidWorks. SolidWorks is a 3D modeling software that can be used to create various forms of 3D prototypes. Once the concept was modeled within SolidWorks, the file was then converted into an .stl file to be compatible with the Raise3d ideaMaker software. Once the print was formatted in ideaMaker, the file was sliced and exported as a .gcode file. After the 3D printer finished printing the segments, they were then assembled to make the final concept. The design stage was then completed and now time to move on to the Proof of Concept (POC) presentation.

The POC presentation is a presentation that demonstrates the purpose of the chosen concept and to verify that the chosen concept has the potential for real-world applications. The group presented the chosen concept by explained the reasons for the chosen concept and steps for why and how it was brought about. This presentation gave the class and professor the chance to see the group's progress and plan of attack moving forward. Overall, project planning helped the group foresee and predict as many dangers and problems as possible along with planning, organizing, and controlling activities so that the project is completed as successfully as possible in spite of all the risks on time.

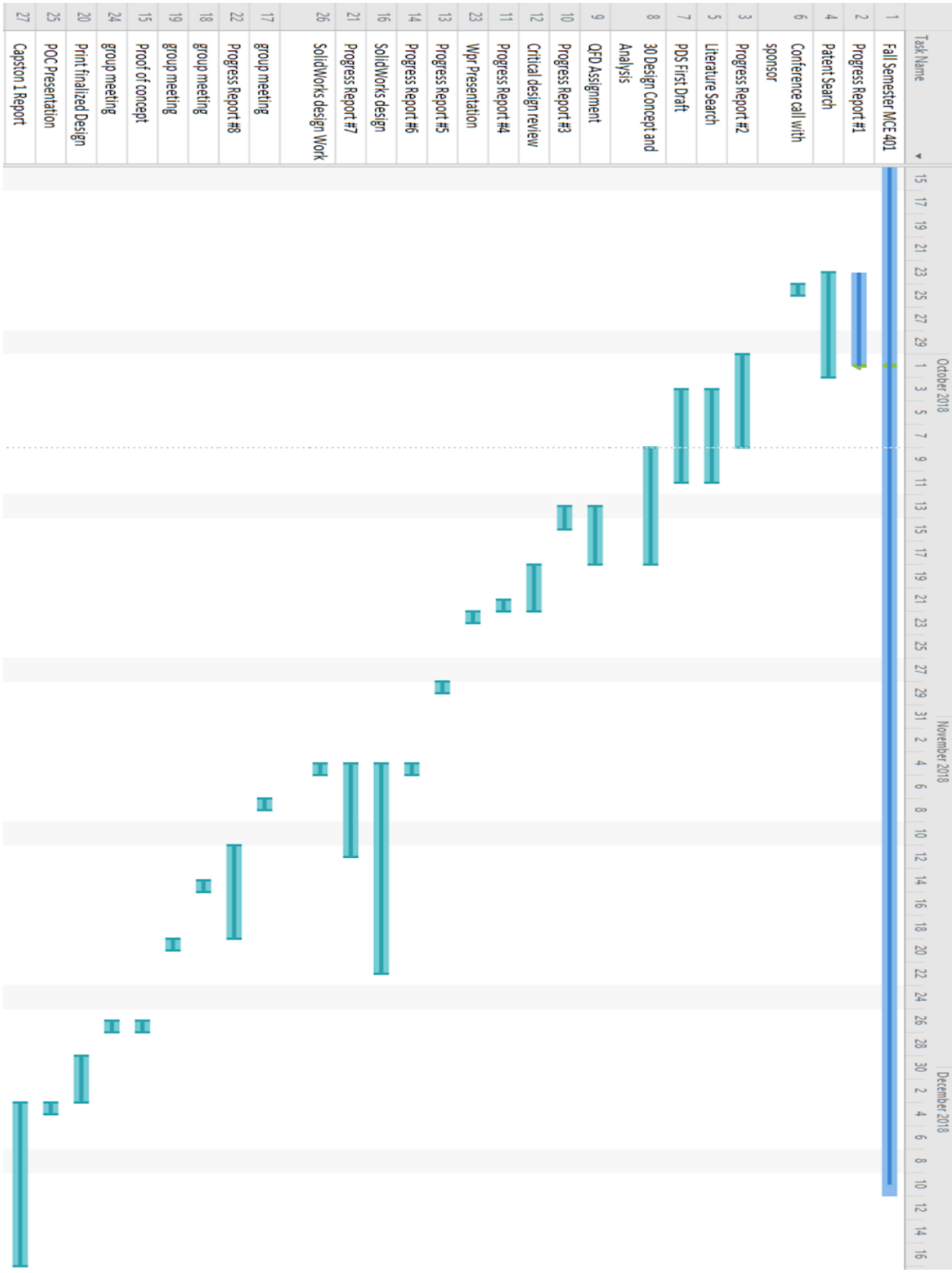

Figure 24: Gantt Chart First Semester

Spring 2019

As the spring semester started, so did the testing stage of the project. This stage involved extensive testing of material properties as well as the overall design of the product. The testing stage was used to determine if there were any failures with our original design from the previous semester. Tests such as tensile and compression tests were conducted on the original material as well as a variety of others. A second set of tests were conducted once the new material was chosen. The next test was used to verify the strength of the J.B. Weld adhesive used in our project. Further tensile tests were conducted to compare joint connection with and without the adhesive. The third and final test that was conducted for this project was to validate the use of a waterproofing sealant. The test was run by comparing the resultant tensile stress between an uncured dog-bone and a dog-bone submerged in water after one week. After receiving the results from the tests, the next stage in the project began.

The second stage in the spring semester was the redesign stage. In this stage of the project, teams were tasked with coming up with ways to redesign their projects. If any failure of the project was found in the previous testing stage, then teams were tasked with finding a solution to that problem.

After completing the testing stage of the spring semester, team 12 held a meeting to discuss the next steps towards redesigning the project. After multiple meeting and determining the best course of action, team 12 immediately began to readjust the Computer Aided Design (CAD) model to eliminate the errors found while testing. The team then prepared all updated files for printing to be started. With these new prints on the way, team 12 met again to discuss if any future redesigns may be necessary that weren't an issue for testing. Redesigns for ease of use such as printability and time to print were discussed as a possibility and were later implemented.

Once the final design was determined, the team then met with Raytheon to present the project in its current state as well as discuss the possible next step for the project. As there was not much left for the team to do, it was time to prepare for the Capstone Design Showcase. During this showcase, the team displayed its efforts throughout the semester to the mechanical engineering faculty and the other capstone sponsors. Many people visited the teams showcase and were interested to hear about the capabilities of 3D printing.

As the semester came to a close, the team wrapped up all final documentations and began to prepare for the final report. Throughout this 2018-2019 academic year, team 12 had learned many important lessons that the team members will carry with them into their careers.

Figure 25: Gantt Chart Second Semester

Financial Analysis

For a boat length of 0.989 ft and an infill density of 15%, the Raise3D printer will use an estimated 0.3 lbs of ASA filament calculated from the SolidWorks costing simulation and require approximately 18.08 hours to complete. The ASA filament was purchased from a supplier named HatchBox for $20.20 per pound. This means that the cost of material used for a 0.989 ft model costs approximately $6.06 calculated from the SolidWorks costing simulation. Then considering the manufacturing cost, which is the cost of operating the Raise3D printer. The cost per hour to operate the Raise3D printer is $4.00 per hour. The total time for all 4 sections of the boat hull to be manufactured is provided by the Raise3D ideaMaker software. The total time for the boat hull to completely print was approximately 18.08 hours. So, the manufacturing/printing cost was $72.32. Intern the total cost of the prototype came to be $78.38.

At full scale, the SolidWorks costing simulation estimated that the boat will weigh 743.45 lbs. This means that a full-scale print would require approximately 743.45 lbs of ASA filament. This would equal a material cost of about $15,322.69. Due to the size of the job (13.79 ft) this would require an industrial sized 3D printer. Additive Engineering Solutions BAAM (Big Area Additive Manufacturing) industrial 3D printer is one of the world's largest 3D printers [15] and will provide the manufacturer with the appropriate mass flow rate to print these parts up to an entire boat hull at a time. This printer uses a variety of different nozzles and nozzle sizes that allow the manufacturer to achieve different print resolutions. The BAAM printer can print approximately 80 lbs of ASA filament per hour which allows for very large products to be created at a very fast rate.

Figure 26: BAAM Industrial 3D Printer

The total investment was $36,146.08 consisting of labor costing $35,160.00 (hours of 1,016); Equipment and Facilities of $560.00; Material cost of $347.70 and ASA Prototype cost of $78.38 for the project.

A full size boat hull in production costs $108,222.69 consisting of a material cost of $15,322.69 and Manufacturing/Overhead Cost of $ 92,900.00 to produce. The sale price of each boat hull is $116,880.51 resulting in a profit of $8,657.82 per hull. With the upfront investment of $36,146.08 it's going to take just over 4 hull sales to break even. It is expected that the first year sales will be 10 boats. This would result in the first years profit to be $50,432.12 after upfront investment. The second year projection would be 15 boat hulls resulting in $129,867.30 in profit.

Table 3: Financial Analysis of Full Scale Model

Boat Hull Model ASA Rectilinear 5% Density					
Piece	Bow	2nd Piece	3rd Piece	Stern	Total
Weight (lb)	147.22	188.95	191.24	216.04	743.45
Shell Thickess (in)	0.04	0.04	0.04	0.04	
Volume (in^3)	3881.0423	4981.2147	5041.5514	5695.3548	19599.1632
Shop Rate/Printer Cost	$10000.00/hr	$10000.00/hr	$10000.00/hr	$10000.00/hr	
Print Time (hr)	1.84	2.36	2.39	2.7	9.29
Material Cost	$3,034.21	$3,894.33	$3,941.50	$4,452.65	$15,322.69
Manufacturing Cost	$18,400.00	$23,600.00	$23,900.00	$27,000.00	$92,900.00
Total Cost	$21,434.21	$27,494.33	$27,841.50	$31,452.65	$108,222.69

Tables 3 and 4 represent the individual along with total values for each section of the test and full scale respectively. The weight, volume, print time, material cost, manufacturing and total cost per section are represented as shown. The shell thickness and shop rate/printer cost were constant for each section based on test or full scale.

Table 4: Financial Analysis of Test Scale Prototype

Boat Hull Prototype ASA Rectilinear 15% Density					
Piece	Bow	2nd Piece	3rd Piece	Stern	Total
Weight (lb)	0.06	0.07	0.08	0.09	0.3
Shell Thickess (in)	0.02	0.02	0.02	0.02	
Volume (in^3)	1.5233	1.9582	1.9805	2.2934	7.7554
Shop Rate/Printer Cost	$4.00/hr	$4.00/hr	$4.00/hr	$4.00/hr	
Print Time (hr)	4.5	4.33	4.25	5	18.08
Material Cost	$1.19	$1.53	$1.55	$1.79	$6.06
Manufacturing Cost	$18.00	$17.32	$17.00	$20.00	$72.32
Total Cost	$19.19	$18.85	$18.55	$21.79	$78.38

Table 5 and Figure 26 represents the budget pricing based off of all the purchases throughout the extent of the project. The maximum budget provided was $1,000.00 and the minimum budget goal was $500.00. The total cost spent through the budget happened to be $347.70 which is less than the minimum budget. That means that the group was on track and has achieved the minimum budget goal.

Table 5: Budget

Product	Price
Flex Seal	$12.99
Liquid Rubber Waterproof Sealant	$49.95
Marine Adhesive	$16.97
Flex Glue Waterproof Adhesive	$12.88
46 Quart Storage Box	$25.98
Mini Dehumidifier	$14.97
ASA 3D Printer Filament	$34.00
ASA 3D Printer Filament	$34.00
Polycarbonate 3D Printer Filament	$32.99
Polycarbonate 3D Printer Filament	$32.99
Nylon 3D Printer Filament	$39.99
Nylon 3D Printer Filament	$39.99
Total cost	$347.70

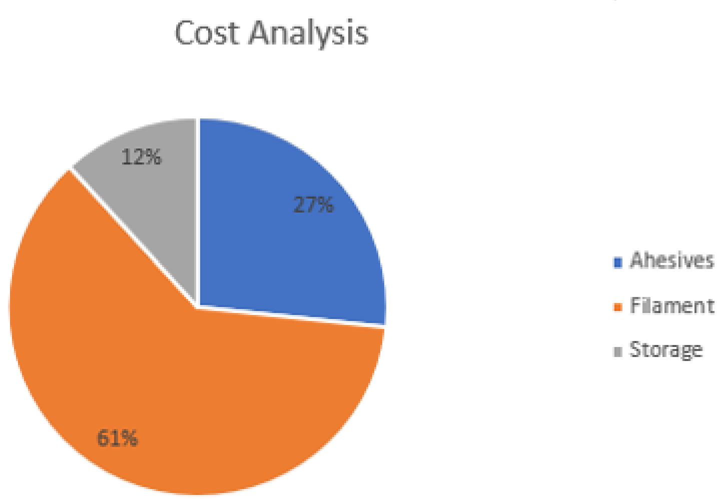

Figure 27: Cost Analysis chart based on budget purchases

Table 6 represents the expenditure funds of the project. The expenditure funds are the costs based off of time put in by people to work on the project.

Table 6: Expenditure Funds

Expenditure Funds			
Title	Time (hr)	Cost/hr	Total Cost
Member 1	144	$20.00	$2,880.00
Member 2	144	$20.00	$2,880.00
Member 3	144	$20.00	$2,880.00
Member 4	144	$20.00	$2,880.00
Grad Student 1	144	$30.00	$4,320.00
Grad Student 2	144	$30.00	$4,320.00
Prof. Nassarshariff	144	$100.00	$14,400.00
Prof. Taggart	3	$100.00	$300.00
Sponser	5	$60	$300.00
Total	1016		$35,160.00

Table 7 represents the costs to operate the equipment and facilities. The total costs for this table were determined by total use and price per piece of equipment.

Table 7: Equipment and Facilities

Equipment and Facilities			
Title	Time (hr)	cost/hr	Total cost
Solidworks	20	$5.00	$100.00
Abaqus	10	$5.00	$50.00
Open Foam	2	$5.00	$10.00
Instron	4	$100.00	$400.00
Total	36		$560.00

Table 8 and Figure 27 represents the entire cost of the project. Total cost includes the costs of everything implemented through every stage and every use during the timespan of the project.

Table 8: Total Cost of Project

Total Cost of Project	
Title	Cost
Expenditure Funds	$35,160.00
Equipment and Facilitie	$560.00
Materials	$347.70
Prototype (ASA)	$78.38
Total Cost	$36,146.08

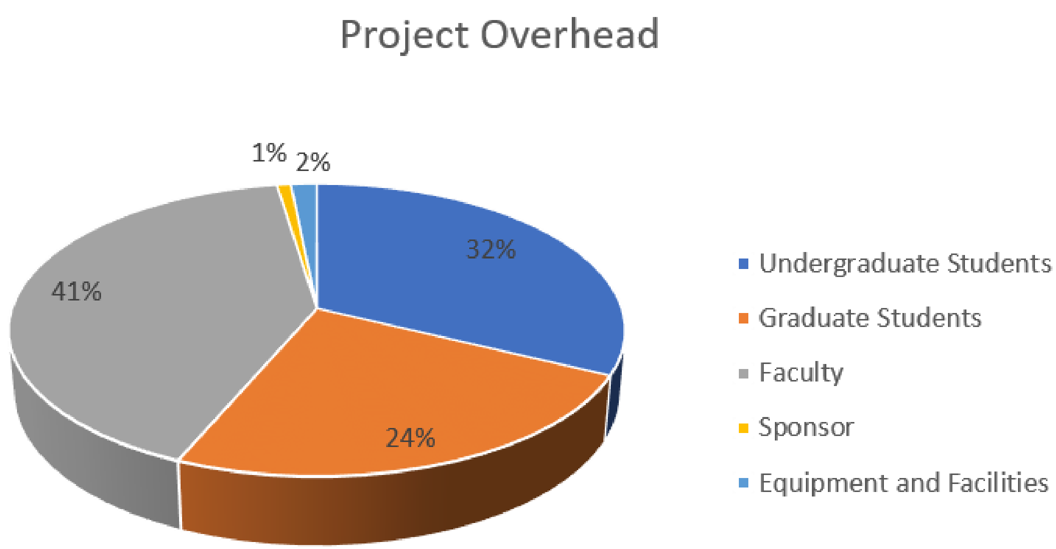

Figure 28: Total cost of Project

Operation

This is a stable hull, safe for leisurely use on calm, small bodies of water. The boat hull is to be fully supported during transport to its destination without motor attached. Once the destination is reached, a motor may be attached if it is desired. Rowing paddles can also be used to move the boat about in water. The boat has a maximum weight capacity of 1800 pounds due to a factor of safety of 1.5.

Maintenance

The boat hull should be washed down after each use. At the beginning of each season the joints should be inspected for cracks and voids, and filled with J.B.Weld if needed. This will ensure the strength of the joints after being exposed to the marine environment for extended periods of time. Prior to storing the boat hull, coating should be inspected. If there is damage to the surface of the boat, the region being treated must receive two coats of XTC-3D for waterproofing to preserve the ASA.

Additional Considerations

Economic Impact

As stated above in financial analysis, the total cost to produce a single boat hull at full scale is approximately $108,000. This cost will be entirely covered by the manufacturer which in this case would be the sponsor.

Figure 29: Economic Significance of Boating

Figure 30: Economic Impact of Recreational Boating

Societal & Political Impact

These impacts will depend highly on what the sponsor decides to use the product for in future operations. Specifically, in the case of a societal impact, this product may have an impact if it is to be made available to the public. But, its high cost of production may cause possible customers to avoid the product.

Environmental Impact

The boat hull, being made of a 3D printed polymer, has a major environmental impact. The hull material, ASA, can be toxic to the environment if dissolved in water. However, with the coating of XTC-3D as an outer layer it will prevent any material deterioration from occurring. XTC-3D is a hydrophobic material that has no threats to the environment [14].

Ethical Impact

The ethical impact of this boat hull is to be determined by Raytheon's usage of it. Because of Raytheon's work in military applications, this project may end up being used as a vehicle of war.

Conclusions

Team 12 was selected by Raytheon to design a boat hull in segments using additive manufacturing. Raytheon gave the team a lot of freedom with this project to be creative with the design and allow collaboration with other teams. It was up to the team to decide what factors were most important and what to focus the most time on. The project spanned over the course of two academic semesters between 2018 and 2019. Throughout the fall of 2018, the design team focused on gathering information and generating concepts for the boat hull. The latter half of the semester was aimed toward achieving a proof of concept to validate that the design would accomplish the teams proposed solution. In the spring of 2019, a prototype was created to show a physical representation of the boat hull that would later be made into a full-scale boat. The second half of the semester consisted of testing of materials used in the printing process as well as the strength of the joints holding the segments together. The results were summarized into a poster as well as a brochure and presented to at the University of Rhode Island Mechanical Engineering Design Showcase.

The team decided research on 3D printing and different methods to achieve successful prints was one of the most important factors when starting our design. With this in mind a flat bottom hull was created in SOLIDWORKS. The printers provided made it difficult to print complex geometries even when using support material. For this reason, we decided to not print complicated hull designs such as a deep v hull or a modified v hull.

Before now a boat hull has never been created using additive manufacturing to be used directly as a boat. Hulls have been created using additive manufacturing but only as molds to create the actual hulls out of different materials. The fact that this has never been accomplished before gave an emphasis to try and create a hull that is easily mass produced in segments rather than a complicated design that will have many failed attempts when printing. The original design was a simple flat bottom hull similar to many lake fishing boats.

For the next step in the design process the team had to address was how these segments would be put together. Research was conducted on different types of joints for different applications as well as marine adhesives. The ideal joint the team decided on was a finger joint used mostly with woodworking. This joint is simple to help prints run smoothly but is also very strong when designed correctly. These joints need to be very strong in order for the boat hull to travel at high speeds and not split into the original segments. A tolerance was calculated for the joints and when implemented into the prints, snapped very tightly into place. To further strengthen these joints an adhesive is needed to ensure a passenger's safety when in motion. Marine adhesives were researched and J.B. Weld, a metal based marine adhesive, was chosen to do to its great strength and ease of application. The J.B. Weld was applied to the receptacle ends of the finger joints for each section and were snapped into place. After the J.B. Weld had cured after sixteen hours the next step in the project was started.

The next step in the design process was to waterproof the boat so the 3D printed material would not become brittle and crack. After talking to other teams having to waterproof their projects and doing extensive research, the team came to a conclusion on how to waterproof the boat hull. XTC-3D was chosen due to its strength and its resistance to soak up water over time. At first, the team wanted to apply a spray on rubber coating which works well in many outdoor applications such as a leaky roof or gutter. This option would be relatively cheap but is not a great long-term solution. The rubber spray tends to peel off under an extensive amount of friction which it would have to endure at the high speeds the boat hull would travel. XTC-3D is more expensive but long term would be a much more viable option. After the XTC-3D was applied and allowed to dry, the team tested for leaks. The XTC-3D performed very well, and water would slide right off stopping it from being absorbed by the material and potentially affecting the performance.

The first major issues the team had with printing this hull was printing the front and back segments. The back segment had a shallow fillet running from the bottom of the hull to the very back and would finish with a rough surface. To fix this the fillet was changed to a forty-five-degree angle in order to follow the forty-five-degree rule which applies to printing certain geometries. This worked, and the team was able to continuously get smooth prints on the back fillet. As for the front segment of the hull, it was really difficult to print the piece without the middle sagging. Everything had to be as smooth and uniform as possible to avoid more friction with the hull and water to allow for smoother traveling. To try and fix this issue support material was added which could be broken off after the print. This solution did not work well as the provided printers struggled to print the support material continuously and would fail often. The next solution to this problem was to reverse all the joints to allow all the pieces to be printed standing up, following the forty-five-degree rule. This solution worked, and the team was able to save on cost of material by not using support material.

Although the team was able to accomplish and build a boat hull in segments using additive manufacturing, the cost would be too high to mass produce. Additive manufacturing has come a long way, but such progress has been made largely on the small scale. It is still very expensive when attempting to mass produce a large object such as a boat hull.

Further Work

Taking into account the progress that has been made, there are still many steps that can be taken in improving the design. The team has started the process of conducting both Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) simulations to determine more in-depth performative qualities of the boat hull. Specifically using these software, the team was working towards determining the maximum speed of operation for the hull before failure.

Abaqus is an FEA software that allows for geometries (simple and complex) to be meshed, have their behaviors analyzed under stresses. Using Abaqus, the team's goal was to determine where the boat hull would fail, and what would be the minimum pressure at which the structure would fail. This data would then be used in the next step using CFD to determine the maximum operating velocity.

OpenFOAM v18.06 is a CFD software that is run using C++ code, and operates via the Linux operating system [16]. This software is specialized for solving end-to-end process-driven flows, internal flows in ducts, and aero and hydrodynamics.

For this project, the team began to model the flow problem as a Blasius flow. A Blasius flow is described as a two-dimensional laminar boundary-layer flow in one direction over a plate [17]. Being a flat bottom hull, the boat bottom of the hull can be approximated to a plate.

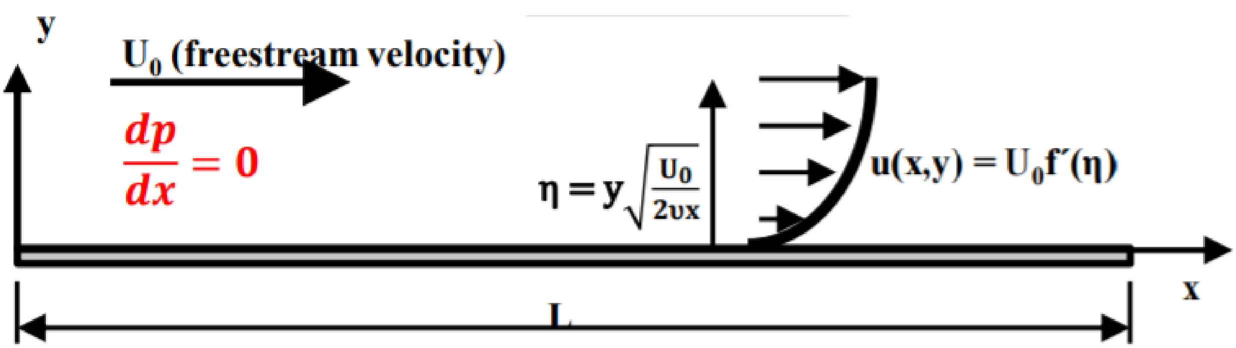

Figure 31: Blasius Flow

Figure 29 shows a Blasius boundary layer flow where U_0 is the velocity of the fluid, η is the kinematic viscosity, and $\frac{dp}{dx}$ is the pressure gradient driving the flow. Knowing that the freestream velocity at the surface of the hull will be equal to that of the hull because of the no-slip boundary condition. By commanding OpenFOAM to output values for the velocity and pressure, the velocity at which the maximum pressure is reached will be determined, and therefore will be the maximum operating velocity.

Lastly, Abaqus can be used in a way that is quite untraditional, and not commonly done. The Coupled Eulerian-Lagrangian (CEL) approach to the finite element method is a way of analyzing large deformations in non-rigid bodies [18]. Using this method, the team will be able to model the behavior of the water as the boat flows over it. This may be desirable for our sponsor as Raytheon specializes in manufacturing many different devices/vehicles for military applications. Therefore, determining how the boat flows through the water may determine its best application. For example, if the streamline left by the boat is minimal, the design may be optimized for use as a stealth vessel.

Overall, the design meets the necessary customer requirements determined by the team. The flat bottom hull design is stable, buoyant, weather resistant, and safe. Improvements need to be made to the design such as fixing the sag issue occurring during printing, resizing the finger joints in SolidWorks, and finding a water proof and reliable plastic adhesive.

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Appendices

Table 9: Engineering Test Matrix

	What is being Tested?	Test Parameters	Results	Planned Resolution
Hull Material (ASA)	ASA tensile test	Yield Strength	When comparing the results of the tensile tests, it was realized that the test specimens that were submerged in water at 38°F for 6 days, lost strength when compared to uncured test specimens of the same geometry.	The reults of these tests confirm the need to use XTC-3D coating on boat hull.
Hull Material (ASA)	How does water affect strength of material?	Yield Strength		
Boat Hull Dimensions	Does the boat take on water?	Draft (Height that boat sits above water)	Boat sits approximately 0.2 in. above water	
Boat Hull Structure	How much weight can the boat support?	How much weight can boat support beforee taking on water	Boat supports approximately 4.5 times its weight	
Boat Hull Structure	ASA tensile test of assembled joints	Yield Stress	Adhesive is strong and failure down not occur because of it. Failure occus and start of joint.	Fillet added to the joint to reduce stresses at base of joints.

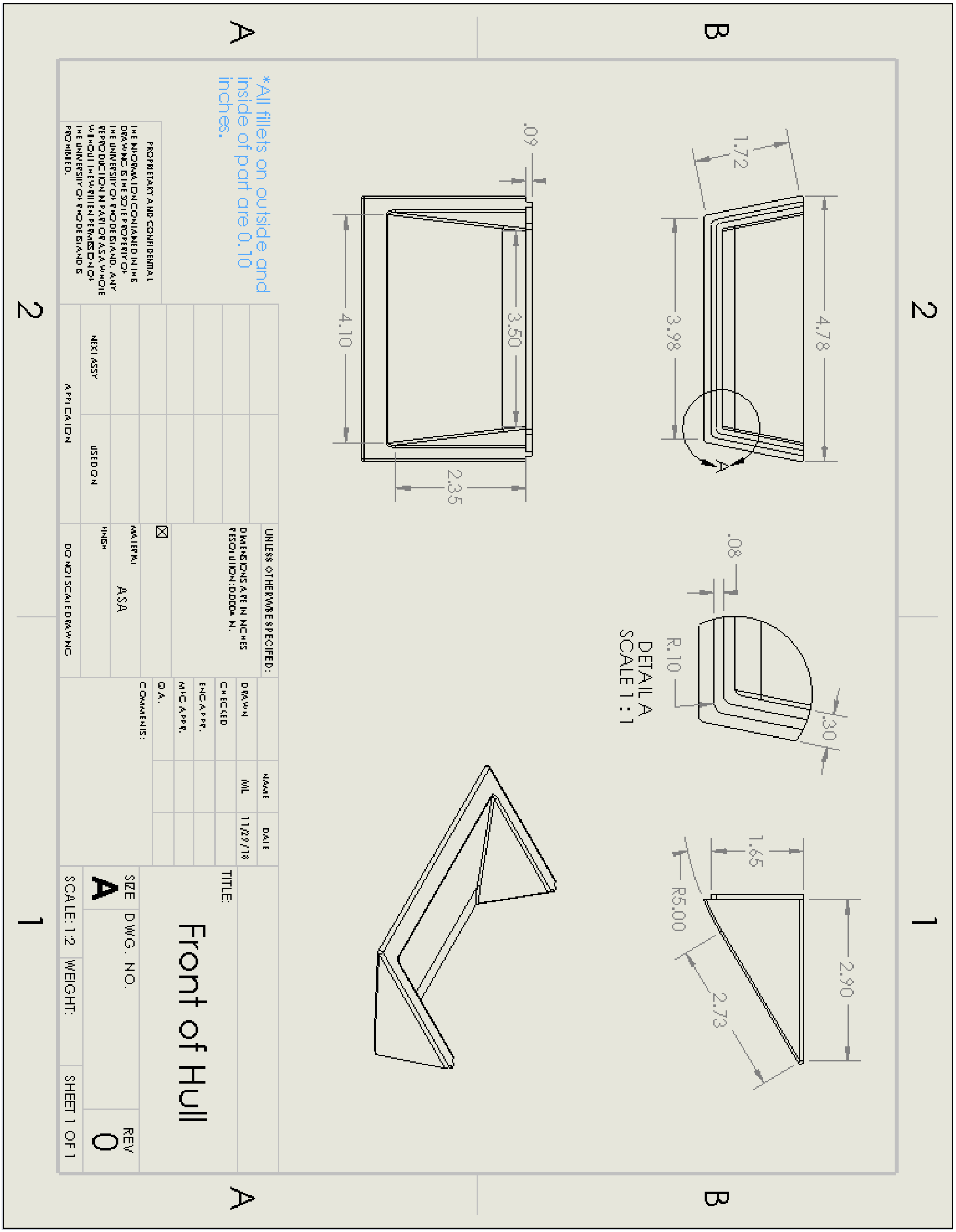

Figure 32: First design for front of hull

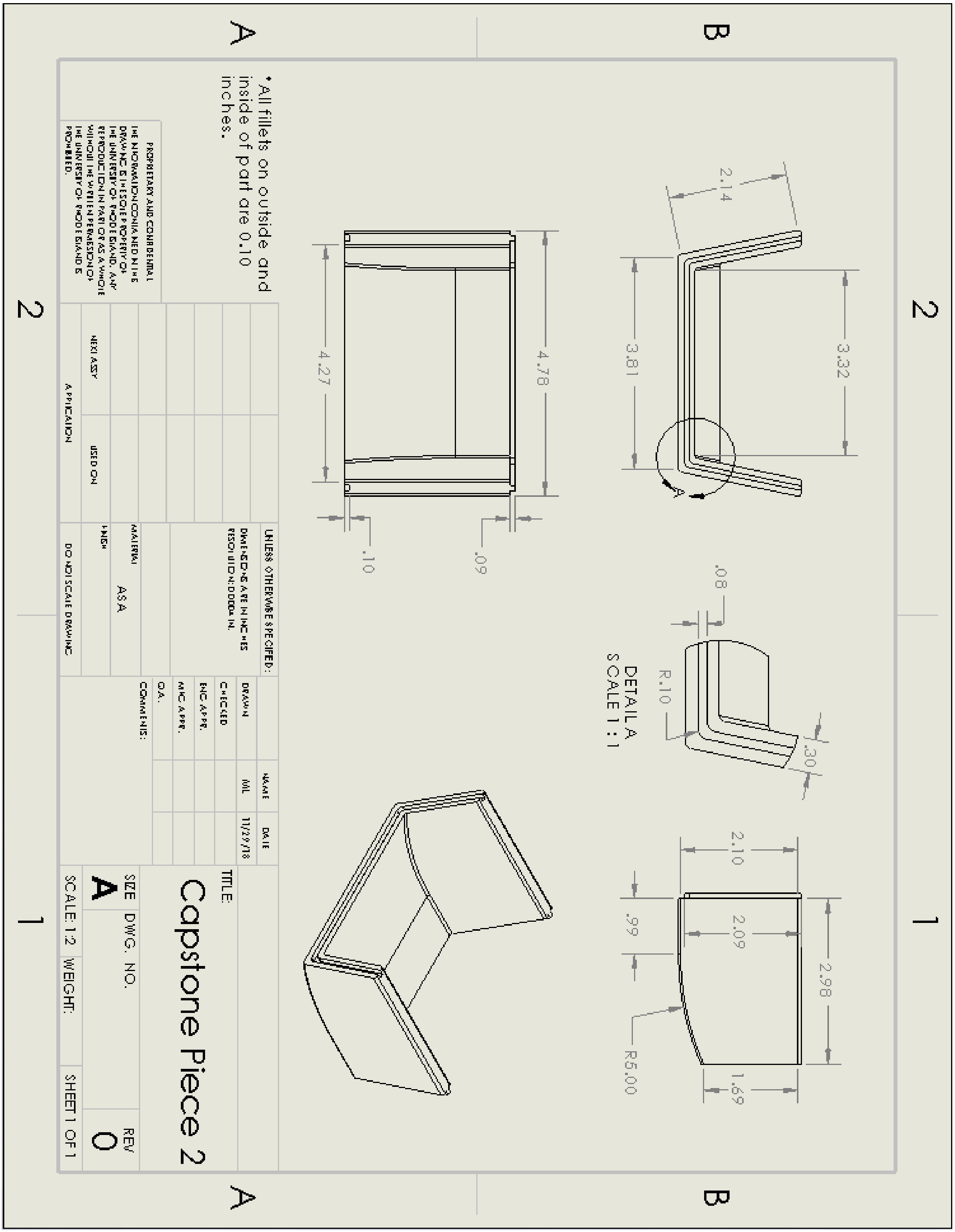

Figure 33: First design for Piece 2

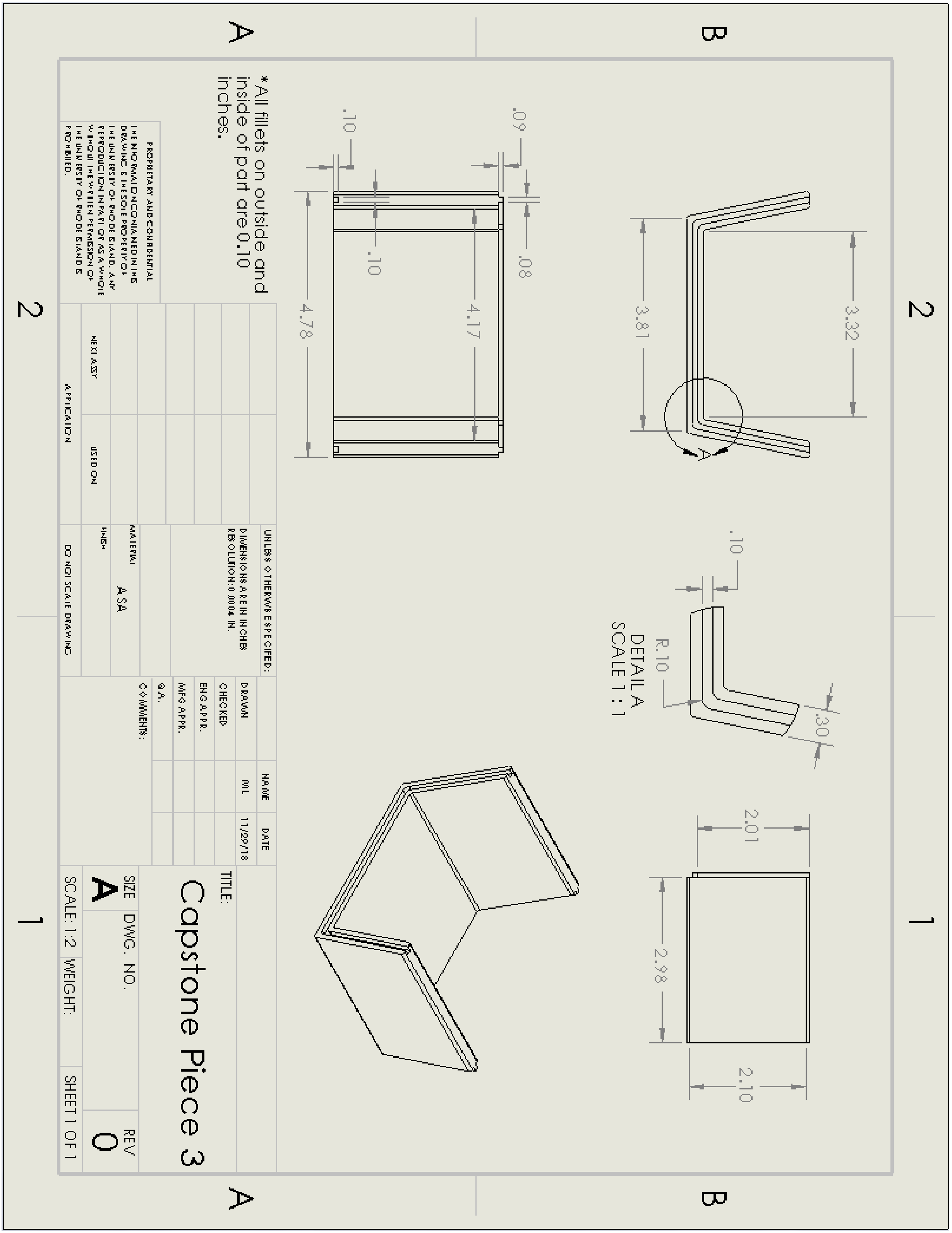

Figure 34: First design for piece 3

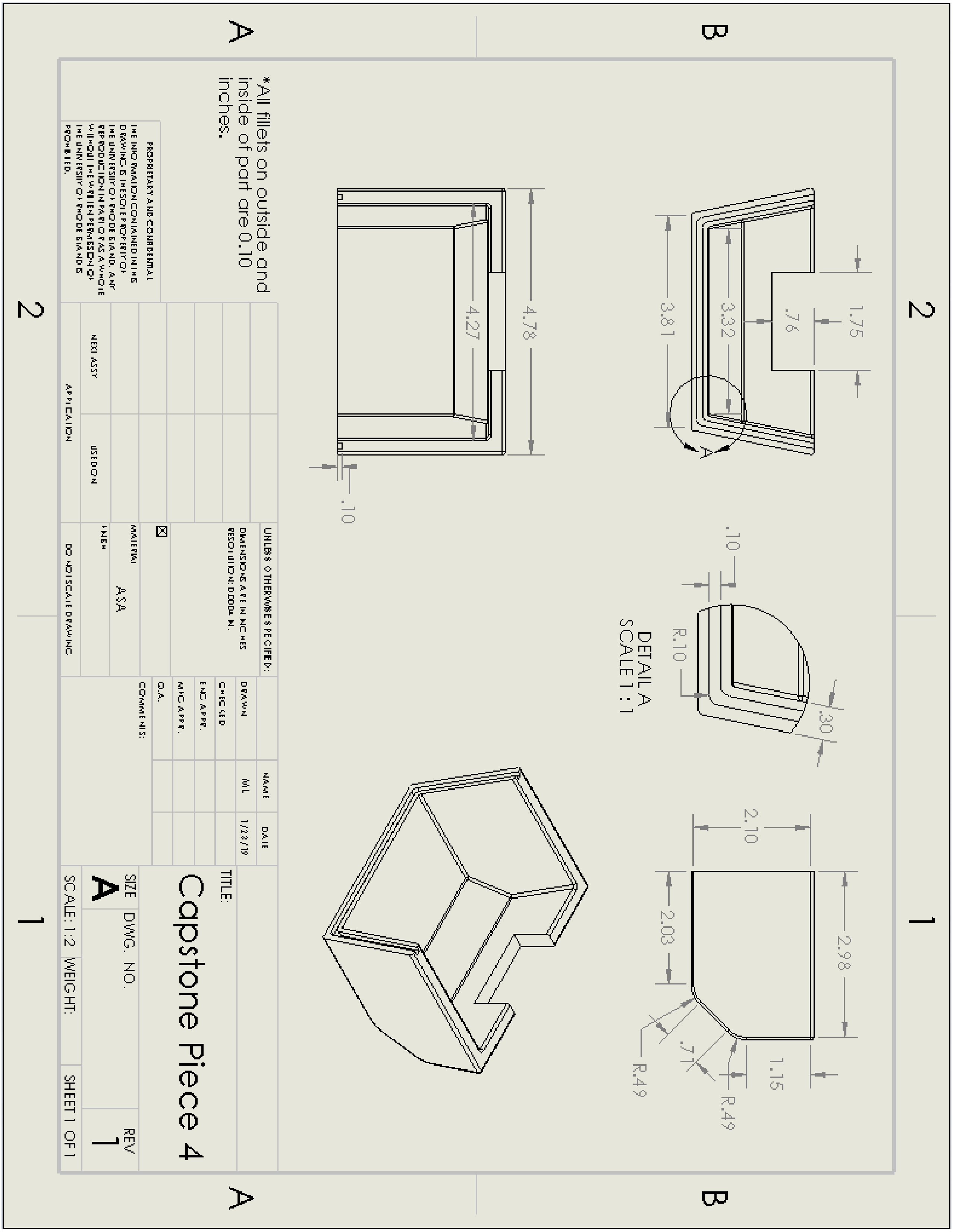

Figure 35: First design for back of hull

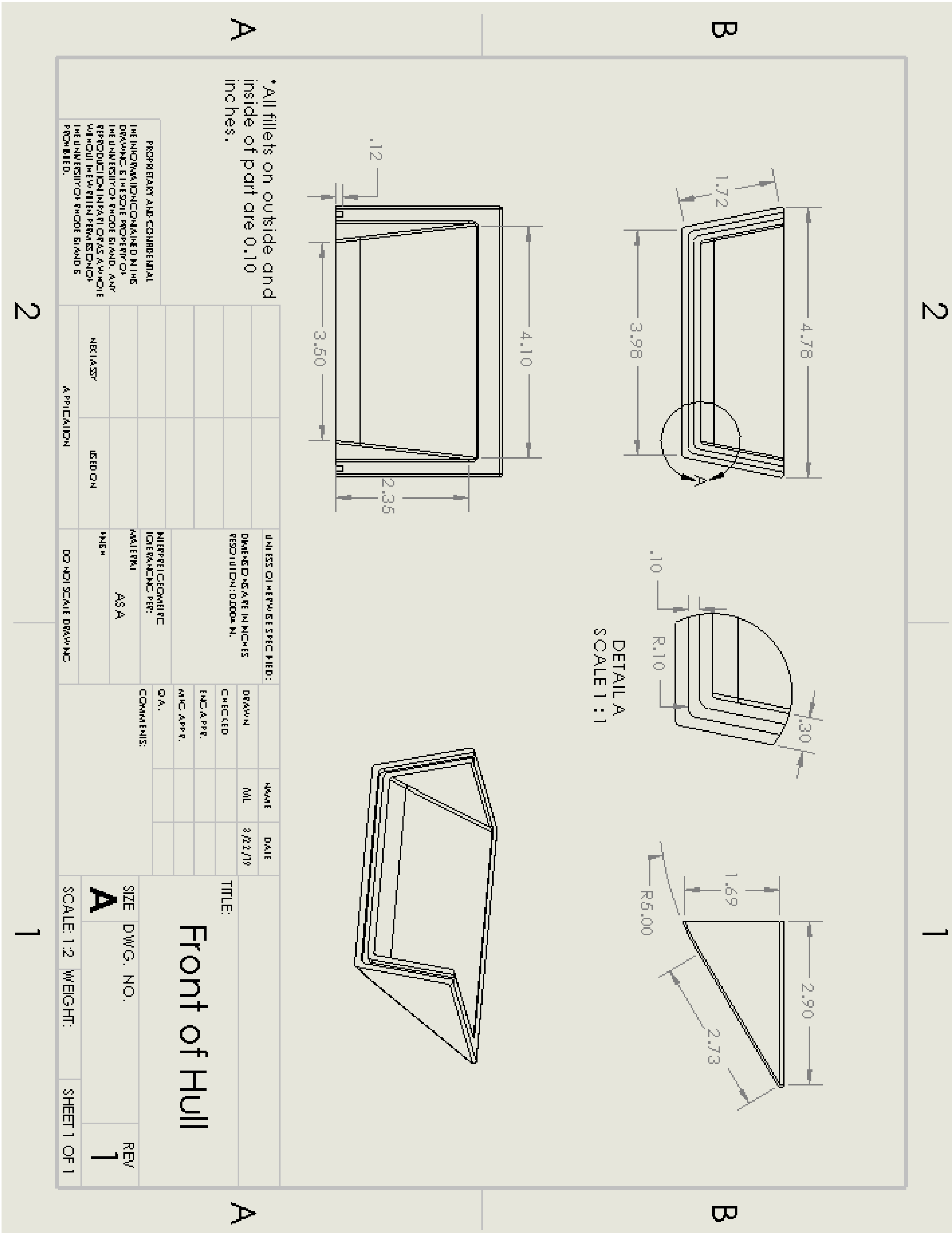

Figure 36: Final Design for front of hull

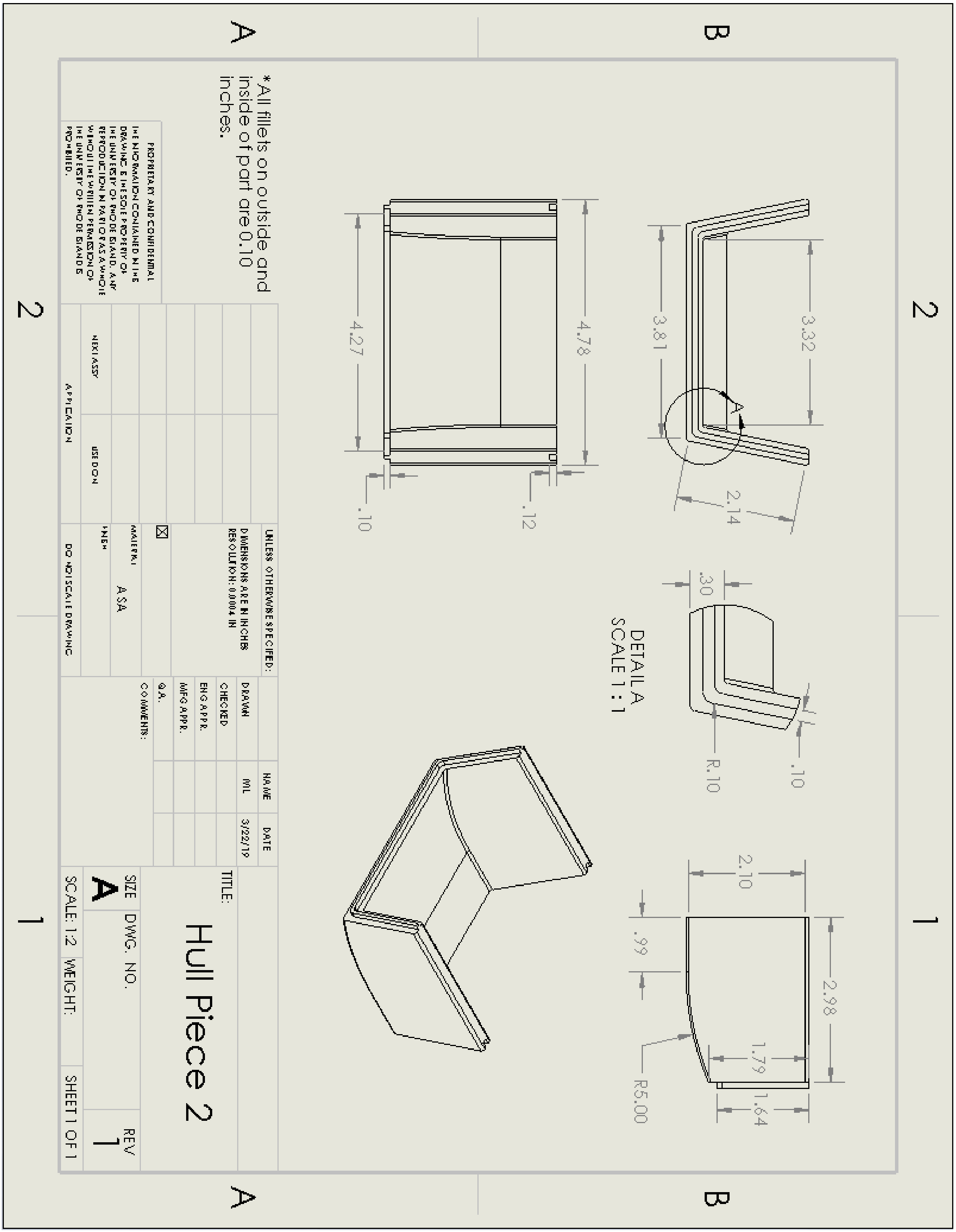

Figure 37: Final design for piece 2

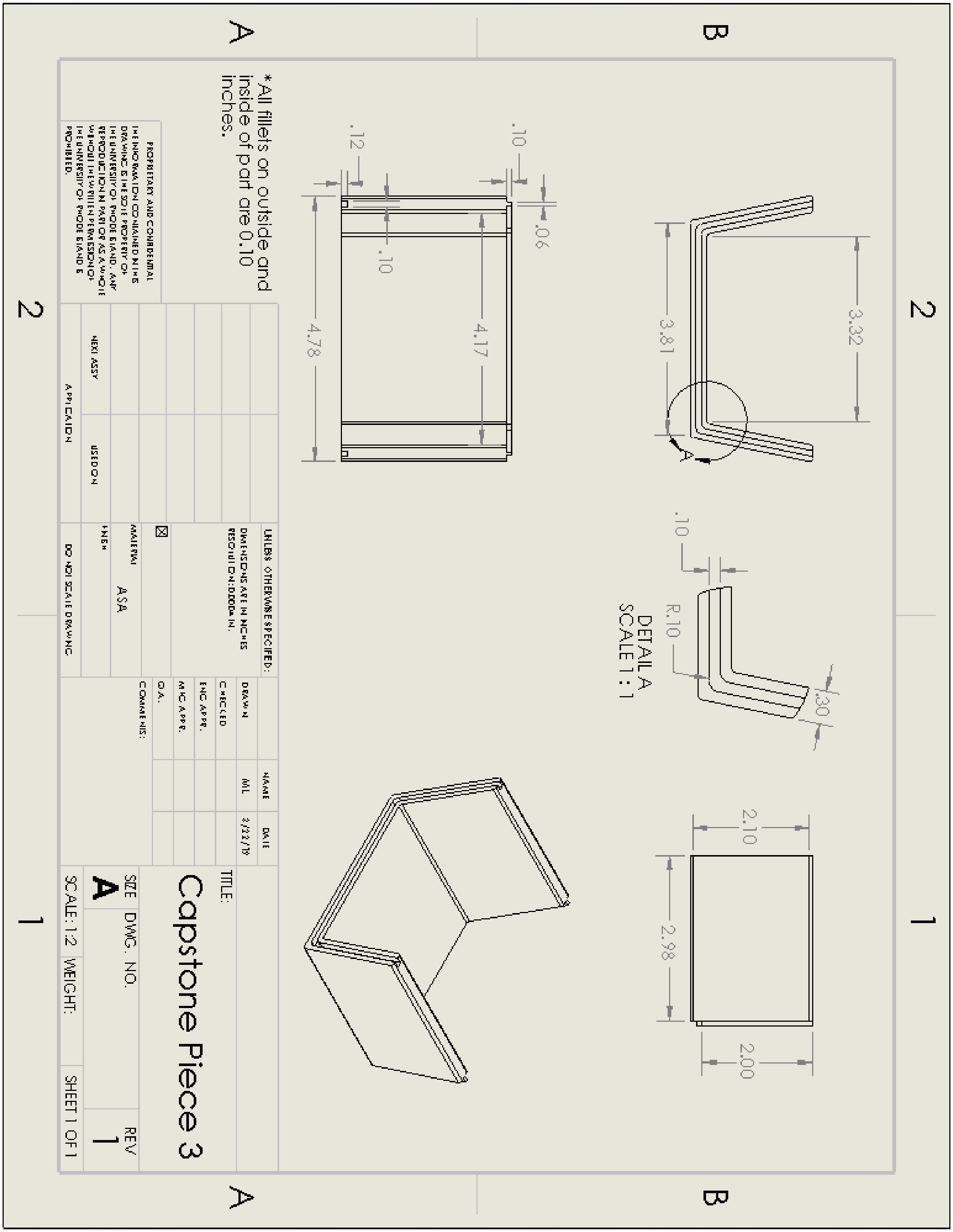

Figure 38: Final design for piece 3

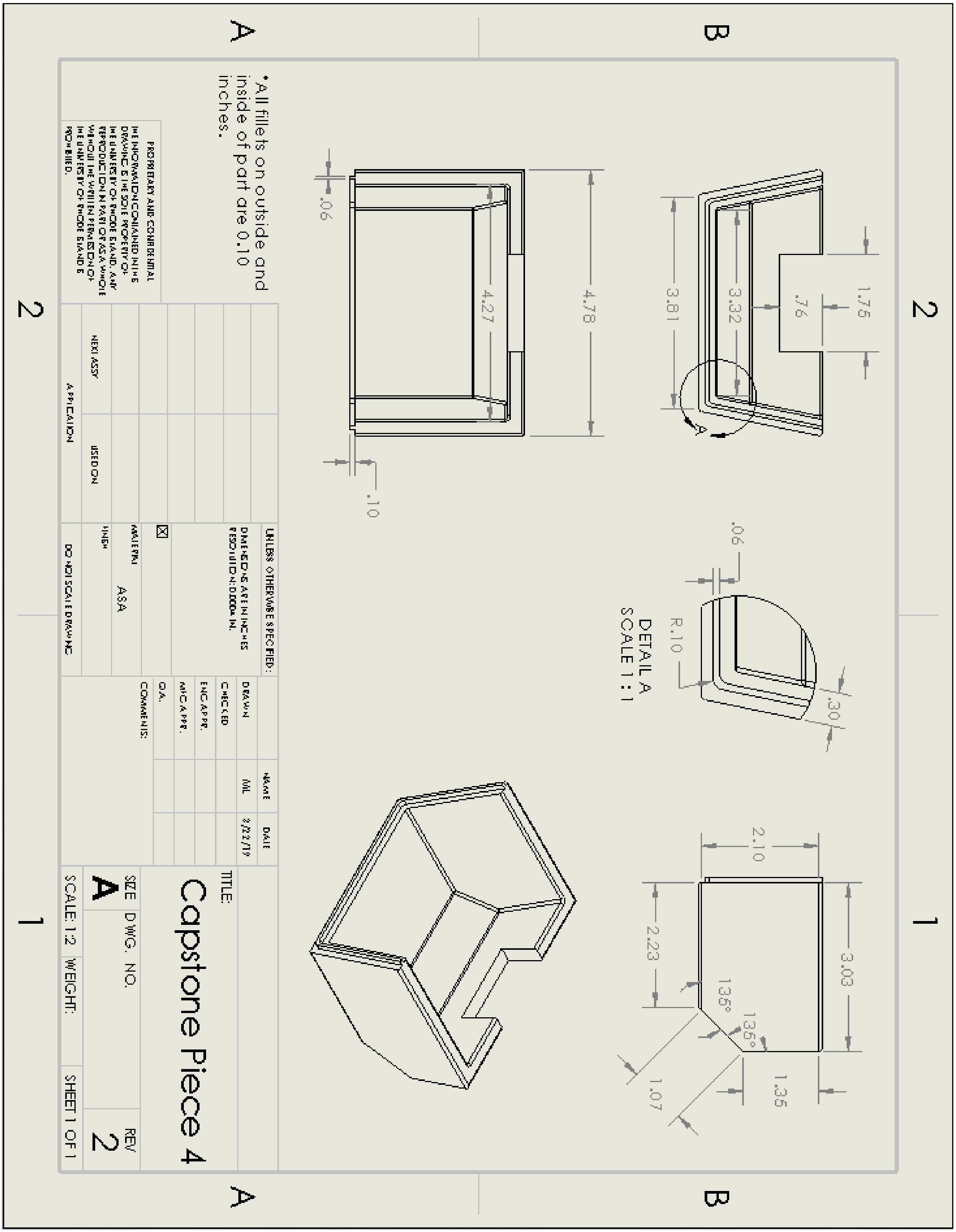

Figure 39: Final design for back of hull

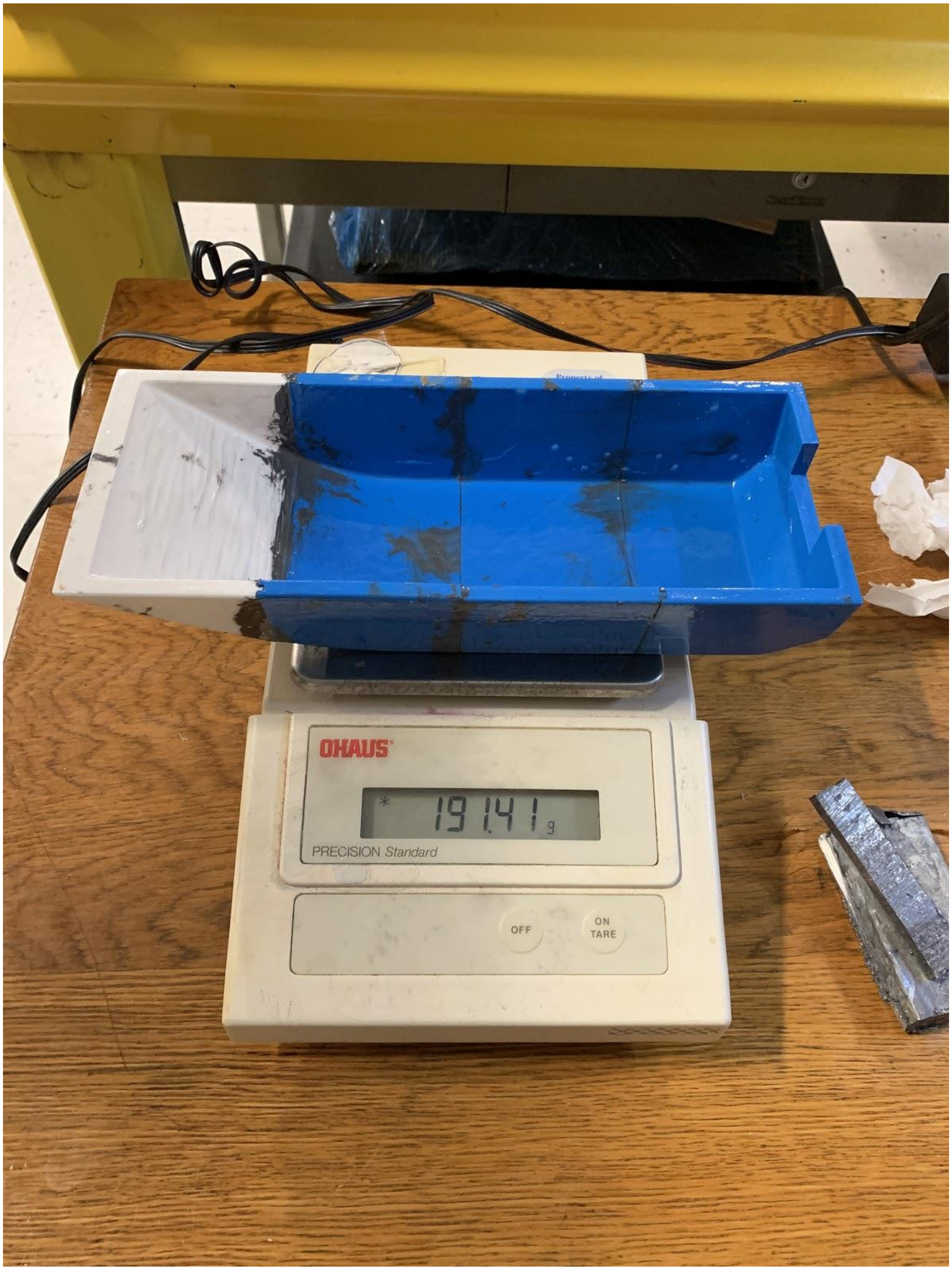

Figure 40: Boat hull weight

Figure 41: Weight that was placed inside boat

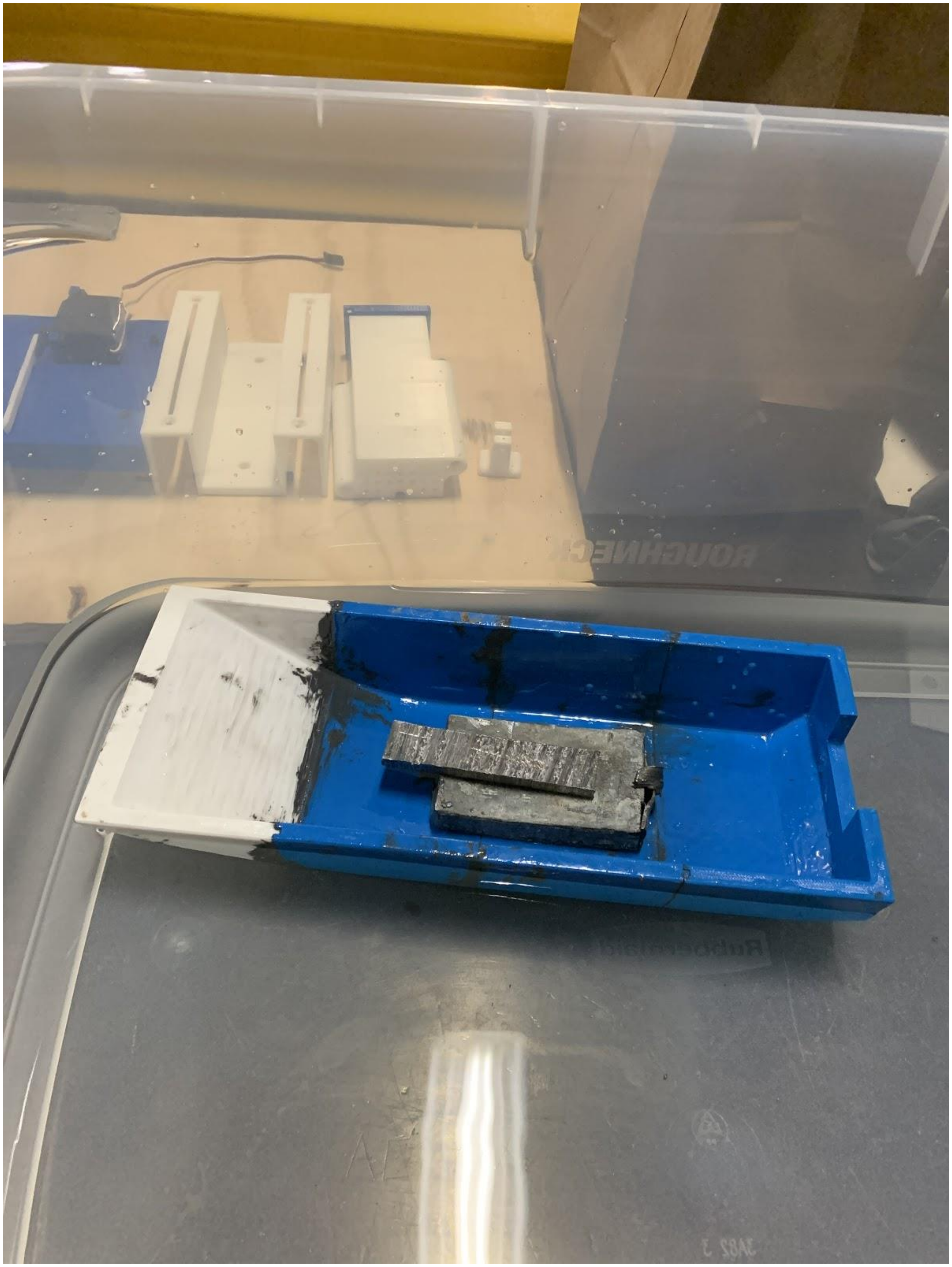

Figure 42: Boat supporting known weight while still afloat

Figure 43: Uncured boat assembly