U of M Solar Car Chassis Manufacturing Optimization

Final Report

Arnold Kadiu
Joe Martin
Garrett Simard
Nick Turnbull

Contents

1 Introduction

The University of Michigan Solar Car team desires to reduce the manufacturing time of their carbon fiber chassis. Current manufacturing times are on the order of eight weeks, which is unacceptable given the tight design and testing timetable prior to competition, as well as the desire to produce and test more than one iteration.

2 Background

In order to develop a solution to this problem it was necessary to gain an understanding of the manufacturing methods used by the U of M Solar Car team as well as current industry manufacturing methods for carbon fiber composites.

2.1 Michigan Solar Car

Every two years the team designs, builds and races a new car similar to the one seen in Figure 1. The car is designed for the World Solar Challenge, a race that is over 3000 Km long and on public roads. The race starts in Darwin, Australia, ends in Adelaide, Australia and takes over four days to complete. Since its establishment in 1990, the team has built 12 vehicles, won the American Solar Challenge eight times, and placed third in the World Solar Challenge five times.

Figure 1: U of M Solar Car (24)

2.2 Composites

On a conceptual scale, a composite is a material that that is manufactured, consists of two or more phases and the characteristics of the composite are not the same as the individual components. A phase is a portion of the composite. Each phase must represent more than 5% of the total composite and have significantly different properties (1). In order for the composite to be considered manufactured, the phases of the composite must be explicitly mixed.

A composite refers to a composite material. In most instances, the two words are interchangeable. The purpose of creating a composite is to combine the phases to create a material that has an improved property. These include improved mechanical, electrical, permeability or thermal properties. Most composites achieve these superior properties by combining a matrix, a 3D continuous phase, and dispersed phases, particles or fibers. Most of the composites this report focuses on will be an epoxy resin matrix and a carbon fiber dispersed phase (2).

2.3 Carbon Fiber Composites in Automotive Applications

The first use of structural carbon fiber composite (CFC) components in the automotive world can be attributed to the motorsports industry, as the use of carbon fiber to construct a monocoque was introduced on the 1981 McLaren MP4-1 Formula 1 car (3). The use of structural CFC components in the production market started with the supercar/niche market, particularly as it applied to chassis construction. This was mostly due to the high cost, driven by manufacturing time; the McLaren F1 road car took almost 3000 man hours to make (3).

Due to this high cost, the introduction of CFC components to the mass production market began with simpler pieces such as drive shafts in the 1990s and early 2000s (3). However, with the push of government regulations in the US (Corporate Average Fuel Economy or CAFE), the desire to incorporate CFC components into the "mass" production market lead to further developments in the manufacturing methods and materials technologies used to produce these parts. It is estimated that CFC components can provide up to a 65% weight reduction in the typical production automobile (3).

General Motors Corvette Production Engineering Team is continuously searching for mass reduction techniques to enhance the performance of the vehicle while maintaining similar cost and manufacturing structures. In 2005 they managed to replace fiberglass-reinforced parts in the front of the vehicle with carbon fiber reinforced parts for an overall mass reduction of 34% using various molding processes, carbon fiber materials, and curing techniques (4).

2.4 Carbon Fiber Composite Construction

The construction of carbon fiber composites generally consists of two main components. A fabric of carbon fibers creates the fiber matrix, while a resin creates the polymer substrate.

2.4.1 Types of Fibers

There are many types of fibers used in the production of CFCs. The most prevalent primers used in the production of fibers are rayon, polyacrylonitrile (PAN) and pitch (1). PAN precursors dominate the current marketplace (1). There are hundreds of PAN based fibers available and the specifics of each is beyond the scope of this paper and this project.

2.4.2 Types of Resin

Polymer matrix resins are dived into two major categories: thermoset resins and thermoplastic resins. Thermoset resins typically are liquid or low-melting solids, and are cured to produce the final form. The curing process for thermoset resins involves a catalyst, heat, or a combination of a catalyst and heat (5). Thermoplastic resins become viscous when heated to allow for proper forming - usually within a mold to form the final part. The resin then becomes rigid upon cooling (5). However, thermoplastic resins are generally not used for structural applications, and do not utilize a filler of any kind (5). Therefore this report will only focus on thermoset resins.

Thermoset Resins

Thermosets are easily processed and utilize improved fiber impregnation due to the liquid resin being used at room temperature. The advantages of thermoset resins are their greater thermal and dimensional stability, improved rigidity, and higher electrical, chemical, and solvent resistance (5). Common thermosets are epoxy, polyester, vinyl ester, phenolics, cyanate esters, bismaleimides, and polyurethane (5).

Epoxy

Epoxies must be mixed with a hardener at the appropriate ratio. They offer many advantages over other thermoset resins including higher strength and stiffness ratings, are tougher, more durable and solvent resistant, and have a higher maximum operating temperature (5) (6). Epoxies typically require high temperatures to complete proper bonding between the hardener and the epoxy, and they are generally more expensive than other resins (5) (6).

Polyester

Polyester resins are created through condensation polymerization when a diacid and a dialcohol are reacted together to form an ester (5) (7). There are two categories of polyester resins: orthophthalic and isophthalic polyesters. Orthophthalic polyesters are inexpensive, but have low chemical and mechanical properties. Isophthalic polyesters are more expensive, but have better thermal stability, chemical resistance, and general mechanical properties (5) (7). A major disadvantage of both polyester resins are the toxic vapors released into the environment when forming the resins (5) (7).

Vinyl Ester

Vinyl esters are formed through reactions of unsaturated acids with epoxies (5). They have high resistance to environmental conditions due to the ease and completeness of the curing process. They also resist elongation better than polyester resins and are thus tougher, while maintaining high chemical resistance. However, vinyl esters commonly contain bisphenol-A (BPA), a highly toxic substance, and thus are not environmentally friendly (5).

Phenolics

Phenolics are commonly formed by reacting phenol with formaldehyde, and then catalyzed with either an acid or base (5). Phenolics are generally used in markets that require low-cost, flame-resistant, and low-smoke products. The advantages are high temperature resistance, creep resistance, excellent thermal insulation and sound damping properties, and corrosion resistance (5) (8). A disadvantage of phenolics is that they create water as a byproduct during the curing process (5) (8).

Figure 2: Phenolic resin (37).

Cyanate Esters

Cyanate esters are created by reacting bisphenol esters and cyanic acid, and are more easily cured than epoxies (5). They offer excellent strength, while having better electrical properties, and lower moisture absorption when compared to other resins (5). However, without the addition of thermoplastics or spherical rubber particles the toughness is low (5).

Bismaleimides

Bismaleimides are produced similarly to vinyl-type esters. They are generally used for high-performance structural composites requiring high temperatures uses, and thus, are typically used in the aviation and space industries (5). The disadvantage of bismaleimides is that they require long curing times at high temperatures (5).

Polyurethane

Polyurethane resins are created by reacting two monomers together, and are very versatile resins (5). They show excellent toughness and resistance to elongation characteristics making them widely used in the automotive industry. Since the mechanical properties will depend on the type of monomer used, typically ether based monomers are used, due to their high mechanical properties. Ether based polyurethanes also have short solidification times making them excellent candidates for faster processing techniques such as reaction injection molding (5).

Resins can be applied to a dry fabric using various techniques at different points throughout the manufacturing process, or they can be pre-impregnated into the fabric. This latter method (prepreg) is the type of material available to the Solar Car team and therefore will be the focus of this project. The main advantage to prepreg is that the resin is already evenly spread throughout the fabric in the appropriate quantity. The main disadvantage is that prepreg must be stored in a freezer to increase its life, as it degrades over time.

2.5 Types of Fabrics

There are many types of fabrics, woven and non-woven, which can be created using different fibers and resins. Mechanical properties of each fabric are given from the properties of the fibers, the percent of the composite made up by the fibers and the orientation of the fibers relative to the direction of the applied stress (1).

2.5.1 Unidirectional

Because CFCs are strongest in the direction of the fibers and in tension, it is often useful to use a fabric in which all of the fibers are oriented in the same direction (hence the term unidirectional). In a composite layup the primary fabric used is typically unidirectional (UD) plies at various orientations to support the transfer of load along the direction of the fibers while minimizing the transfer of load transverse to the fibers.

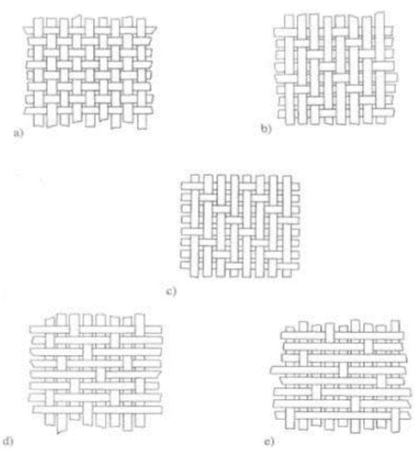

Figure 3: Types of fabric weaves, a) plain, b) 2x2 twill, c) 4x4 twill, d) 5-harness satin, e) 8-harness satin (1).

2.5.2 Woven Fabric

UD fabrics are not always optimal. Sometimes the structure of the part requires a lot of plies paired to other plies in symmetric orientations. This can lead to an excessive number of plies and unacceptable part thickness. In order to reduce this effect, fabrics can be woven with a cross weave at 0 and 90° orientations or other combinations. Cross weaves can be broken down into various types: plain, twill, or satin, the construction of which can be seen in Figure 3 (1). Each of these have their own variations, and tows. Tow describes the number of yarns contained in each strand. Typical automotive CFCs use 1K to 12K tows (3).

2.5.3 Other Types of Fabrics

Fabrics can also be stitched, knit, or braided. Each of these have their own advantages and disadvantages, however they are not commonly used in the automotive industry, particularly as it applies to structural components. Therefore this paper will not focus heavily on these types.

2.6 Types of Composite Tooling

Many materials can be used when producing composite tooling including sheet metal, wood, plaster, cast and machined metals, and even composites. The first choice in the selection process is if the parts need to be produced through an open or closed mold process. Closed mold operations are designed to withstand hundreds to thousands of curing cycles. Therefore, they are produced with expensive and robust tool materials such as cast and machined aluminum or steel. As such, this report will only focus on open molding operations as they are within the scope of this project. Therefore, the most common materials used to produce the tooling are sheet metal, wood, plaster and composites. Since a composite tool will have a similar coefficient of thermal expansion (CTE) to the produced composite part, the shrinkage and thermal expansion will be similar. This gives composite tools a significant advantage over other materials (9).

2.7 Common Manufacturing Methods

There are many methods to manufacture CFCs. In order to direct the efforts of reducing the manufacturing lead time one must have a general idea of the complete landscape for manufacturing CFCs.

2.7.1 Compression Molding

Compression molding uses a heated mold compound which is typically steel. The mold is heated to a high temperature and under extreme pressures, and can be designed to produce parts that are up to five feet long (10). Completed CFC parts can also be produced within 5-15 minutes. However, compression molding is designed for high volume parts (11), and typically involves large up front capital investments for the tooling.

2.7.2 Injection Molding

Injection molding is a technique borrowed from the fiber reinforced plastics industry and has been around for decades (3). During the injection molding process pellets of resin which contain fiber strands are injected into an enclosed mold. The process controls the amount of pellets, and the temperature of the pellets to slowly melt them into the mold. The pellets can contain short or long fibers. Because component strength is directly related to fiber length, long fibers are preferred for structural parts (3).

2.7.3 Hand Lay up

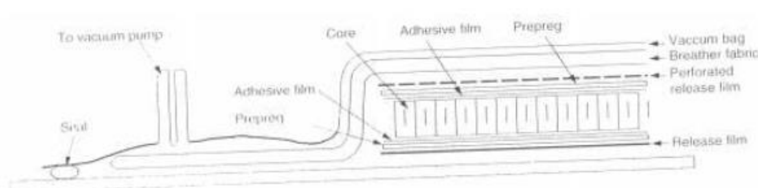

Figure 4: Typical structure for a hand layup using a vacuum bag (1).

The most common form of CFC manufacturing is applying the carbon plies directly to the mold using human labor. Typically, the layers that are being applied to the mold are cut from a large roll of carbon fiber using an automated process. From there the layers are applied to the mold in the proper orientation and sequence. Occasionally the part is put under vacuum pressure to remove voids and defects before continuing to add more layers. Once all of the layers have been applied the part is put under vacuum once more with a structure similar to that seen in Figure 4. Next the part cures in an oven or autoclave. An oven cure provides no additional pressure while the part is curing and is not recommended for structural components. The traditional route for the construction of structural CFCs in the automotive industry is the use of an autoclave (3). Autoclave manufacture uses the same process as vacuum bag manufacturing with the addition of positive pressure from the autoclave. This is well proven to reduce the size and number of voids in the layup (3).

2.7.4 Other Types

There are many other manufacturing methods for the production of CFCs, including: thermoforming, sheet and strand molding compound, spray forming, pultrusion, filament winding, resin infusion and many, many others. The discussion of each type and its advantages is beyond the scope of this project, however, the main types used in the automotive industry, and the types which cover the process currently used by the sponsor have been presented. As the project commences, and developments towards the sponsor's goal have been made the team may choose to investigate some of these methods further.

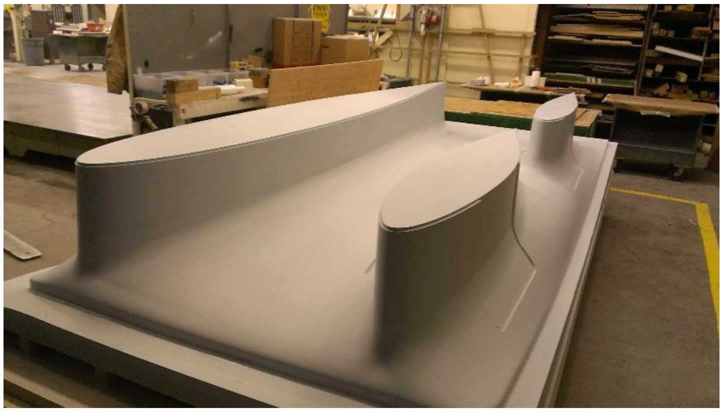
Figure 5: Positive male plug (25).

2.8 Current Solar Car Manufacturing Method

Currently the solar car is made by first machining a male positive plug (Figure 5) of the part. This is a copy of what the final shape will look like and is machined from a large piece of tooling board. This is typically a 5-20 lb/ft^3 density foam board. Once this shape is machined, a layer of gel coat is applied to the mold. This creates a hard surface which allows the surface to be sanded to a smooth finish and this surface makes it less likely that the next part will stick on the mold. After the gel coat is applied, it is sanded in steps of 240, 400, 600, 1000 grit and then polished. Once it is polished a mold release agent is applied to the mold. This release agent acts as a slip barrier. This means that the release agent gets broken off when you pull apart the parts. At this point, the plug is finished.


Figure 6: Female fiberglass mold (25).

Once the plug has been finished, layers of fiberglass are hand laid and hand wetted onto the mold surface. This process must be repeated three to four times because it is difficult to cure more than six layers at a time during a hand layup. During this process a steel frame must be manufactured and attached to the mold. Once all the layers of fiberglass have been applied the mold is allowed to cure. Once fully cured the female mold (Figure 6) is pulled from the male plug. This female mold is then cured again at a higher temperature to allow the coating to harden. This surface is then sanded similar to the plug and released in a similar fashion. Once these steps have been completed, the mold is complete.

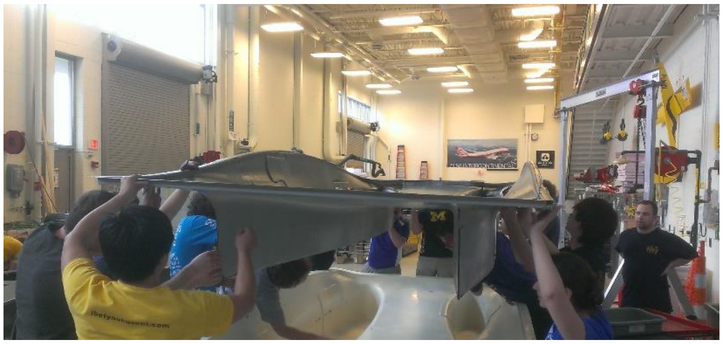
Figure 7: Final carbon fiber component (25).

The next step is to construct the composite parts of the solar car. Layers of carbon fiber are laid onto the mold in the predetermined locations to create a strong, yet lightweight part. Once all the layers of composites are in place the part is placed under vacuum pressure. This creates a pressure that helps eliminate voids and ensures that the parts are well cured. Afterwards the part is either put in an oven or autoclave to cure. Once the part cures in the oven, the part is pulled off of the mold (Figure 7), trimmed multiple times until it is the right dimension and then assembled as a whole.

2.9 Current Solar Car Composites Breakdown

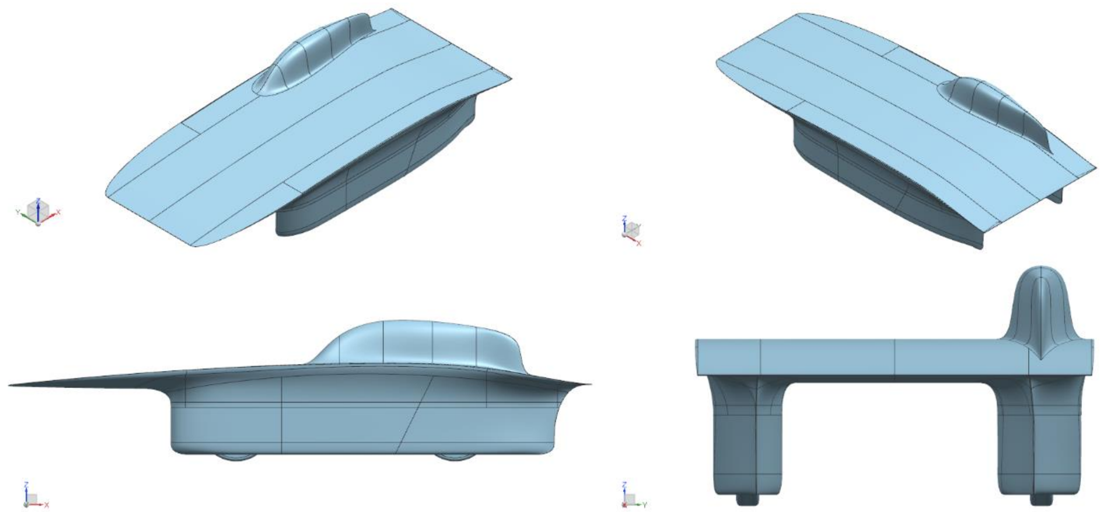

Figure 8: Solar Car aero body surface (25).

2.9.1 Solar Car Aero-Surface

As of February 11th, 2015 Figure 8 shows the current aero surface for the University of Michigan Solar Car Team's chosen vehicle design. For a balance between ease of manufacture, ease of vehicle maintenance, minimization of split lines, and protection again road damage the split lines were determined as follows.

2.9.2 Upper Surface

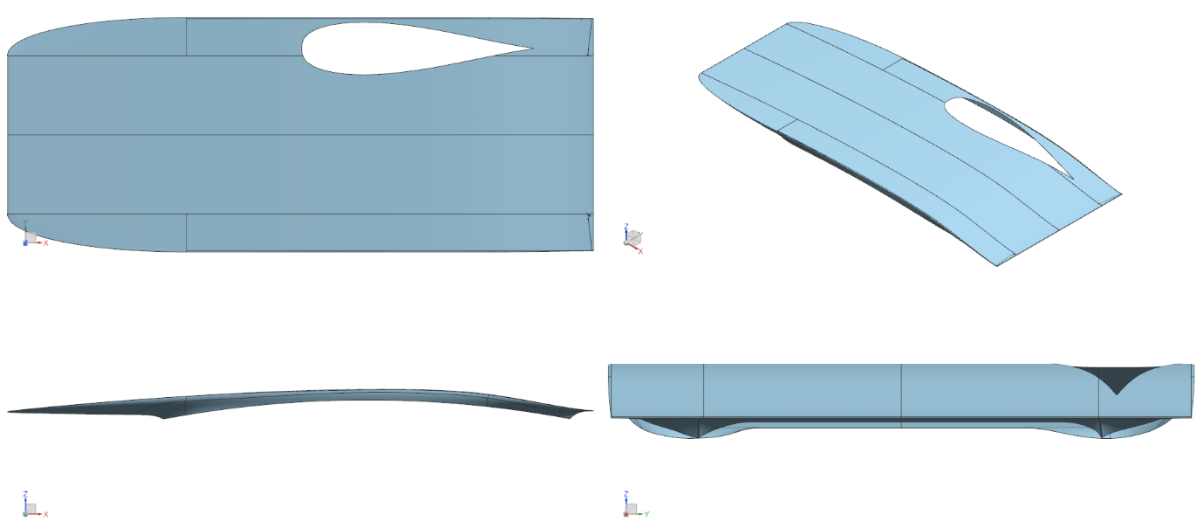

Figure 9: Upper aero surface. Overall dimensions (in) – 175 x 70 x 9, total surface area - 126 ft2 (25).

2.9.3 Lower Surface

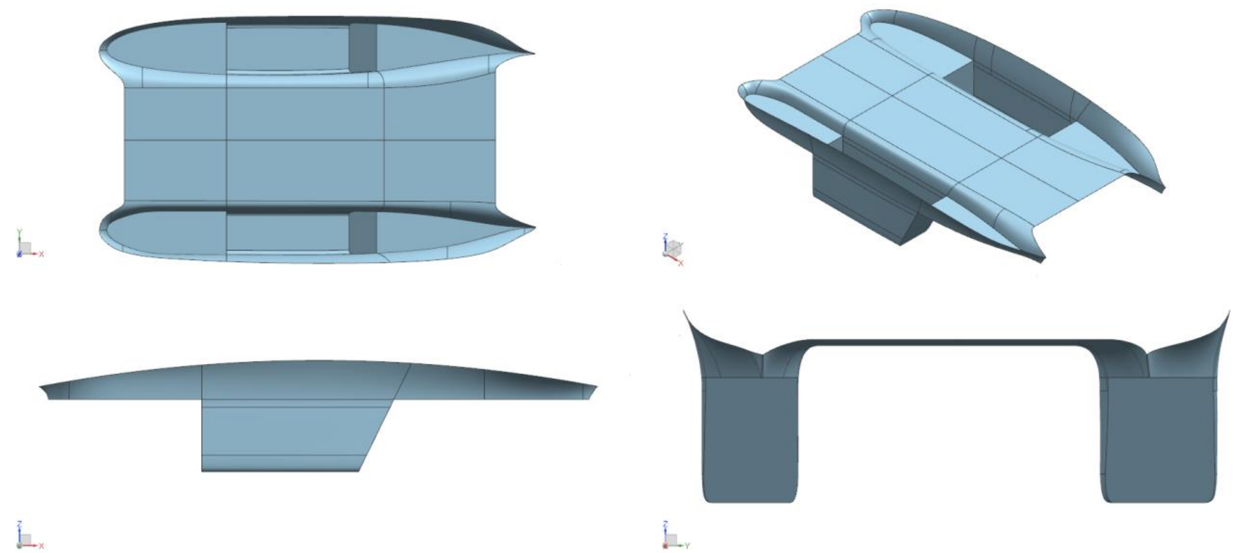

Figure 10: Lower aero surface. Overall dimensions (in) – 122 x 69 x 25, total surface area - 82 ft2 (25).

2.9.4 Fairing Pieces

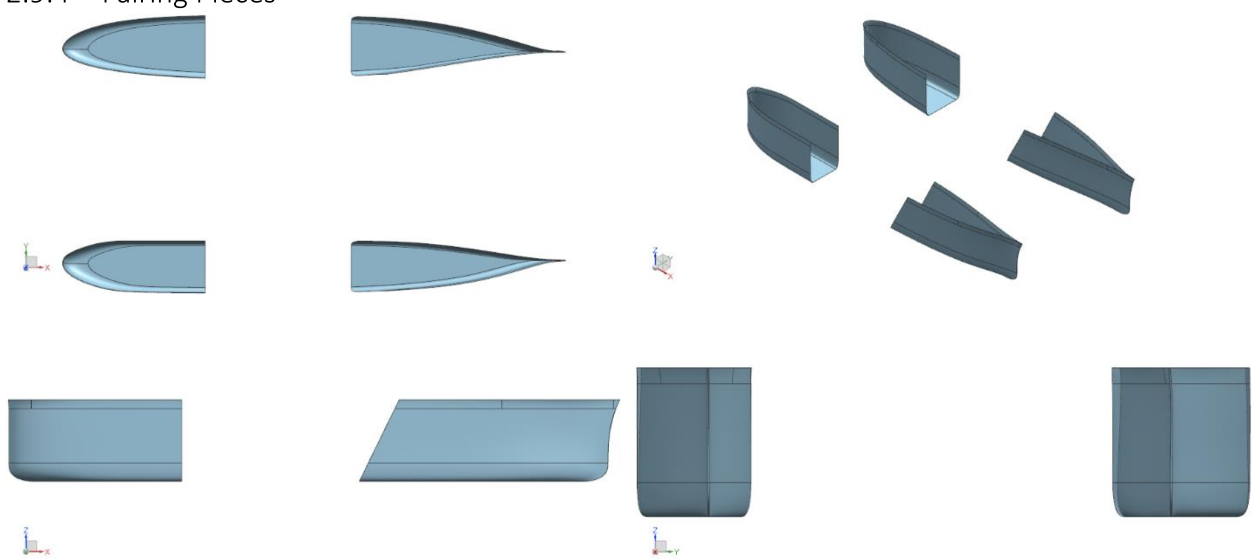

Figure 11: Wheel fairings. Overall dimensions (in, max each) – 50 x 14 x 16, total surface area - 44 ft2 (25).

2.9.5 Chassis

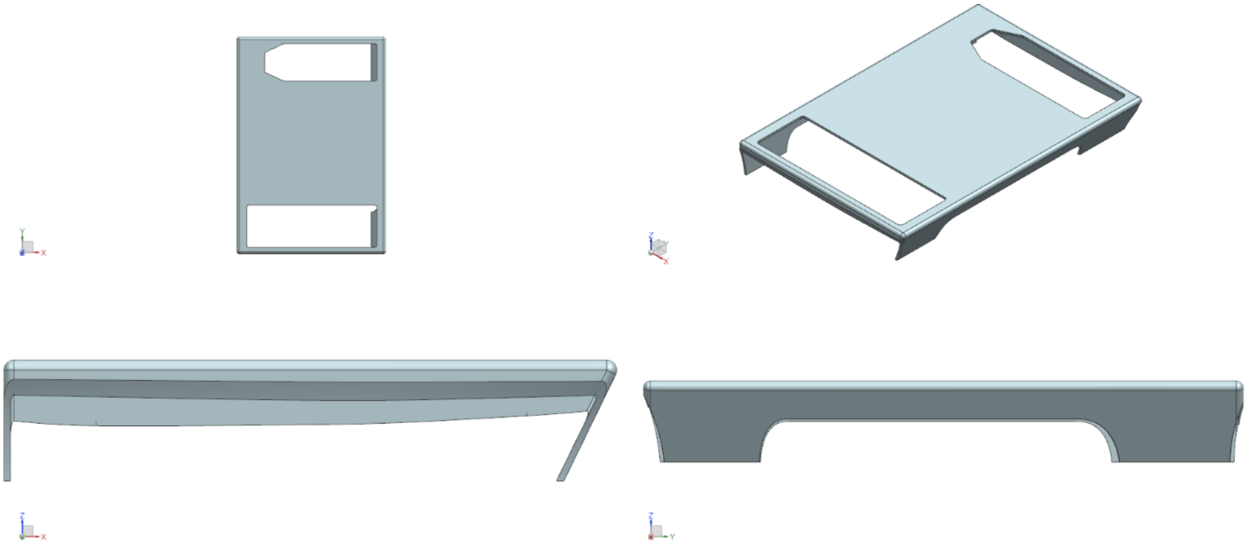

Figure 12: Chassis. Overall dimensions (in, max each) – 47 x 67 x 9, total surface area - 36 ft2 (25).

When integrated with the chassis, the bonded combination would look as follows in Figure 13:

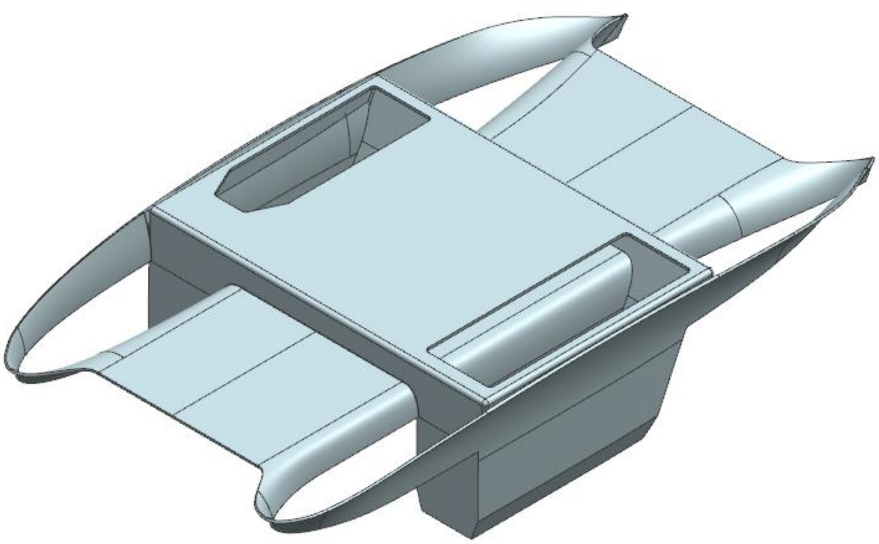

Figure 13: Bonded chassis (25).

3 User Requirements

The main goal of the project is to reduce the manufacturing time from eight to three weeks, however there are many other design constraints which must be taken into consideration. The main requirements are as follows:

- **Total manufacturing time:** three weeks
- **Cost:** new methods should not significantly increase cost to Solar Car team
- **Total human labor hours:** 30 hours maximum
- **Number of parts:** maximum of three parts per composite component
- **Maximum tool weight:** 150 lb if non-rollable, 1500 lb if rollable
- **Material restrictions:** must be able to sustain cure temperatures of prepreg and any adhesives must fully cure above 15 °F
- **Transportation:** all molds/part must fit in the Solar Car trailer
- **Minimize time spent during adhesive curing**

4 Engineering Specifications

Due to the design/manufacturing timeline of the Solar Car chassis, as well as the class duration the ultimate goal for proof of concept is to create an eighth to quarter scale model of the chassis using the new manufacturing method and compare it to the same scale model using the old manufacturing method. Therefore there is a necessity for two sets of specifications.

4.1 Full Scale Specifications

From the sponsor requirements a set of engineering specifications which will ensure the delivered product meets the sponsor's needs was developed. A breakdown of these specifications can be seen in Table 1.

REQUIREMENT	ENGINEERING SPECIFICATION
TOTAL MANUFACTURING TIME	Maximum of 3 weeks
COST	Less than $100,000 Maximum $30,000 in materials Maximum $70,000 in process costs
TOTAL HUMAN LABOR HOURS	Maximum 30 hours
NUMBER OF PARTS	Maximum of 3 parts per component 3 components, therefore maximum of 9 parts
MAXIMUM TOOL WEIGHT	1500 lbs., and rollable tool
MATERIAL RESTRICTIONS	Must sustain 275 °F cure at 60 psi Must fully cure above 15 °F
TRANSPORTATION	Must be less than 84 in by 288 in by 60 in
CURE TIME	3 hours to handle 1 week to full cure strength

Table 1: Full scale engineering specifications

4.1.1 Manufacturing Time

The sponsor has specifically stated that the requirement is to produce the new chassis in three weeks or less. They are looking to provide more time for design and testing and therefore the manufacturing phase needs to be reduced significantly.

4.1.2 Cost

Due to the funds available to the Solar Car team it is important to keep a cost objective in mind. The sponsor has clarified that this should not exceed $100,000 in total cost. Because it is more likely that they can receive sponsorship for the machining and fabrication costs, this category receives a higher budget.

4.1.3 Human Labor Hours

Since the human labor hours will be student hours, which are the least available and most valuable to our sponsor, they have specified that this must be a minimum. Therefore, it was determined that a reasonable goal was to be a maximum of 30 hours.

4.1.4 Number of Parts

Due to restrictions on storage space the sponsor has requested that the number of tooling parts per component be kept to a maximum of three. This quantity was determined through previous experience.

4.1.5 Material Restrictions

Because the sponsor works with donated carbon fiber it must be ensured that any tooling designed be compatible with this prepreg. The most important characteristics were identified as being able to withstand the cure temperature and fully cure without the need to be frozen or chilled.

4.1.6 Transportation

The sponsor plans to transport all tooling and pars with their existing trailer, therefore the full scale designs must be restricted to the dimensions they provided.

4.1.7 Cure Time

To allow the sponsor to quickly proceed with assembling and testing the vehicle, cure times must be kept to a minimum. Prior experience from the sponsor gave a reasonable value for full cure time as one week.

4.2 Scale Model Specifications

From the full scale specifications a new set of specifications for the scale model were created. Some of the specifications have yet to be defined as testing of making the scale model using the current manufacturing techniques has not yet been completed, and the exact scale of the model has yet to be specified. The results can be seen in Table 2.

REQUIREMENT	**SCALE MODEL ENGINEERING SPECIFICATIONS**
TOTAL MANUFACTURING TIME	Maximum of 37.5% manufacturing time of current method.
COST	Less than \$25,000 or \$12,500 (depending on scale) Maximum \$7,500 or \$3,750 in materials Maximum \$17,500 or 8,750 in process costs
TOTAL HUMAN LABOR HOURS	Maximum 2.2% manufacturing time
NUMBER OF PARTS	Maximum of 3 parts per component
MAXIMUM TOOL WEIGHT	375 or 187.5 lbs. and rollable
MATERIAL RESTRICTIONS	Must sustain 275 °F cure at 60 psi Must fully cure above 15 °F
TRANSPORTATION	Must be less than 21 by 122 by 15 in or 10.5 by 61 by 7.5 in
CURE TIME	3 hours to handle 1 week to full cure strength

Table 2: Scale model engineering specifications

5 Project Plan

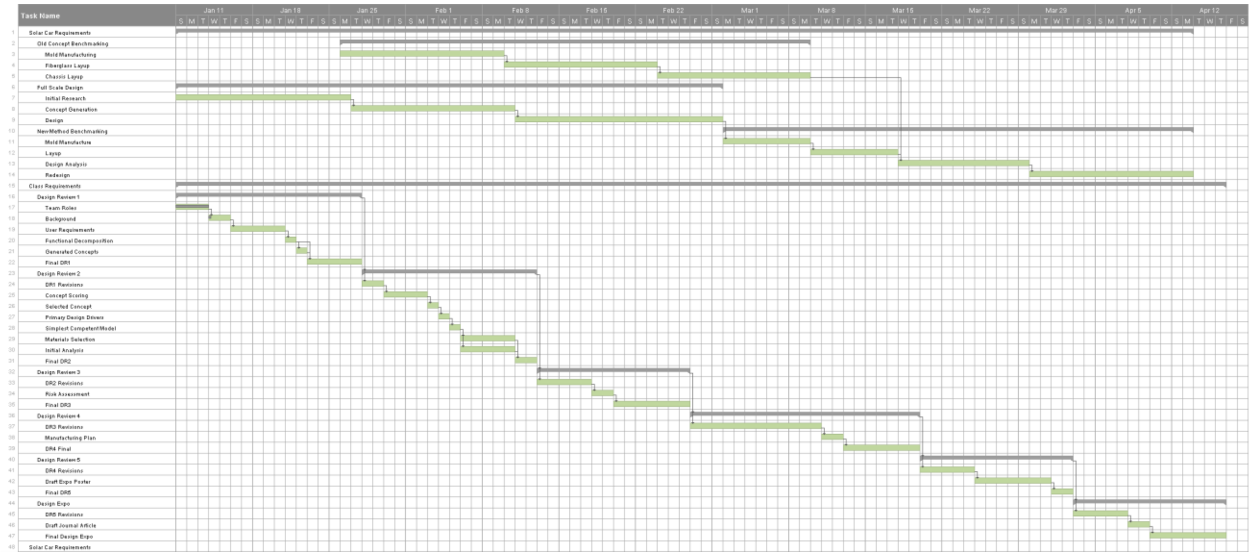

Figure 14: Project Timeline

6 Concept Generation

Many concepts were generated to solve the problem. After an initial elimination the most feasible concepts were chosen. These concepts will be described in the following sections. For the remaining concepts see Appendix A: Secondary Concepts.

6.1 Expandable Foam Mold

A significant portion of the time spent on making the Solar Car chassis is in the layup process for the fiberglass mold. One of the easiest ways to reduce this time is by replacing this step with a faster process.

Figure 15: Expandable Foam Molding (26).

Expandable foam begins as a liquid and is poured into a mold where it expands to fill the shape of the mold. There are many different densities and expansion times for expandable foam, which can provide the user with the desired amount of workability while keeping the hardening time to a minimum. With a medium or high density foam, and a very smooth mold the outer surface finish on the expandable foam would require minimal post processing to work as an acceptable surface for a carbon fiber layup.

6.2 Compression Molding

The majority of the time spent on making the Solar Car chassis is in the layup process, cure time and trimming the components. The easiest way to reduce all of these steps is by using a process that can complete all three steps in one much faster step.

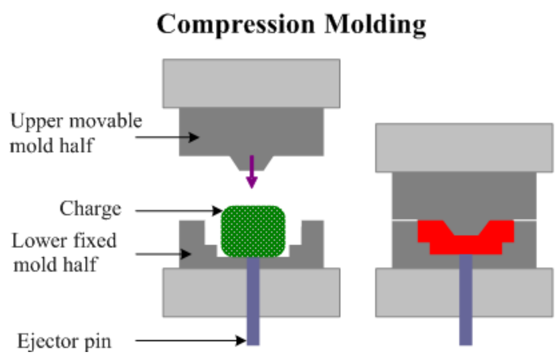

Figure 17: Compression molding technique (27).

Compression molding is one way to achieve this. By using compression molding methods the part creation from resin to finished product can be completed in less than an hour. The composite will be injected and cured at nearly the same time allowing for the greatly reduced part creation time. With steel tools the part will be produced with precise tolerances (.0015”) (12), and smooth surface finishes. There is still significant time required to produce the tooling necessary, but it is comparable to the current method.

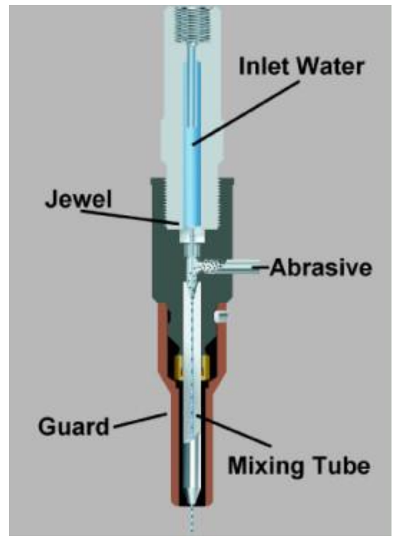

Figure 16: Water jet nozzle construction (28).

6.3 Water Jet Trimming

A large portion of the manufacturing process is trimming all of the components in order to assemble them later. This is typically done by hand and takes multiple days. This process takes a lot of time and many times it is difficult to maintain a tight tolerance using hand tools (~0.1”). One easy way to reduce this time is to replace it with an automated process.

One of the most accepted ways to cut pieces of carbon fiber is using a water jet cutting process. In this method, water is concentrated into a small stream at incredibly high pressures. This is used as an abrasive stream which cuts the composite. Typically, the capabilities of this method only extend in two dimensions and it is limited to cutting flat sheets. However, currently some firms also have the capability to attach a water jet to 7 axis arm. This would allow the user to trim surfaces that Solar Car currently makes, but it would also allow the user to use more complicated curvature which requires even more advanced methods of manufacturing. Also, this method would allow for the trimming of all required components in less than one day and hold a very tight tolerance (<0.01”).

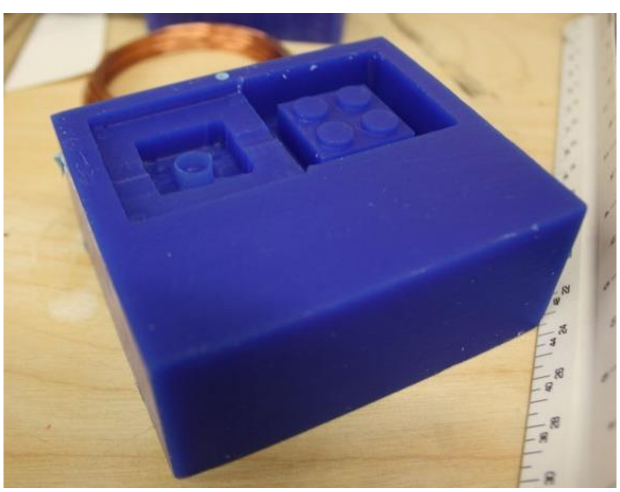

Figure 18: Machined wax mold (29).

6.4 Wax Mold

Similar to the expanding foam mold a wax mold is a solution by replacing the mold medium. With a wax mold the user could form the male plug completely from wax, complete the layup and melt the wax out. A major difficulty of this method is choosing the proper wax as it must withstand the heat from the curing process and still melt at a reasonable temperature. In addition the wax will require sanding similar to the current process.

6.5 Aluminum Honeycomb with Paste

An additional alternative mold material process, the aluminum honeycomb sheets would serve as the base of the straight to negative mold, in place of the more typical tooling board or aforementioned expanding foam. Due to its high stiffness/weight ratio, and ease of forming from common hand tools, it would be possible to block up a near net section tool of similar stiffness but of relatively low mass.

Once the net section was obtained, an epoxy paste would have to be applied to the tooling surface of the blocked up honeycomb and cured. This hardened and cured surface would then be final machined to the final surface ready for layups.

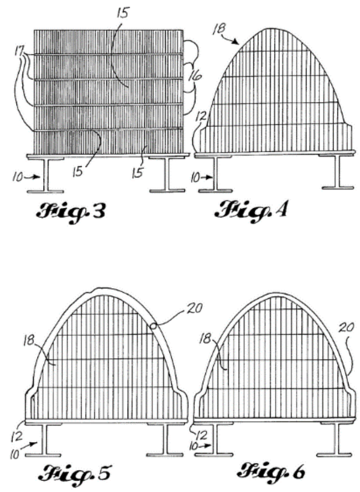

Figure 19: Example of manufacturing processes for aluminum honeycomb tool. (21)

6.6 Rolled Aluminum Flanges

One of the most time consuming and part critical steps is the trimming of the component. Most of this time is varied by the decision by the mold designer who makes a compromise between mold manufacturing time, mold cost, tolerance required by final part and labor time.

Essentially, there are two types of mold termination. There is in-plane runoff and out of plane runoff. In-plane runoff is much easier to design and manufacture the mold, but it requires much more time to trim

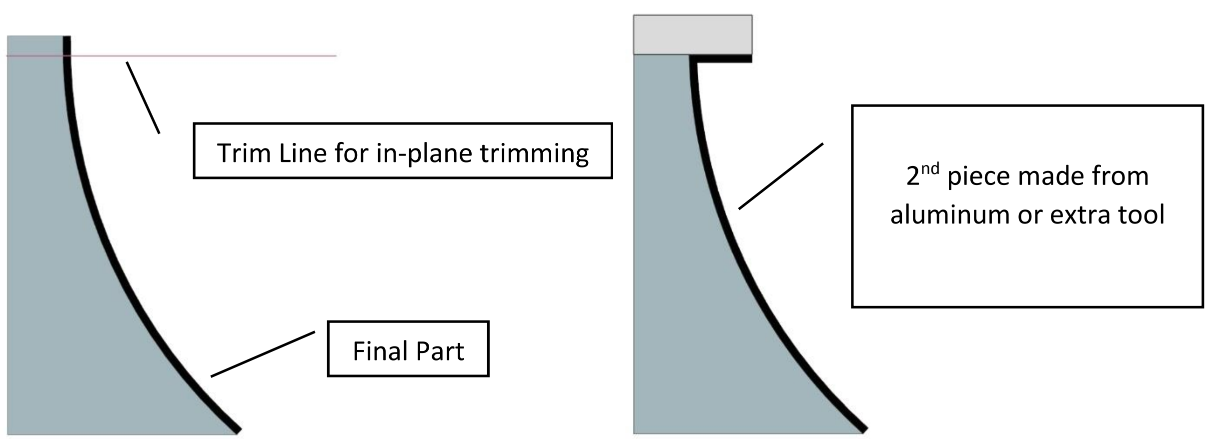

Figure 20: In-plane and out-of-plane (left to right)

when a manual operator is used. In this method, it is up the operator to manage the tolerance of the part. This is extremely difficult. The other method is out of plane runoff, but requires a 5-axis machining in most cases in order to be done correctly. However, this method makes it significantly easier to trim when a manual operator. In this method, the tolerance surface is machined into the mold which means the operator is not worried about trimming the surface incorrectly.

The method that is proposed here is using an aluminum sheet to create the out of plane runoff with an in-plane mold. This allows the user to make a mold using a 3-axis machining process, reducing costs and manufacturing time while still allowing the easier manufacturing with a manual operator.

The reason a manual operator distinction is used is because with CNC trimming services the difficultly is the same whether it is in-plane or out or plane runoff.

6.7 No-sand Primer

With the polyurethane tooling board process, the current method is to apply a primer/gel coat to the surface. This surface must then be sanded through a multi-step sanding process. The step can take as long as 3-4 days if people are sanding constantly. Alternatively, there is a primer that can be applied by wiping it onto the surface. This means that after the surface is machined, a primer can be applied and then the layup can continue. This process still needs more investigation before implementation, but this would be an immense savings in time.

6.8 Carbon Fiber Foam Negative Mold

Currently a significant amount of time spent during the manufacturing process is during the layup process of the fiberglass mold. By modifying this step the manufacturing time will be greatly reduced.

Figure 21: Machined CFoam Material (31)

One way of reducing the time involved in this step is to create the mold by using a carbon fiber based foam. This can be poured over the original positive where it will then harden to form the negative mold. This also creates a mold with a CFE that is nearly identical to the carbon fiber used to create the finished product. Unfortunately, this material is not easily accessible to our team, but if received, it would result in significant time savings.

6.9 Plywood and Steel Cross-sections with Machinable HexTOOL

Figure 22: HexTOOL mold (13).

To significantly reduce cost and machining time a plywood frame could be constructed with steel supports and a machinable HexTOOL. HexTOOL is a composite tooling material which combines tolerance accuracy with extreme lightness (13). This creates an extremely lightweight mold which is more thermally matched to the CFC component being created (the coefficient of thermal expansion of HexTOOL is very close to that of CFCs). HexTOOL was developed as an alternative to Invar, a concept discussed in A.5 Machined Invar Mold.

6.10 Expanding Foam and Hard Sealant

As described in the previous section on expanding foam, there are many advantages to using expanding foam to create a mold. Unfortunately there are also many disadvantages. One of the most prevalent is the porosity of expanding foam as well as the brittleness. Both of these issues can be addressed by adding a hard sealant to the outer layer of the mold. However, this increases the manufacturing time significantly as the sealant must be sanded to a smooth surface and requires cure time. In addition the application process for the hard sealant is a human one, which inevitably leads to lower tolerances in the mold.

7 Concept Scoring

After the concepts were generated a scoring system was designed. The major design criteria presented by the sponsor as well as team criteria were used. The additional team criteria were scalability and acquireability. Scalability is an important criteria as the chosen method for proof-of-concept is a scale model comparison of manufacturing times. Certain manufacturing methods are not easily reproduced for small scale parts. Acquireability is an important factor as the material must be accessible to the design team as well as to the Solar Car team for use in future years.

Each criteria was then given a weight to describe its relative importance to the other criteria. A scale of one to five was used to describe the importance of each criteria. As the reduction of manufacturing time was the major goal of this project, it was given the highest weight. In addition, heat resistance and coefficient of thermal expansion were given weights of five due to their importance in the manufacturing of CFCs. Human labor is a major point of concern for the sponsor, therefore it has been given a score of four, in addition to the internal criteria of scalability. Cure time is currently a large portion of the manufacturing process, and therefore has been given a medium importance separate from the overall manufacturing time requirement. Due to the presence of sponsorship for the Solar Car team cost and acquireability have been given a relatively low priority. In addition, weight has been given the lowest priority as most concepts should easily meet this requirement, and the procurement of alternative transportation methods is an option.

In addition to the criteria weight each concept was given a score from one to five for each criteria. The initial scores for the current manufacturing method were the first determined by consensus from the design team. Each concept was then scored relative to the baseline current manufacturing method. The scores were then multiplied by the weight and summed together. Two concepts were not scored as they only addressed small portions of the manufacturing process: water-jet trimming and rolled aluminum flanges. As can be seen in the final concept selection these two concepts were not discarded completely, just not scored.

CRITERIA	**WEIGHT**	***CURRENT MANUFACTURING METHOD***	**EXPANDABLE FOAM**	**COMPRESSION MOLDING**	**WAX MOLD**
MANUFACTURING TIME	5	***2***	4	2	3
COST	2	***4***	5	1	5
HUMAN LABOR	4	***2***	3	4	2
WEIGHT	1	***2***	5	1	3
HEAT RESISTANCE	5	***4***	1	4	1
CURE TIME	3	***3***	5	4	2
SCALABILITY	4	***4***	4	3	5
ACQUIREABILITY	2	***4***	5	1	4

THERMAL EXPANSION	5	***3***	1	4	1
TOTAL	**155**	***96***	**98**	**95**	**80**

Table 3: Concept scoring

CRITERIA	**WEIGHT**	**ALUMINUM HONEYCOMB + PASTE**	**NO-SAND PRIMER**	**CARBON FIBER FOAM MOLD**
MANUFACTURING TIME	5	5	5	4
COST	2	3	5	1
HUMAN LABOR	4	1	3	2
WEIGHT	1	3	2	4
HEAT RESISTANCE	5	2	4	5
CURE TIME	3	3	3	3
SCALABILITY	4	4	5	4
ACQUIREABILITY	2	3	5	1
THERMAL EXPANSION	5	1	2	5
TOTAL	**155**	**84**	**118**	**111**

Table 4: Concept scoring

CRITERIA	**WEIGHT**	**PLYWOOD AND HEXTOOL**	**EXPANDING FOAM + SEALANT**
MANUFACTURING TIME	5	4	3
COST	2	1	5
HUMAN LABOR	4	4	2
WEIGHT	1	2	4
HEAT RESISTANCE	5	5	1
CURE TIME	3	3	4
SCALABILITY	4	3	4
ACQUIREABILITY	2	2	5
THERMAL EXPANSION	5	5	1
TOTAL	**155**	**115**	**85**

Table 5: Concept scoring

As seen in Table 3 through Table 5 the highest scoring concept was that of the no-sand primer. The lowest scoring concept was the wax mold. The selection of our final concept will be outlined in the next section.

8 Concept Selection

Out of all the possible concepts for the creation of these tools, we didn't find any single concept that suited the needs of the solar car team perfectly. However, there was a combination of solutions that could combine the best features of each. Ultimately the no-sand primer was the highest scoring concept in conjunction with a straight to negative tooling board mold. As outlined in section 6.6 a direct tooling board mold can be quite time consuming during the trimming process. Therefore rolled aluminum flanges were also incorporated into the final concept.

At the time of this design review the no-sand primer has not yet been tested, and therefore the validity of the claims on surface finish have not been verified. In the event that the no-sand primer does not perform as expected further concepts will need to be generated, however the team is positive that the best route is to use a straight to negative tooling board design with rolled aluminum flanges.

One of the major downsides to this concept is that high density, high heat tooling board is very brittle. As some of the sponsor requirements involve the transportation of the molds between the sponsor's workshop and the autoclave/layup workshop there will have to be extra precaution taken not to damage the molds.

9 Design Drivers

Because the team is redesigning a process rather than designing a part or component, the key design drivers won't look the same. Essentially the design drivers are the specifications with the addition of being robust, repeatable and reliable. The final chosen design drivers are:

- Minimize manufacturing time
- Minimize human labor hours
- Maximize repeatability
- Maximize reliability

10 Engineering Analysis

As the ultimate goal of this project is to alter the Solar Car manufacturing process it is critical that the chosen design both satisfy all of the specifications and provide a smooth transition. The team must easily learn, adapt, and implement the process in a short period of time as the competition schedule is very demanding. In addition, the solution must be robust, repeatable, and reliable. Therefore, significant testing is required to ensure the design drivers have been satisfied.

Because the project is to alter a process, the main method to assess and refine the chosen design is by reproducing the manufacturing process. Team members who are familiar with the current method will be asked to perform the new method to confirm that it is indeed easier and less demanding on them. In addition, a comparison of the old method to the new one will be used to quantify the reduction in manufacturing time.

The main engineering disciplines used in this project are material properties and manufacturing processes. Various methods described would involve many other disciplines, however the chosen method is simple which helps address the design drivers.

10.1 Minimization of Manufacturing Time

The main design driver is to minimize the manufacturing time and this is where the chosen concept is focused. In order to quantify and validate the reduction of time a combination of empirical testing and a mockup was used.

Figure 23: No-sand primer.

10.1.1 Mockup Construction

The no-sand primer (Figure 23) was tested on a piece of tooling board with no shape to it to determine the viability of using this and pulling parts off with an acceptable surface finish.

10.1.2 Empirical Testing

Because the no-sand primer is a new technology to both the design team and the sponsor it was necessary to perform multiple tests to optimize the process. As is laid out in Section 12 one of the major challenges with this process was properly sealing the tooling board to ensure the proper surface conditions were met. The total time to complete a test component with this process was 6 hours plus 1 hour of cure time for the no-sand primer and 3 hours of cure time for the part. The estimated time using the conventional method was 48 hours. This was a large time delta, proving the feasibility of this method. Further testing will be conducted on the scale models after the molds are received from Ford.

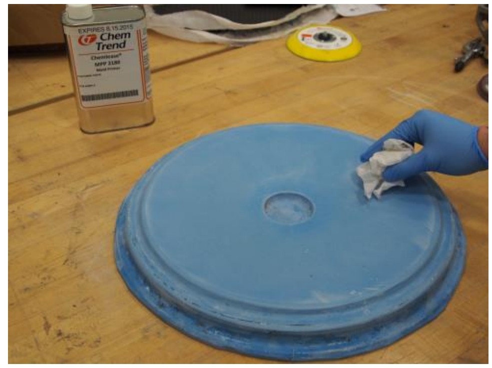

Figure 24: Application of no-sand primer to test mold.

10.2 Minimization of Human Labor Hours

As a secondary design driver to the minimization of total manufacturing time, the minimization of human labor hours is also a critical design driver around which the chosen concept is focused. The quantification of this parameter was performed similarly to the manufacturing time.

10.2.1 Empirical Testing

The empirical testing performed for this design driver was the same as that for the overall minimization of manufacturing time. The human labor hours were 6, while the estimated total human labor hours for the conventional technique was 36 hours.

10.3 Maximization of Repeatability

This process will be used for multiple components and at least two of each component. Therefore, it must be repeatable on a small scale. Because the process is still being perfected this design driver is not yet fully realized.

10.3.1 Empirical Testing

In the testing for reducing manufacturing time the repeatability can be measured. At this point the process needs further improvement before it can be properly quantified.

10.4 Maximization of Reliability

As with the maximization of repeatability it is important that this process reliably produce final products. Each component involves a lot of labor and a large amount of expensive materials. If the process is not reliable then significant resources will be wasted in each attempt. Therefore it is important to ensure that this design driver is meant.

10.4.1 Empirical Testing

The same testing was conducted as that for the other design drivers. This will be further quantified after the process is perfected. In addition a simple model like that used for initial testing cannot replicate the complex geometry and curvature of the final part. This will require testing with the scale model.

10.5 Scale Model Testing

Further testing to prove the overall time delta will be conducted using the scale model construction with both the old method and the new method. Due to restrictions in time and materials it will not be possible to conduct multiple tests with the scale model. Ideally multiple tests would give an average and a more robust estimate of the time delta. In addition, because the old method is well known and practiced the users are familiar with the process and will work more efficiently and confidently, providing a lower time to complete the construction of the scale model. The new method will become more familiar with each run and therefore it is expected that the time to completion will reduce with each use.

As each part of the process will scale differently a formula has been constructed to estimate the full scale time delta.

$$\Delta t_{total} = t_{old} - t_{new}$$

$$t_{old} = s^3 t_{pos_{sc}} + s^2 \left(t_{pos_{post_{sc}}} + t_{fg_{sc}} + t_{fg_{post_{sc}}} + t_{CFC_{sc}} + 2t_{cure_{sc}} + t_{CFC_{post_{sc}}} \right)$$

$$t_{new} = s^3 t_{neg_{sc}} + s^2 \left(t_{neg_{post_{sc}}} + t_{CFC_{sc}} + t_{cure_{sc}} + t_{CFC_{post_{sc}}} \right)$$

where Δt_{total} is the full scale time difference between the old and new methods of manufacturing, t_{old} is the full scale time require for the old manufacturing method, t_{new} is the full scale time require for the new manufacturing method, s is the scaling factor between the scaled down models and the full scale models, $t_{pos_{sc}}$ is the time required to produce the positive scaled down model, $t_{pos_{post_{sc}}}$ is the time required for the post processing on the positive plug, $t_{fg_{sc}}$ is the time required to produce the scaled down fiberglass negative, $t_{fg_{post_{sc}}}$ is the time required for the post processing on the negative fiberglass mold, $t_{CFC_{sc}}$ is the time required to produce the final scaled down carbon fiber component, $t_{cure_{sc}}$ is the cure time for both the fiberglass negative and carbon fiber positive, $t_{CFC_{post_{sc}}}$ is the time required for the post processing on the carbon fiber component, $t_{neg_{sc}}$ is the time required to produce the negative mold scaled down model, $t_{neg_{post_{sc}}}$ is the time required for the post processing on the negative mold

11 FMEA

In order to determine the associated risk with the chosen concept it was necessary to complete an FMEA. The results can be seen in Table 6.

FUNCTION	POTENTIAL FAILURE MODE	POTENTIAL EFFECT(S) OF FAILURE	SEVERITY (S)	POTENTIAL CAUSE(S) OF FAILURE	OCCURANCE RATING (O)	CURRENT PROCESS CONTROLS	DETECT RATE (D)	RISK PRIORITY NUMBER (SXOXD)	CRITICALITY RATING (SXO)	RECOMMENDED ACTION(S)
PULLING PART OFF TOOL	Poor surface finish	Delamination, excessive drag over aero surface	9	part not fully cured, tool not properly sealed	3	Inspect tool before starting laup	3	81	27	Ensure proper inspection, use laser scanning/imaging
	Part breaks	Scrap part	10	user error	2	Experience	1	20	20	Proper training
TRIMMING PART	Not Trimmed properly	Part overweight, mating surfaces undersized	5	user error	4	Experience	2	40	20	Proper training
	Part breaks	Scrap part	10	user error	1	Experience	1	10	10	Proper training
SURFACE FINISHING	Uneven surface	excessie drag over aero surface	5	part not fully cured, tool not properly sealed	5	Inspect cure prior to removing bag	4	100	25	Ensure proper inspection
	Damage the part	delamination	9	part not fully cured, tool not properly sealed	2	Inspect part prior to use	4	72	18	ensure proper inspection
RESIN CURING	Part does not cure properly	delamination	9	improper curing process	1	Follow curing process from manufacturer	3	27	9	Proper training
LAYUP	Improper layup	delamination	9	user error	2	Experience	6	108	18	Proper training
VACUUM BAGGING	Improper seal	part doesn't cure	8	user error, or expired materials	1	Materials inspection	2	16	8	ensure proper inspection
	Over pressurized	part doesn't meet tolerances	4	user error	1	Follow curing process from manufacturer	6	24	4	Proper training

Table 6: FMEA of chosen concept

After completing the FMEA it was concluded that the three biggest risks were a poor surface finish upon pulling parts off the tooling, uneven surfaces after surface finishing procedures, and improper layup of the composite material. The highest risk according to the FMEA is achieving an uneven surface finish after surface finishing procedures have been conducted as seen in the risk priority number and criticality ranking.

Uneven surface finish occurs when the parts require sanding, when the part did not cure properly, or the tool was not properly sealed. Due to the human aspect of hand sanding the parts it is difficult to control the tolerances of the parts. Therefore, parts can be damaged from too much sanding or simply be uneven. Regardless of the cause for an uneven surface the result will be excess drag over the aero surface lowering the overall performance and, depending on the severity of the unevenness, possible delamination. Currently an inspection of the part is how this failure is controlled.

One of the main purposes of this process redesign is to allow for multiple iterations if there is a failed part. However, by reducing the process time the team is also implementing more robust procedures, such as the no-sand primer, which will allow the sponsor to control the surface finish at a more precise level since the sanding has been eliminated.

To help further reduce the risk associated with the new process proper inspections at each step of the process must be implemented. This will allow for failed parts to be discovered sooner so that minimal time is spent fixing failed parts. Currently, the new process is at an acceptable level of risk.

12 Current Challenges

The challenges associated with this project stem from the design being process driven, and that major improvements to the current method must be made. Therefore, each step must be analyzed to find the root cause of the time associated with each step. This then limits the options available to the team when designing a new method for manufacturing the CFC chassis.

At this point the largest challenges with this project have been fulfilling class requirements. The requirements are written for the express design of a system, component or idea. Many of the methods and requirements described do not apply to the design of a process. Process engineering and optimization is an important tool for any mechanical engineer and might be a slight oversight of the class.

In addition, the team has experienced some issues implementing the no-sand primer. Testing so far has not yet produced a part exactly as desired. It was discovered that the sealant supplied to the team was expired, which lead to too high of a porosity in the tooling board. In addition the no-sand primer seems to leave some residue on the final part. Further experimentation is being conducted to address these issues, as well as further communication with the manufacturer of the no-sand primer. In addition the team is looking for a source for high-temp tooling board to compare initial tooling board porosity with that of the tooling board currently used by the Solar Car team.

As the construction of the scaled down models begins, environmental conditions as well the material conditions must be considered. It is possible that the tooling board currently being used is not high enough quality. It was also discovered that the sealer being used was expired. New materials are being sourced, but ensuring high quality materials will continue to be a challenge for the team.

13 Initial Manufacturing Plan

The nature of the project requires two separate manufacturing plans – one for the old method and one for the new. The old method will be followed based on the methods described in Section 2.8, and Appendix B: Further Illustrations of Current Manufacturing Process. The scale mold used can be seen in Figure 26, which was machined by Ford Motor Company. Machining drawings can be seen in Appendix C: Manufacturing Drawings.

The new manufacturing process is outlined in Figure 25. As can be seen it is still a very involved process, however the amount of sanding and the intermediate step of making a second

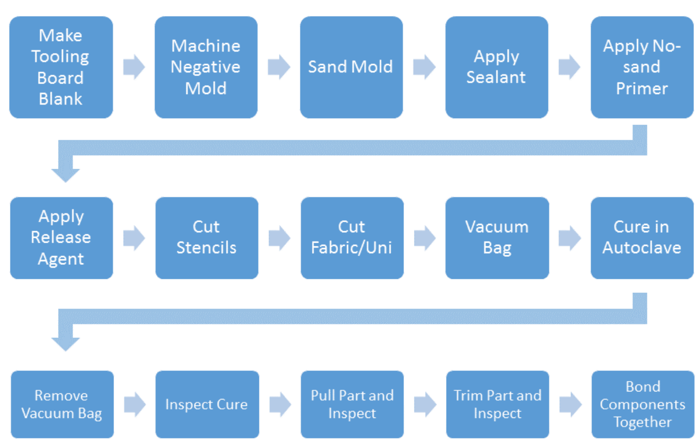

Figure 25: New manufacturing process

mold will reduce time considerably. As with the mold for the old manufacturing process it will be machined by Ford Motor Company.

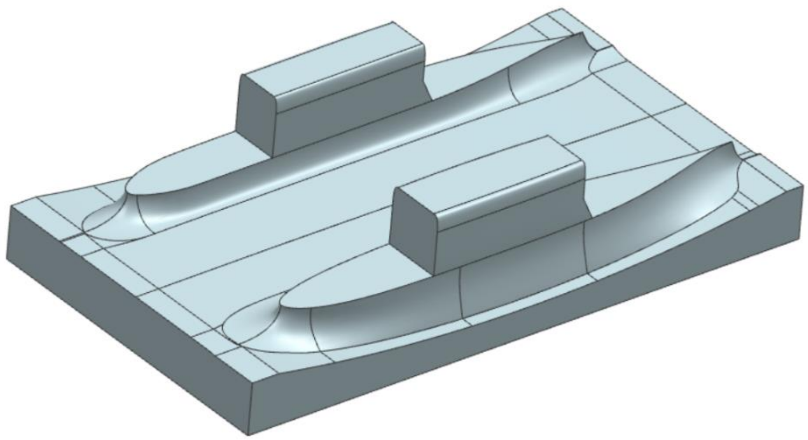

Figure 26: Plug used for scale model manufacturing

Photographs of initial testing of this process can be seen in Section 10. Further refinement will be necessary to overcome some of the issues presented in Section 12.

14 Final Concept Design

The finalized concept for the mold was produced in CAD which was then sent to Ford for manufacturing. The model and drawings can be seen below as well as pictures of the initial manufacturing process.

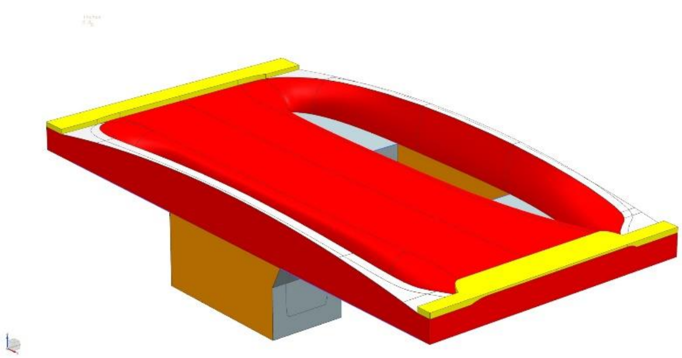

Figure 27: Final mold for new method

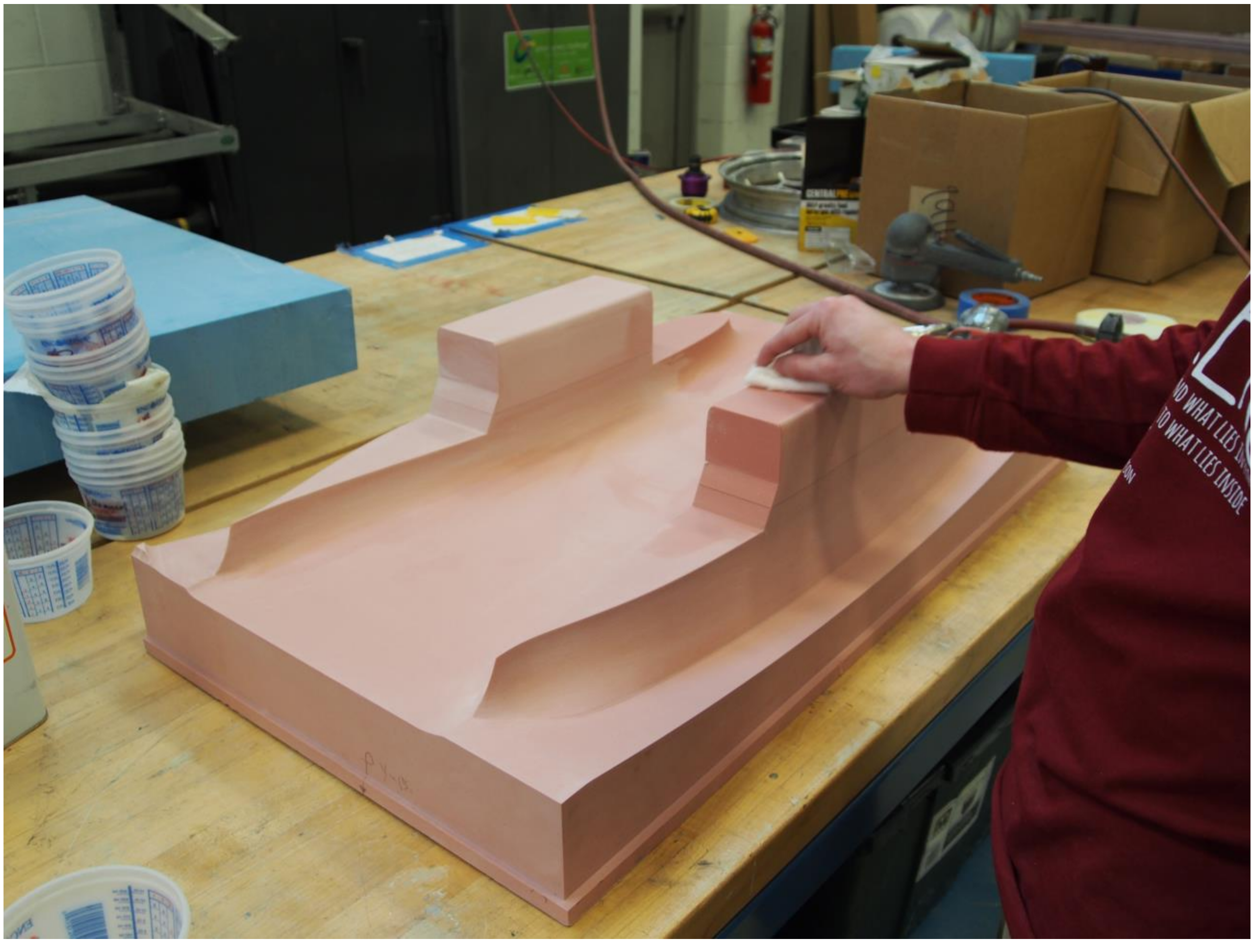

Figure 28: Machined old method mold

Figure 29: Painted and sanding old method mold

Figure 30: Buffing old method mold

Figure 31: Buffing old method mold

Figure 32: Released old method mold

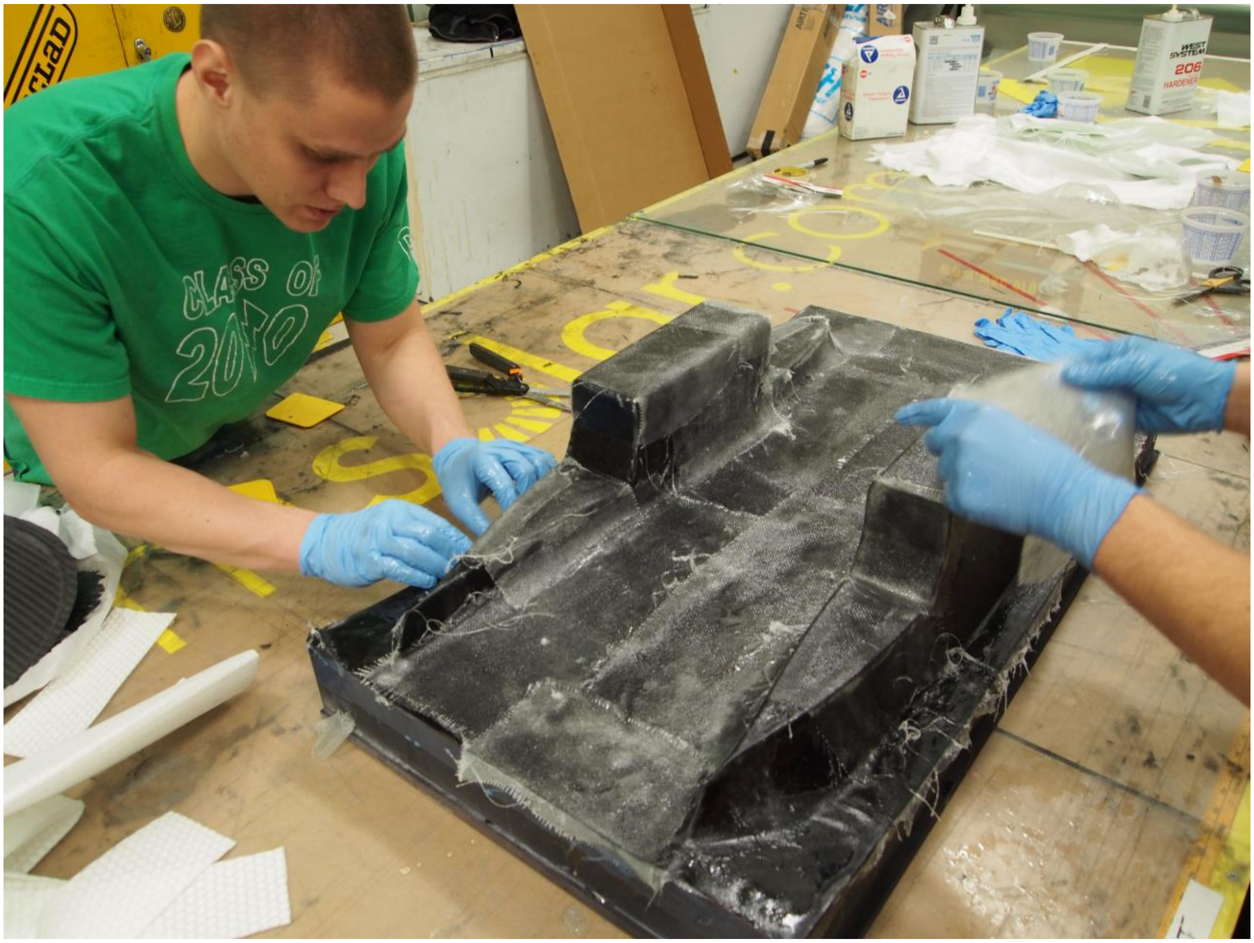

Figure 33: Laying fiberglass

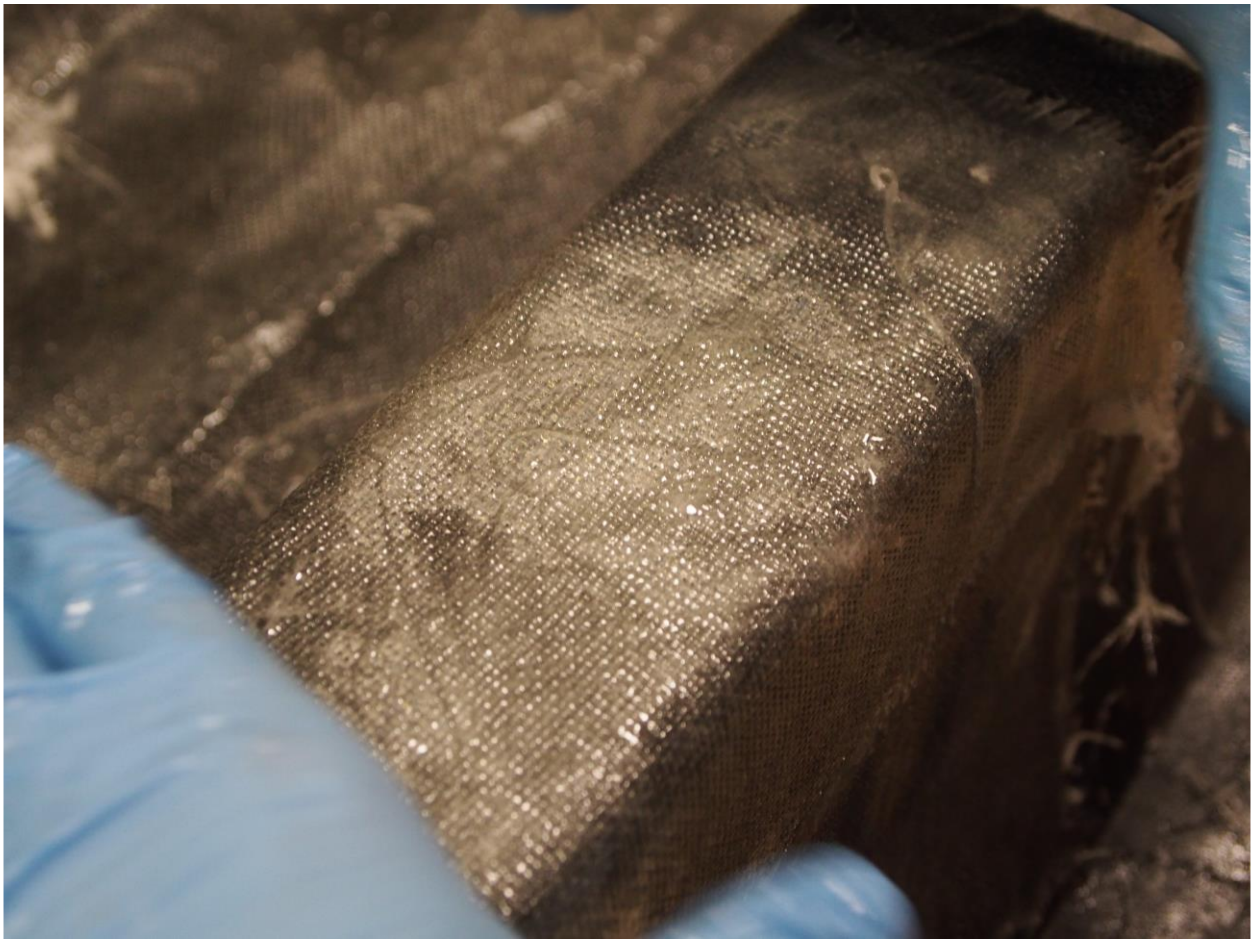

Figure 34: Applying resin/fiberglass

15 Results of Empirical Testing

As outlined in Section 10 empirical testing was conducted on a scale model. The respective time to completion for each stage of the processes were recorded and can be seen in Table 7 on the following page.

	OLD METHOD			NEW METHOD		
	Value	Degree	Total	Value	Degree	Total
MACHINING	2	3	8	2.5	3	15.625
PRIMING MOLD	2	2	4	3	2	9
CURE	24	1	24	3	1	3
SAND	2	2	4			
RELEASE	4	2	16			
GELCOAT	2	2	4			
LAYUP TO MAKE MOLD	2	3	8			
CURE	24	1	24			
DEMOLD	1	2	1			
TRIM	0.5	1	0.5			
SAND	2	2	4			
MOLD PREP	2	2	4	1	2	1
LAYUP	2	2	4	2	2	4
CURE	24	1	24	24	1	24
POST OPS	2	2	4	0.5	2	0.25
TOTAL			**133.5**			**56.875**
SCALE FACTOR			40			40
SCALED TOTAL			**5340**			**2275**
TIME DELTA						**3065**
PERCENT DECREASE						**235**

Table 7: Time delta calculation results. All values in hours.

As seen above the current equation overestimates the old method significantly based on the time presented from the sponsor (~1344 hours). Therefore it will be necessary to re-address the details of the scaling equation. However, it can be determined that the chosen method provides a 235 % reduction in overall hours. After the equation has been finalized it will be possible to determine the total reduction in human labor hours as well as the total reduction in manufacturing time for the full scale car.

16 Engineering Ethics and Sustainability

In the sections below each team member's outlook on the aspects of ethics and sustainability in the solution can be seen.

16.1 Arnold Kadiu

16.1.1 Engineering Ethics

In our group we have redesigned the process by which a composite part is made. We looked at the final process and made sure to look at the different aspects of the design to ensure that it was ethically correct. One of the largest areas where we focused on is making sure that we issue statements in an objective and truthful manner. This is especially important when our client would be taking our results, data and analysis, and using it to create a product that they will entrust someone's life in. Any potential skirting of the facts could lead to issues with the final part and therefore endanger the driver of the solar car.

An additional focus was that we should only act in the areas of our own competence. In our segment, there are numerous different process to get to the exact same process in the next step of the manufacturing chain. In order for us to make intelligent and thoughtful decisions, we need to become experts in the areas we are trying to advise with. In our process of design these mold manufacturing processes we decided to go with a method that was used by a number of people in industry, but do to it's infancy, there was very little documentation and research into how the technology worked. Without intense investigation into different aspects of using this manufacturing method, it would be unethical for us to recommend this process.

16.1.2 Sustainability

In our project, I believe we have lowered the environmental impact in a number of ways, but there are still additional ways that we can improve the environmental impact of the manufacturing process. In the old process it required:

1. Tooling board foam
2. Gel Coat
3. Sand Paper
4. Epoxy Resin
5. Fiberglass
6. Consumable plastic bagging material
7. Sand paper

None of these items are recyclable. This creates a huge environmental impact due to the shear amount of waste material and plastic. In contrast the new method needs:

1. Epoxy Board Foam
2. No Sand Primer

This is huge decrease in the material amount required. However, it is not recyclable. A future improvement would be to find an Epoxy tooling board foam that can be recycled.

16.2 Joe Martin

16.2.1 Engineering Ethics

In approaching ethical design the team had to consider the impacts of the final design. The main concern was ensuring that the new manufacturing process would produce a part which is just as reliable and safe as the previous manufacturing process. As the product will be used in a student competition it is important to provide the driver with an appropriate safety cell. In addition it was important to consider that we were following both the old and new manufacturing procedure as closely as possible without skipping and corners. This was essential to creating a fair and unbiased conclusion on the time difference of the two methods.

Both instances required the team to take extra caution in performing the tasks and for all models other SolarCar team members were present and documenting the process to ensure it was followed appropriately. This precaution also ensures that future team members know the correct process to follow. By following this process the produced carbon fiber components will be free of voids with properly cured parts and edges to reduce the possibility of delamination.

16.2.2 Sustainability

In terms of sustainability CFCs are not a top candidate as they require a high amount of consumables. However, the elimination of the fiberglass component reduces the amount of consumables used in the process significantly. The biggest reduction is the amount of harmful chemicals used as a significant number of steps are eliminated. This is an important environmental impact as well as a social impact. The reduced need for these chemicals makes the project more sustainable while the users of the process face a lower exposure to harmful or potentially life threatening chemicals.

16.3 Garrett Simard

16.3.1 Engineering Ethics

The solar car team races a car 3000 km from Darwin to Adelaide, with a human driver behind the wheel every mile down that stretch of the outback. While aerodynamics and mass are crucial factors that can lead to winning the race, the safety of the driver is of utmost importance and means that corners cannot be cut in the manufacturing of the solar vehicle. There were many aspects of the design process where we had to choose between a lighter, easier to make, faster to obtain composite piece at the expense of reliability and longevity but we had to make the decisions to not cut those corners and produce the safest component possible.

In the design of the mold, the possibility of delamination is a huge concern for the structural integrity of the final component. If air gaps exist in between the layers of the vehicle chassis or lower surfaces near the driver and splinter in the event of an accident, that means the safety cage we thought we had created was compromised and we had placed the driver in a dangerous situation. It was this reason that we discarded some options for reducing manufacturing time, including skipping one or more bagging operations and removing core splice or adhesive film between some of the layers and relying on the resin content in the fibers.

The code of Ethics has been applied to the design process. While our final design was a manufacturing process more than a physical component design, we still had some input into the manufacturing operations of the composite part the solar car team is going to create. The most important canon we tried to uphold was holding the safety, health, and welfare of the public (the solar car drivers and drivers on the road with the solar car) in the performance of our professional duties. Every step in the final manufacturing process was chosen to maximize the reliability and performance of the final component, such that the engineering analysis performed by the team is a conservative estimate of the manufactured component and what drives on the road is actually safer than the numbers from their analysis.

16.3.2 Sustainability

The environmental impact of our chosen solution is dramatically lower than that of the previous methods. Both methods (direct to tooling board negative and positive tooling board plug to fiberglass negative) involve both a machining operation on tooling board and a carbon fiber layup process, and as such have an impact involved in the creation of the fibers, resins, release agents, and tooling board required for that manufacture. Additionally, we are responsible for the electricity required for the machining operations on the tooling board, the heating of the oven or autoclave, and the airconditioning during the layup process. The direct to negative process is a huge positive comparatively to the old method because that is the entire extent of the environmental impact of the manufacturing process. With the fiberglass method, that is a huge addition of both new materials (fiberglass, gel coats, etc) and a huge increase in the amount of other materials already being used (resin). There is also considerably more electricity to be used in the sanding, painting, vacuum bagging, and trimming operations necessary for the fiberglass tool that could be eliminated if the tool was also eliminated.

The issue of disposal at the end of the project cycle is also in the favor of the direct to negative process. With the large fiberglass molds, they are impossible to edit and when the car is redesigned two years from now the mold has zero used and must be thrown away, it is impossible to recycle. The plug, if not destroyed, could be used as the base for next year's tooling board plug, saving a considerable of new material necessary. With the direct to negative process, the mold itself is easily editable, and while the car is completely redesigned it is completely possible that with a minor addition of more tooling board the entire mold can be re machined into a completely different aero surface – saving a considerable amount of time, money, and energy, with that remachined component able to be remachined the next year or broken back into pieces and reblocked in a different configuration with more losses.

16.4 Nick Turnbull

16.4.1 Engineering Ethics

While our team did not have to design a specific product to meet a certain need, we were responsible for proposing a new system for manufacturing a product. Therefore, we had to not only improve the manufacturing process, but ensure that we were not compromising the end product due to the streamlined process. We also had to design our process such that it was similar enough to the old process that any workers involved in the process would not find themselves in harm's way by following the previous method's safety precautions.

For the end product we analyzed the effect of using tooling board for the mold as opposed to the previously used fiberglass mold on the structural rigidity of the final parts. We deemed that the tooling board mold would be acceptable if a maximum of two parts were pulled off the mold. Any more than that and the part would not be able to withstand the structural tests and would be deemed unsafe to use. The Code of Ethics for Mechanical Engineers helped guide our decision to enforce a maximum number of parts allowable for each mold produced using tooling board.

For the manufacturing process we had to research the negative side effects associated with the new materials being used such as epoxy tooling board and the no-sand primer. No major or critical negative side effects could be associated with using the epoxy tooling board as the team is already equipped to work with polyurethane tooling board. The no-sand primer is a toxic substance, but not one that required any new procedures for handling and application. Therefore, the team is already well equipped to work with the new materials that we are proposing. The Code of Ethics for Mechanical Engineers helped guide our analysis during the material selection phase of the project. We made sure to select materials that the Solar Car team already had safety precautions for.

16.4.2 Sustainability

Our proposed manufacturing process does create relatively large amounts of waste. However, by eliminating the fiberglass lay-up we are using significantly less materials. Therefore, while our proposed method does generate large amounts of waste, some of which can and is recycled, it is significantly less waste than the old manufacturing method used by the Solar Car team.

Also, while this manufacturing method cannot be considered sustainable, the ultimate goal of the Solar Car team is to drive global awareness for alternative energy methods used during transportation including solar powered automobiles. That end result is truly sustainable. However, the means to the end result cannot be overlooked. Therefore, many of the materials used by the Solar Car team are sent for recycling or safe storage after they have been used. This greatly reduces the overall impact of the manufacturing methods used for the creation of the carbon fiber parts.

17 Team Bios

Information about each of the team members can be found in the sections below.

17.1 Arnold Kadiu

Arnold was raised in the Metro Detroit area and showed in interest in cars and engineering from a young age. This interest drove him to pursue engineering at the University of Michigan. Arnold is now a senior in Mechanical Engineering. While in college he has participated actively in the University of Michigan Solar Car Team. In 2012 and 2013 his focus on the team was composite design, analysis and manufacturing of the Solar Car. In 2014 and 2015 his role was the Engineering Director of the team. His role was to ensure that the most competitive vehicle was designed and manufactured. He enjoys designing carbon fiber components, biking, and running. After graduation, he hopes to compete in the 2015 world solar challenge and then pursue a career in composite design and manufacturing.

17.2 Joe Martin

Joe Martin was born and raised in Waukesha, WI. He became interested in cars very early on and this drove his desire to pursue a career in engineering. In high school Joe participated in the engineering program, as well as National Honor Society and was the German Club president. He also played football each year, earning a letter, and was part of the ski/snowboard club. Joe is a fifth year senior in Mechanical Engineering, with a dual minor in German and Multi-disciplinary Design. He has continued his interest in cars through his time on the MRacing Formula SAE team at U of M, where he has been the drivetrain system leader, project manager, and team captain. Currently Joe is advising the team and working on a team capstone project for the Multi-disciplinary Design Minor. Joe has a strong interest in motorsports and has completed an internship at BMW Motorsport in Munich, Germany in the German Touring Car Championship as well as other internships in the automotive field. He hopes to work as a full time engineer for a global automotive company or supplier and hopes to spend some time working in other areas of the world.

17.3 Garrett Simard

Garrett Simard is a 4th year senior Mechanical Engineering student at the University of Michigan, originally hailing from Richmond, Virginia. Within ME he is focusing his studies in component design and analysis with an emphasis on balancing weight reduction and manufacturability in lightweight and high performance applications. The University of Michigan Solar Car Team has been his true creative outlet throughout his collegiate career, having served as the Mechanical Engineering Lead for the 2013 vehicle and currently acting as the Mechanical Engineering Lead and Crew Chief for the 2015 vehicle. Additionally, he had the opportunity to spend 8 months interning under the mentorship of previous UMSolar engineering director at SpaceX to broaden and sharpen his knowledge related to design engineering and analysis. He hopes to re-enter the aerospace or space industry upon graduation, and his other interests include music - encompassing both trumpet performance and ballroom dance.

17.4 Nicholas Turnbull

Nicholas Turnbull was born and raised in the Metro Detroit area, and is a fourth generation University of Michigan student currently studying mechanical engineering. He originally thought his passion was in chemical engineering, but quickly realized he only cared about why certain processes were happening, thus the switch to ME. As a freshman Nick joined the internship program, Young Entrepreneurs Across America, where he ran an exterior painting business throughout the state of Michigan. During his three years he oversaw over $1M in revenue and employed approximately 125 other managers and painters. In 2012 he entered into an eight month co-op with TransCanada as a Plant Reliability Engineer where he helped develop maintenance and reliability programs for natural gas compression stations ranging from Louisiana to northern Minnesota. Additionally, for the past three and a half years Nick has been leading the local start-up, TurtleCell, as its co-founder and Director of Quality and Operations. His primary role is overseeing the complete manufacturing process from tool design to mass production of TurtleCell's products. The flagship product is a smartphone case with retractable headphones built inside the case. He is currently concluding the initial order of 40,000 units for the iPhone 5/5s model while simultaneously launching two models for the iPhone 6. Nick hopes to drive TurtleCell to become a successful lifestyle company, and then continue his entrepreneurial journey with many future ventures.

References

1. **Savage, G.** *Composite Materials Technology in Formula 1 Motor Racing.* s.l. : Honda Racing F1, 2008.

2. **Strong, A. Brent.** *Fundamentals of Composites Manufacutring.* 2009.

3. **Rehkopf, Jackie D.** *Automotive Carbon Fiber Composites: From Evolution to Implementation.* Warrendale, PA : SAE International, 2012. 978-0-7680-3495-0.

4. **Remy, John and al, et.** *2006 Corvette Z06 Carbon Fiber Structural Composite Panels- Design, Manufacturing and Material Development Considerations.* Detroit, MI : SAE International, 2005. 0148-7191.

5. **Park, Soo-Jin.** *Carbon Fibers.* Incheon, ROK : Springer Science+Business Media Dordrecht, 2015. 978-94-017-9478-7.

6. **Dodiuk, Hanna and Goodman, Sidney H.** *Handbook of Thermoset Plastics (3rd Edition).* Burlington : Elsevier Science, 2014. 978-1-4557-3109-1.

7. **Chung, Deborah.** *Carbon Fiber Composites.* s.l. : Butterworth-Heinemann, 2012. 978-0-0805-0073-7.

8. *The dynamic response of carbon fiber-filled polymer composites.* **Dattelbaum, D.M. et al.** s.l. : EPJ Web Conferences, 2012, Vol. 26. 20122602007.

9. **Staff.** Tooling. *Composites World.* [Online] January 1, 2014. [Cited: January 27, 2015.] http://www.compositesworld.com/articles/tooling.

10. **Howell, DeWayne and Gabriel, Jason.** Compression Molded Composites: Processes, Benefits and Applications - An Interview with TenCate. s.l. : G.P. Thomas, January 25, 2015.

11. **Advanced Composites, Inc.** Compression Molding. *Advanced Composites, Inc.* [Online] 2012. [Cited: January 24, 2015.] http://www.advancedcomposites.com/index.php?option=com_content&view=article&id=49&Itemid=79.

12. **MCM Composites, LLC.** Thermoset Compression Molding Services. *MCM Composites: Ideas to Reality.* [Online] 2014. [Cited: February 8, 2015.] http://www.mcmusa.net/thermoset-compression-molding-services.html.

13. **Hexcel Corporation.** HexTOOL Composite Tooling Material. *Hexcel.* [Online] 2015. [Cited: February 13, 2015.] http://www.hexcel.com/products/aerospace/atooling-materials.

14. **Mills, Andrew, Frost, Matthew and Castanos, Axel.** *Development of a Carbon Fibre Composite Ultra Lightweight Vehicle Structure for the Aero-Stable Carbon Car - Fastframes.* Warrendale, PA : SAE International, 2002. 0148-7191.

15. **Solid Concepts Inc.** Steroelithography (SLA). *Solid Concepts: A Stratasys Company.* [Online] 2014. [Cited: February 8, 2015.] https://www.solidconcepts.com/technologies/stereolithography-sla/ .

16. **Hamilton, Leonard, et al.** *Production of a Composite Monocoque Frame for a Formula SAE Racecar.* s.l. : SAE International, 2013. 10.4271/2013-01-1173.

17. **Wu, Jingsi, et al.** *Design, Analysis, and Simulation of an Automotive Carbon Fiber Monocoque Chassis.* s.l. : SAE International, 2014. 10.427/2014-01-1052.

18. **Lu, Charles Y. and Pilla, Srikanth.** *Design of Automotive Composites.* Warrendale, PA : SAE International, 2014. 978-0-7680-8132-9.

19. **Dorworth, Louis C., Gardiner, Ginger L. and Mellema, Greg M.** *Advanced Composite Fabrication and Repair.* s.l. : Aviation Supplies and Academics, Inc., 2009. 978-1560277521.

20. **Jones, Melissa L.** *Composite Tooling Containing Carbon Nanotubes and Production of Parts Therefrom. 20120280430* USA, May 5, 2011.

21. **Matviya, Thomas M.** *High density carbon foam composite tooling. 8,071,065* USA, May 22, 2007.

22. **Cloud, David J.** *Model for composite tooling mold. 5,773,047* USA, February 11, 1997.

23. **The right stuff. *Racecar Engineering.* 2014, Vol. 24, 8.**

24. Soderberg, Scott. Flickr. [Online] [Cited: January 26, 2015.] https://www.flickr.com/photos/umsolar/11214626026/?rb=1.

25. Team, U of M Solar Car. Team Photos.

26. Industrial Polymers Corporation. Rigid Expanding Foams. *Industrial Polymers Corporation.* [Online] 2015. [Cited: February 9, 2015.] http://www.industrialpolymers.com/category/product-list/rigid-expanding-foams/.

27. Kopeliovich, Dimitri. Compression of molding of polymers. *SubsTech Substances & Technologies.* [Online] [Cited: February 9, 2015.] http://www.substech.com/dokuwiki/doku.php?id=compression_molding_of_polymers.

28. How do waterjets work? *WaterJets.org...the most complete waterjet resource on the web.* [Online] 2014. [Cited: February 9, 2015.] http://www.waterjets.org/index.php?option=com_content&task=category&sectionid=4&id=46&Itemid=53.

29. Wang, Nicole. Molding and Casting. *How to Make (Almost) Anything.* [Online] [Cited: Februrary 10, 2015.] http://fab.cba.mit.edu/classes/863.12/people/njwang/five.html.

30. Nuplex Industries Ltd. Hand Lay-up. *nuplex.* [Online] 2014. [Cited: February 13, 2015.] http://www.nuplex.com/Composites/processes/hand-lay-up.

31. Touchstone Research Laboratory. Composite Tooling with Cabon Foam. *cfoam.* [Online] 2014. [Cited: February 13, 2015.] http://www.cfoam.com/tooling.htm.

32. Process Fab Inc. *Process Fab Inc.* [Online] 2012. [Cited: February 22, 2015.] http://www.processfab.com/spv-44.aspx.

33. Constellium. Aluminum Molds. *Constellium.* [Online] 2015. [Cited: February 22, 2015.] http://www.constellium.com/markets/industry/molds.

34. UBM Cannon. Adoption of 3D printing for cores/cavities remains low in spite of advantages. *Plastics Today.* [Online] 2012. [Cited: February 22, 2015.] http://www.plasticstoday.com/articles/Adoption-of-3D-printing-for-cores-cavities-remains-low-in-spite-of-advantages-141124.

35. Southbrook Technologies Inc. Composite Tooling and Process Consulting. [Online] December 5, 2014. [Cited: February 23, 2015.] http://www.southbrook-tech.com/maxpages/Consulting.

36. J-E Nystrom. Veijo's front truck patterns. *Spare Time Labs.* [Online] 2007. [Cited: February 23, 2015.] http://sparetimelabs.com/animato/animato/3003/vemppu.html.

37. Chemamde. Products detail. *Jinan Leader Group Co.,Ltd.* [Online] [Cited: February 23, 2015.] http://jinanleader.globalchemmade.com/product/d-43456.html.

38. DIYsite.com. Speical Epoxy tooling board for Axis prototype modeling. *DIY Trade.* [Online] 2014. [Cited: February 23, 2015.] http://www.diytrade.com/china/pd/9852689/Speical_Epoxy_tooling_board_for_Axis_prototype_modeling.html.

Appendix A: Secondary Concepts

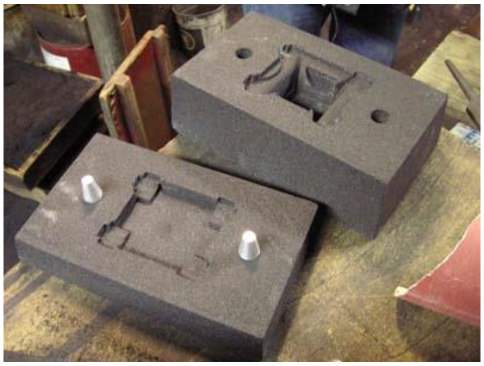

Figure 35: One time use sand casting mold (36).

A.1 One Time Use Single Piece Mold

A one-time use mold would follow a straight to negative procedure using an easily disposable procedure. An example of this is the wax mold covered in the main body of the report, however there are certainly many other material options.

A.2 Fiber Blasting

The current method of hand lay-up is an easy technique to use, and allows for reliable results. However, it is a cumbersome and time consuming method for creating CFC. By switching to a spray lay-up technique the time for laying the composite material can be drastically reduced. This method also enables most of the already familiar process to remain unchanged allowing for easy integration of this technique.

Figure 36: Carbon and foam beam section (14).

A.3 Structural Composite and Foam Space Frame

As described in the Aero Stable Carbon Car paper (14), carbon fiber foam beams can be used to create a space frame rather than the monocoque design currently used. The space frame is essentially a series of beams forming a driver protective structure. Unfortunately this does not address the needs of the aero body surface. In addition the joining techniques are not structural enough to provide satisfactory equivalency for the Solar Car Challenge competition.

A.4 Fiber Stamping Process

Many steel components in the automotive industry are stamped. The concept of stamping prepreg fibers into shape with enough pressure and heat to set the thermoset is a new one and would require significant capital investment and time to perfect. This falls out of the scope of both this class and the timeline specified by the sponsor. Therefore this concept has been discarded for the purpose of this project.

Figure 37: Invar composite tooling (32).

A.5 Machined Invar Mold

Trimming the components to enable easier assembly is a major time consuming step. One method of eliminating this is to use molds that yield smooth surface finishes. One such hard tooling material is Invar. Invar also has a similar coefficient of thermal expansion to carbon fiber composites allowing the finished product to have tight tolerances. Unfortunately, this material is expensive and difficult to procure.

A.6 Machined Aluminum Mold

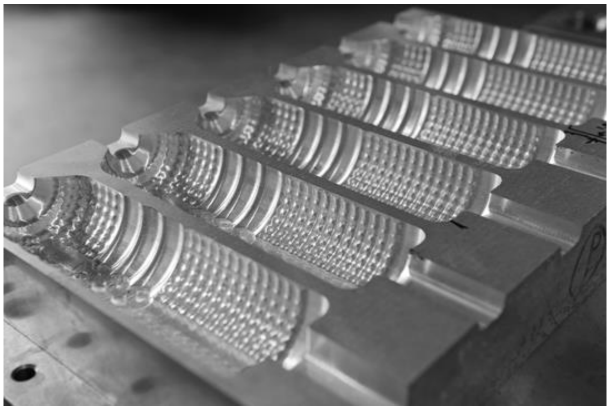

Figure 38: Aluminum composite mold (33).

All tool and plug designs should be designed for single plane tool movement (i.e. no side pulls). Therefore, a 6-axis mill can completely create the entire tool and plug automatically. This will greatly reduce the number of man-hours required to complete the tooling. All other processes remain the same. This will also allow for a smooth surface finish on the finished product allowing it to be ready for assembly with minimal surface finishing.

A.7 Resin Infusion

In the resin infusion process, a dry fabric or weave is placed in a mold and enclosed. Under low pressure liquid resin is then injected into the mold. This allows an even application of the resin and a higher degree of control versus a manual resin spreading process (3). In contrast to a hand spreading process, the resin must be extremely low viscosity as it must permeate each layer. In the hand application resin can be applied between each layer when a low cure time resin is used.

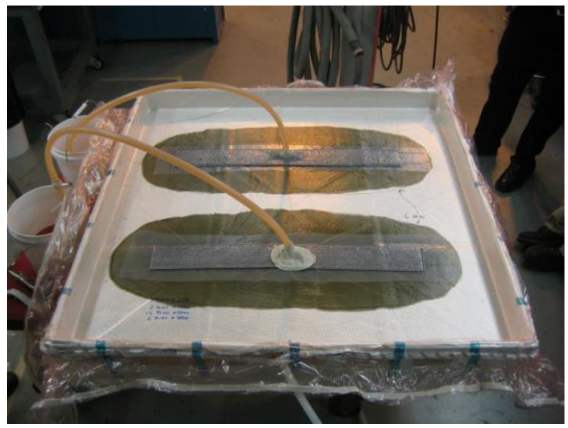

Figure 39: Resin infusion process (35).

A.8 Improved Layup Process

If the current hand lay-up technique must be used, then it is possible that the overall process can be improved with the use of roller impregnators. These pump resin into a roller that is similar to a paint roller while applying the resin to the fiber lays. This allows the resin to be applied evenly and at fast rate. All other manufacturing steps would remain unchanged so transitioning to this method would be relatively simple.

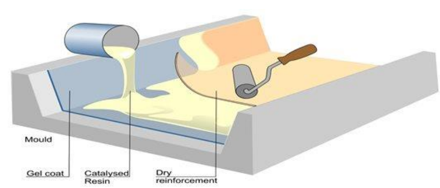

Figure 40: Roller used during hand layup process (30).

A.9 Improved Materials

There are many different combinations of materials that can be used to produce CFCs. Each material has its own positives and negatives. It is possible that faster cure times can be achieved by using different combinations of resins and fibers. There are many epoxies and phenolics that offer advanced curing times.

A.10 3D Printed Mold

Tooling creation is a time consuming process that can be greatly reduced by using a 3D printer to produce the molds. Also, the process can be entirely automated reducing the number of man-hours required to get the parts ready. With SLA 3D printing the surface finish on the mold can be smooth due to the tolerances of the 3D printed parts ranging from 0.001" – 0.01" (15). This greatly reduces the after treatment of the parts, thus reducing the overall time required.

Figure 41: 3D printed mold (34).

Appendix B: Further Illustrations of Current Manufacturing Process

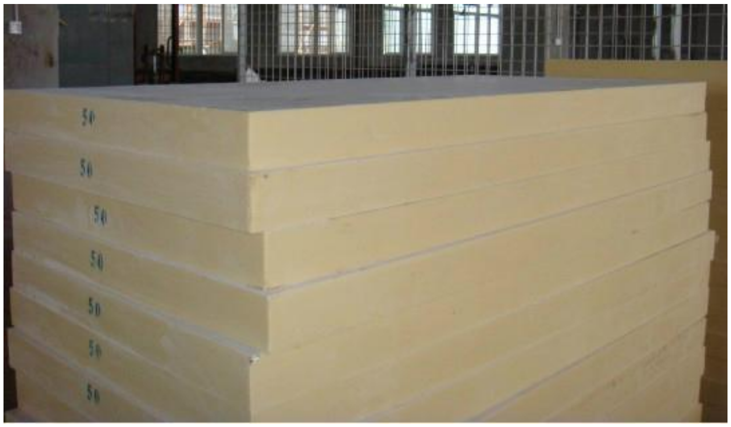

Figure 42: Tooling board blocks (38).

The first step in the manufacturing process is to bond the necessary pieces of tooling board together to create a blank for machining.

Once the blocks have been bonded together the final shape of the mold is machined using a router. For the Solar Car team this mold is the same shape as the final CFC part. The tooling board mold is used to make a fiberglass mold, which is in turn used to make the CFC component. Therefore, the tooling board mold is referred to as a male mold (or positive plug). This can be seen in Figure 43 and Figure 45.

Figure 43: Tooling board being machined.

After the mold has been machined it must be prepared and sanded as outlined in Section 2.8. After this process the fiberglass mold can be laid up in steps as outlined in Section 2.8. This creates a female mold (or negative). As discussed previously the fiberglass has a coefficient of thermal expansion closer to that of CFCs providing a part which is closer to tolerance.

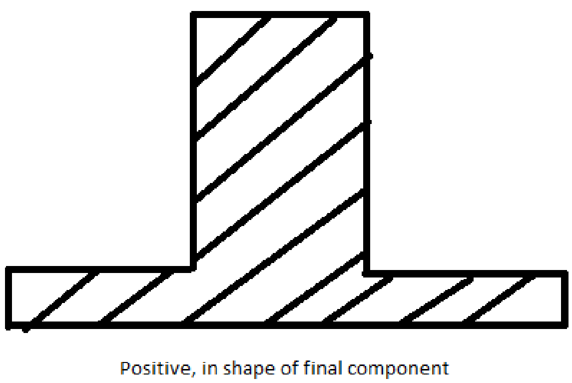

Figure 45: Step one in current layup process, machined tooling board mold.

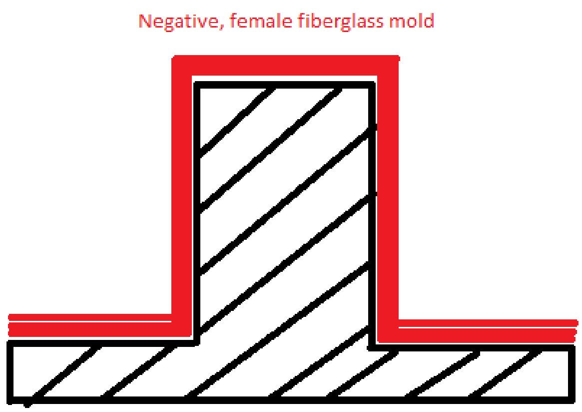

Figure 44: Step two in current layup process (fiberglass layup negative mold).

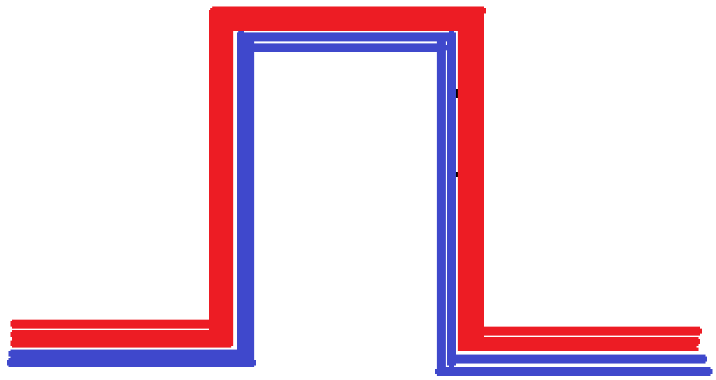

Figure 46: Step three in current layup process (carbon fiber layup final part).

After the fiberglass procedure has been finished (see Figure 6), the CFC component can be hand laid onto the fiberglass mold (). Each layer of fabric is cut (Figure 47) and oriented in a way which will provide the most efficient means of load transfer (along the direction of the fibers) (Figure 48). This layup is then covered with a vacuum bag and placed in an autoclave to start the curing process.

After the part has cured it is inspected for quality, and pulled from the mold. All remaining surfaces/edges must be trimmed at this point to provide the correct tolerances (Figure 49).

Figure 47: Carbon fiber being cut to proper size and orientation using stencils (25).

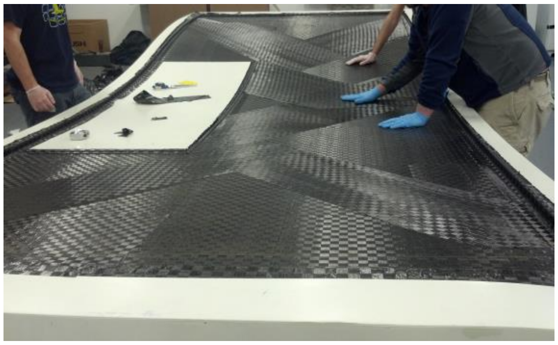

Figure 48: Carbon fiber laminates being applied in specific order and direction onto fiberglass mold (25).

Figure 49: Cured carbon fiber component being rough trimmed with hand tools (25).

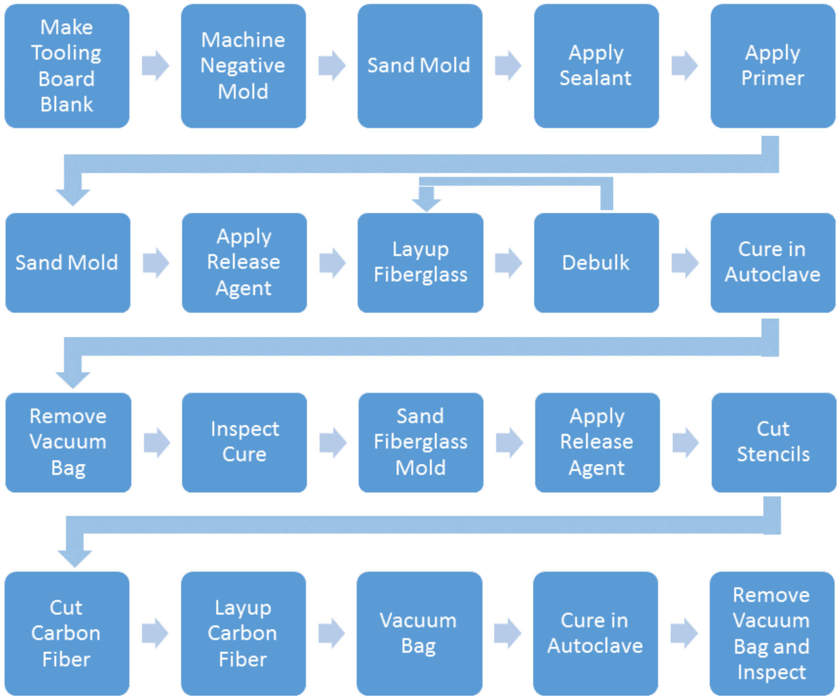

Figure 50: Old manufacturing process

Appendix C: Manufacturing Drawings