AN ABSTRACT OF THE THESIS OF

Austin L. Zuck for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on June 2, 2014. Title: Engineering Design Matrix for Carbon Fiber Monocoque Chassis Selection.

Abstract approved:

____

Robert K. Paasch

The Formula Society of Automotive Engineers (FSAE) has provided a platform for teams like Oregon State's own Global Formula Racing Team (GFR) to produce a formula style race car and compete with other schools across the world. The GFR team has used the same carbon fiber monocoque chassis since the 2010 competition season and will be designing a new chassis for the 2015 season. In order to select a new chassis there must be ample research and consideration put into the process. A selection matrix will provide the GFR team with a quantifiable source of information in order to help with this design and selection process. The engineering matrix will provide valuable information for present and future chassis design teams.

Keywords: Design Matrix, GFR, Chassis, Formula SAE

Corresponding email address: alzuck@gmail.com

Engineering Design Matrix for Carbon Fiber Monocoque Chassis Selection

by

Austin L. Zuck

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering (Honors Associate)

Presented June 2, 2014
Commencement June 14, 2014

Honors Baccalaureate of Science in Mechanical Engineering project of Austin L. Zuck

presented on June 2, 2014.

APPROVED:

____

Mentor, representing Mechanical Engineering

____

Committee Member, representing Mechanical Engineering

____

Committee Member, representing Mechanical Engineering

____

Chair, School of Mechanical, Industrial, and Manufacturing Engineering (MIME)

____

Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

____

Austin L. Zuck, Author

Table of Contents

List of Figures

List of Tables

1) Introduction

The Society of Automotive Engineers (SAE) is an organization that was initially founded in 1905 as a place for engineers and technical experts to start a collection of papers related to creating functional vehicles. SAE fosters the power of joint research and combination of resources to advance the world of automotives and foster the development of new engineers. SAE International presents 12 Collegiate Design competitions around the world which provide students an opportunity to design, manufacture, test, and compete with a vehicle against other universities around the globe.[2] SAE provides an array of design competition opportunities, of which Oregon State University Global Formula Racing Team (GFR) is currently active. The GFR team participates in the following Formula SAE (FSAE) competitions: SAE Michigan, SAE California/Lincoln, Student UK, Student Germany (FSG), Student Austria, and SAE Italy. [7]

2) Background

Oregon State's Formula team began SAE competitions in the 1999 season and has been working to continuously improve the development process and vehicle ever since. At first, the formula car was designed using a metal chassis. During 2010, OSU teamed up with the German university Duale Hochschule baden-Wurttemberg (DHBW) to create the Global Formula Racing team (GFR). Despite the language barrier and distance the relationship between the two universities proves to be extremely rewarding. The time difference, while challenging, also allows both universities to be working simultaneously during the day, and continuously throughout the night. It has also required a detail oriented management system. This is an invaluable asset due to the information available from past and present successes or failures as well as future plans. During 2009, almost ten years after the creation of GFR, the team went away from the metal frame and stepped into the world of composite materials by creating a Carbon-Fiber monocoque chassis. The monocoque design proved to be a rewarding design change both in the engineering education process and competition results. In 2011 GFR designed two (almost) identical formula cars; one powered by a combustion engine, the other powered by an electrical motor.

Figure 1. 2008 Steel Chassis [1]

Figure 2 2001 Monocoque Chassis [4]

The OSU & DHBW team has been able to bring in an impressive amount of 1st place finishes in the past years and continues to strive for that result in every competition. This includes a recent 1st place overall finish at SAE Michigan in May of 2014, FS Germany in the 2013 season and the top overall spot in both FSAE Michigan and FS Austria in the 2012 Season. The GFR team has been successful through the philosophy of: "Simplicity, reliability and simulation validated by physical testing". [3] This functional simplicity allows the team to build a competitive car that is as complicated as necessary but as simple as possible. The team is dedicated to analyzing how to increase total points at competition in order to end up with the most at the end of an event. A typical SAE competition involves the following events and point values associated with it: Technical Inspection, Presentation (75 pts) Cost (100 pts), Design (150 pts), Acceleration (75 pts), Skidpad (50 pts), Autocross (150 pts), Endurance and Fuel Efficiency (400 pts)

GFR designs a lightweight and less powerful car, compared to some teams, which gains points in categories such as fuel economy and allows the car to handle effectively through corners. The design has proved successful for the GFR team but means that the chassis design must consider the total weight of the chassis as well as how it interfaces with other aspects of the car. The chassis will still be designed to gain max points at competition but also designed to reduce manufacturing time and difficulty.

Ever since the inaugural use of the monocoque chassis in 2010 there has not been a major change to the main chassis design. There have been various changes made to the chassis but the 2015 chassis will be completely redesigned. Since this monocoque chassis is the centerpiece feature that holds all the other parts of the car together it is imperative to have a chassis design that continues the success of the GFR team. The main deliverable of this project report is to create a high level design matrix to aid in the design and selection of a new chassis. This project is an important part of the design phase for weighing the different options and permutations of the chassis design. Although the initial reward is to use this matrix for the 2015 chassis, the matrix can be used in future years to assess the current chassis and consider possible improvements. The matrix will have to include analysis of more than technical requirements. For example: how the design will affect the cost report and how the chassis design can help other sub teams can use the improved chassis to gain more points. An engineering design matrix will improve the selection process and quality of a SAE racing monocoque chassis, specifically that of the Oregon State and

DHBW Global Formula Racing team.

3) Rules and Constraints

All the following rules are taken from the SAE rules documentation provided for the 2014 competition season. The complete design of the chassis involves many parts in the direct construction (Hard points, Material selection), attachment (hoops), or interfacing (brakes, suspension).This report is focused on the whole chassis and, therefore, some specifics will be left out to keep the focus on a more general idea. However, the following rules are instrumental in considering a new chassis design.

Rule: T2.2 Bodywork

There must be no openings through the bodywork into the driver compartment from the front of the vehicle back to the roll bar main hoop or firewall other than that required for the cockpit opening. Minimal openings around the front suspension components are allowed

Impact: There have been small openings in the front there is a cut away for access to pedal and brake settings but it is not allowed to create non-essential openings in the front section of the monocoque.

Rule: T3.2 General Requirements

Among other requirements, the vehicle’s structure must include two roll hoops that are braced, a front bulkhead with support system and Impact Attenuator, and side impact structures.

Rule: T3.8.2 Composite materials are not allowed for the Main Hoop or the Front Hoop.

Rule: T3.29 Involves inspection that has to do with ensuring that roll hoops meet all requirements; specifically thickness and attachment points.

Impact: This rule is a defining guideline of the monocoque design. It must feature two roll hoops, which have their own set of rules, and other features mentioned in the rule that will be compatible with the chassis. These rules also clarify the necessary technical requirements and material needed for the roll hoops.

Rule: T3.8.1 If any composite or other material is used, the team must present documentation of material type, e.g. purchase receipt, shipping document or letter of donation, and of the material properties. Details of the composite lay-up technique as well as the structural material used (cloth type, weight, and resin type, number of layers, core material, and skin material if metal) must also be submitted. The team must submit calculations demonstrating equivalence of their composite structure to one of similar geometry made to the minimum requirements found in Section T3.4.1. Equivalency calculations must be submitted for energy dissipation, yield and ultimate strengths in bending, buckling, and tension. Submit the completed “Structural Equivalency Spreadsheet” per Section T3.9.

Rule: T3.28.4 Composite monocoques must meet the materials requirements in Rule T3.8 Composite Materials

Impact: This rule requires teams to demonstrate the way in which their carbon sandwich structures meets the rules. Proper design, documentation and evidence are essential to compile throughout the design and building phases. GFR currently uses T700 Carbon Fiber which is an acceptable composite but if there should be any desire to change carbon weave it is imperative that it complies with all rules and regulations.

Rule: T3.10.3

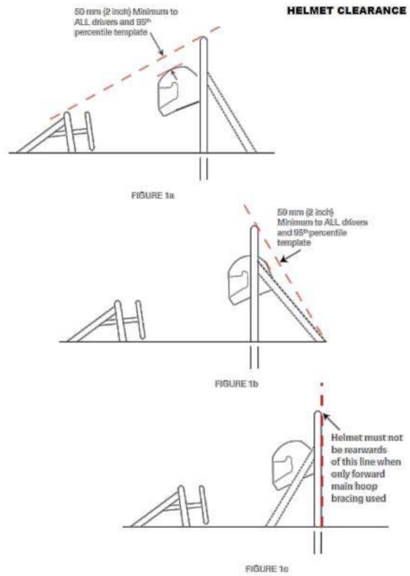


Figure 3 Rule T3.10.3 [6]

Impact: These rules have to do with the chassis and roll hoop design and allowable helmet location and corresponding driver seating.

Rule: T3.10.4

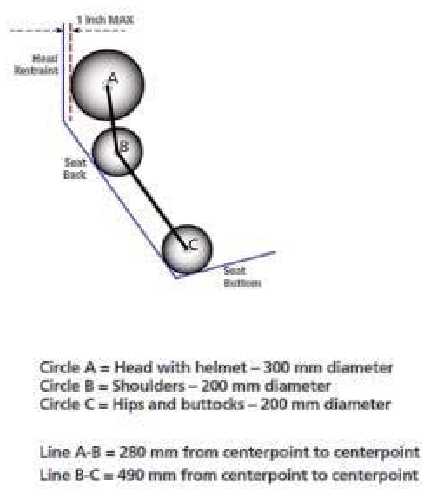


Figure 4 Rule T3.10.4 [6]

Impact: This basic template is referred to as "Percy" which is representative of the 95th percentile man to ensure that the entirety of the seat is similar and allows the opportunity for most persons to drive the car since the design project is not to design it for one or two individuals but design a deliverable and marketable car. This is important to chassis design because it must understand the minimum dimensions required to cater to Percy.

Rule: T3.34.3

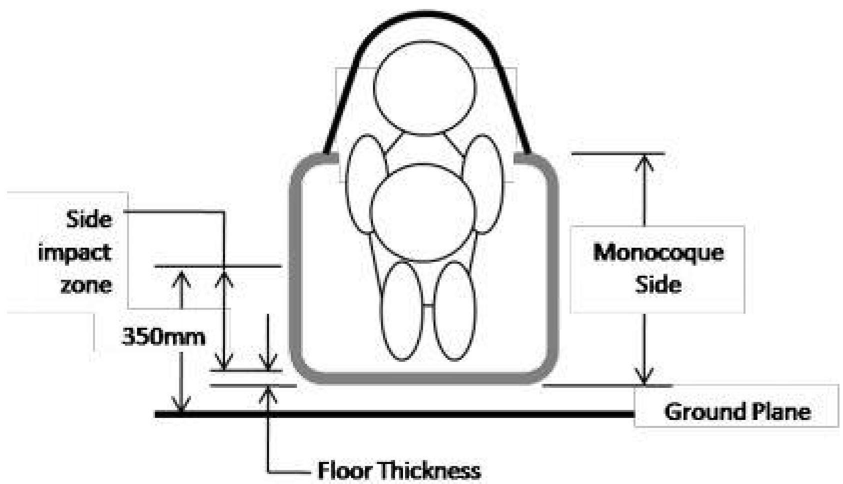


Figure 5 Rule T3.34.3 [6]

Impact: Dimensions needed for monocoque design.

Rule: T4.1.1 In order to ensure that the opening giving access to the cockpit is of adequate size, a template shown in Figure 6 will be inserted into the cockpit opening. It will be held horizontally and inserted vertically until it has passed below the top bar of the Side Impact Structure (or until it is 350 mm (13.8 inches) above the ground for monocoque cars). No fore and aft translation of the template will be permitted during insertion.

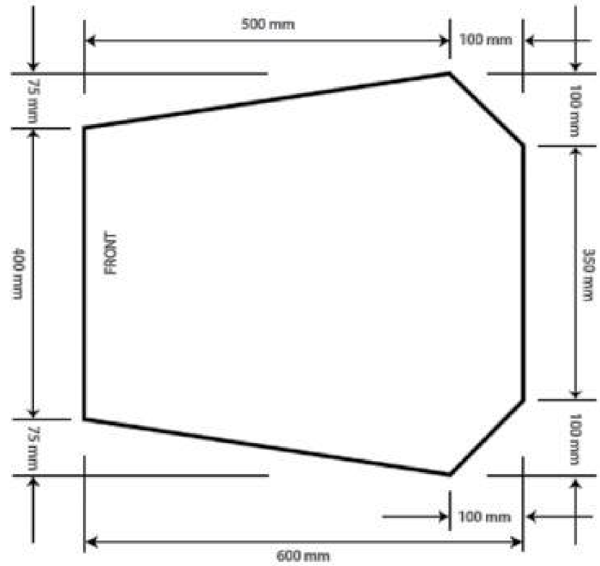


Figure 6 Rule T4.1.1 [6]

Impact: This template will be lowered directly in and out of the chassis. If the opening in the monocoque is smaller than this template the car will not be allowed to continue in the competition. Driver opening dimensions, including tolerances and uncertainties, must be at least this large.

Rule: T4.2.1 A free vertical cross section, which allows the template shown in Figure 7 to be passed horizontally through the cockpit to a point 100 mm (4 inches) rearwards of the face of the rearmost pedal when in the inoperative position, must be maintained over its entire length. If the pedals are adjustable, they will be put in their most forward position.

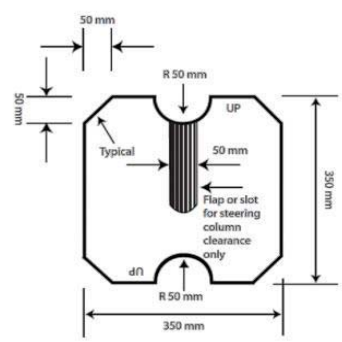


Figure 7 Rule T4.2.1 [6]

Impact: Similar to driver template this will be guided down the inside of the monocoque to ensure that it is to the dimension specifications. The monocoque must be at least this large, with no obstructions up to 4 inches behind the rear-most pedal.

Rule: T4.5.1 A firewall must separate the driver compartment from all components of the fuel supply, the engine oil, the liquid cooling systems and any high voltage system (PART EV - EV1.1). It must protect the neck of the tallest driver. It must extend sufficiently far upwards and/or rearwards such that any pointless than 100 mm (4 ins.) above the bottom of the helmet of the tallest driver shall not be in direct line of sight with any part of the fuel system, the cooling system or the engine oil system.

Impact: Chassis design must bring into account the firewall separating driver from specified dangers.

a) Future Rules Concerns and Considerations

The following rules are proposed changes in the 2015 season. Since they are strictly proposals and are open to rejection they are not what the design will be based on, but will still be a factor and kept in mind if situations arise where a rule change may affect a part of the chassis.

Rule: T15.4 Chassis – The committee is considering defining the main hoop bracing requirements more precisely for equivalency purposes. This is most likely to affect teams with monocoque chassis that use very short main hoop braces.

Impact: This rule may affect the height or thickness of the main roll hoop design for the 2015 Chassis. This could also affect the location of where the main roll hoop braces are attached or govern the length of the roll hoops.

Rule: T15.10 Design Event – The committee is considering including the objective of value in the design event objectives. This is to make it clear to all participants that a cost effective car which is well executed should be able to score well in the design event. This will result in the design event being judged on the three main objectives of Design for Performance, Design for Value and the knowledge of the team members. The committee hopes that this will change the perception of the design event so that it is clear that a large budget is not a prerequisite to winning the design event.

Impact: Doesn't affect chassis design but the design matrix could aid in the design event in helping simplify some of the engineering decisions made in chassis selection.

4) Design Requirements

A design selection matrix for a carbon fiber monocoque chassis is to be made in order to better advise the selection of the next GFR chassis. A ranking system must be cautiously balanced between points gained, manpower needed, manufacturing time, and manufacturing simplicity. The design matrix will help to narrow the design down to narrow down the chassis concepts. Dr. Paasch and the graduate students associated with GFR advised the process to ensure that the design matrix and properties associated with it will meet the chassis needs.

Preliminary interactions between sub teams and team members helped in understanding the current interfacing difficulties associated with the chassis. Initial research in old reports showed that students are not inclined to write about their failures or difficulties in a documentation process they are being graded on. However, the resources and information will help in understanding the needs of a new monocoque chassis tailored to the GFR philosophy.

5) Current State Analysis and Benchmarking

After analysis of previous documentation I began to get a grasp on the current design process situation. GFR has many documents on Google drive, Google sites, and a communal hard drive to review past information and design reports. There are several reports that are concerned with the design of the formula chassis. It is important to note how the change from a steel frame chassis to a carbon monocoque chassis came about and how the team decided on a finalized concept.

a) 2008 Design Process

The first report that is pertinent to this decision matrix is the 2008 chassis design report. In this document there are insights into the thinking behind how the chassis should be designed from the start. The steel chassis in 2008 was designed as a bracket holding everything together and had a designed place or joint for every connection on the chassis. The driver interface was a big part of the design which emphasized compatibility with a large range of driver sizes. The design criteria in the '08 chassis design report emphasized that the chassis would be safe, stiff, and lightweight while also having a low center of gravity that provides enough down force for traction. The idea of a monocoque chassis was discussed in this report but it was decided that there was not time to change the design for the 2008 FSAE season. It was mentioned that a carbon fiber chassis would be much more expensive and time consuming but could be comparable in strength while also greatly reducing weight. The report of the 2008 season was followed the next year by a 2009 report which laid out the preliminary design of a carbon fiber monocoque design.

b) 2009 Design Process

The importance of continuous documentation is stressed in design report from 2009. Posting pictures and explanations of why changes were made to various parts of the chassis and having all steps and documents properly labeled is a huge part of GFR's success. The report has a series of monocoque designs that have been drawn in CATIA which allows for FEA stress analysis to be performed. The design is shown in Figure 8 [9] is a basic design, with flat sides, bottom, and a rounded front and would be easy to manufacture. The preliminary chassis was oversimplified so a more intricate design was necessary. There were various iterations of the initial concept that were refined for different reasons. One of the first changes in the design process was moving the lowest point in the driver opening because of the stress concentrations in the monocoque. The flat rear wall and sides were most favorable for attachment points, aerodynamic considerations, and carbon fiber layup. With the 6 different monocoque designs presented in the report, the design team decided that the best concept was the one shown in Figure 9 [9].

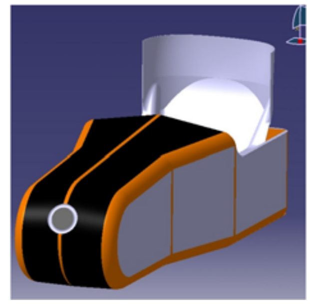


Figure 8 Preliminary 2009 Design

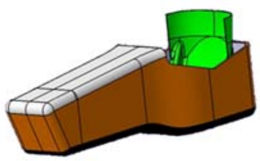


Figure 9 Final 2009 Chassis Design

The team realized their design weaknesses in this design in areas such as the side walls; the walls were designed to be perfectly vertical but this could not be achieved due to the carbon fiber layup technique used. The walls ended up having an angle of 3 but remained flat. The headrest, steering layout, cable/wire locations and electronic positioning were issues that were hard to design into the preliminary drawings since the OSU team did not have experience building a carbon chassis. The front roll hoop design was changed late in the 2009 season and had to be adapted to the chassis concept which made for some integration difficulty but this problem was and solved in the 2010 season.

c) 2010 Design Process

The 2010 design report takes the design in the previous report and refines specific parts in order to make a more efficient chassis that incorporates the interactions with other parts of the car. For example, the side and rear openings allow for the motor to be placed in the rear of the chassis as well as allowing room for maintenance. The 2010 chassis rear end can be seen in Figure 10 [10].

Many of these openings seen in the rear of the chassis were determined because of motor maintenance needed. Figures 11 and 12 show the maintenance needs of the CRF450X engine that is still used in the 2014 Formula cCar. These access points are still necessary to consider and govern the openings in the chassis.

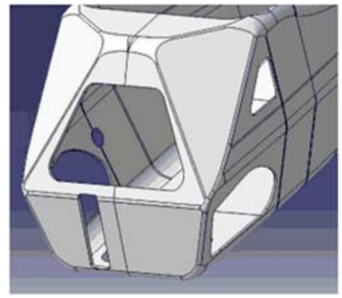
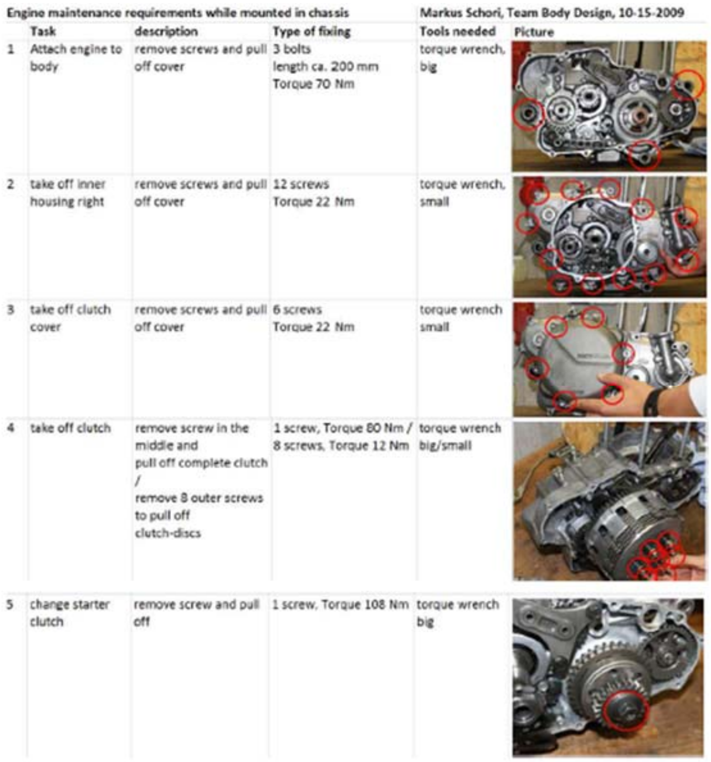


Figure 10. 2010 Chassis Design



Engine maintenance requirements while mounted in chassis — Markus Schori, Team Body Design, 10-15-2009

	Task	description	Type of fixing	Tools needed	Picture
1	Attach engine to body	remove screws and pull off cover	3 bolts length ca. 200 mm Torque 70 Nm	torque wrench, big	
2	take off inner housing right	remove screws and pull off cover	12 screws Torque 22 Nm	torque wrench, small	
3	take off clutch cover	remove screws and pull off cover	6 screws Torque 22 Nm	torque wrench small	
4	take off clutch	remove screw in the middle and pull off complete clutch / remove 8 outer screws to pull off clutch-discs	1 screw, Torque 80 Nm / 8 screws, Torque 12 Nm	torque wrench big/small	
5	change starter clutch	remove screw and pull off	1 screw, Torque 108 Nm	torque wrench big	

Figure 11 Engine Maintenance Requirements

6	check oil level	remove cover screw and check	1 cover screw, see picture	allen wrench	
7	dismantle cooling water tube	remove screws and take off	2 screws	torque wrench, small	
8	drain water	remove screw and drain water through the bottom	1 screw, length 33 mm	torque wrench, small	
9	check oil level	unscrew lid by hand	screw lid	by hand	
10	drain transmission oil	remove screw and drain through bottom	1 screw, Torque 16 Nm, length 73 mm	torque wrench, small	
11	take off cylinder head	remove screws and pull off	3 screws, length 80 mm, torque 68 Nm	torque wrench, big	

Figure 12 Engine Maintenance Requirements

It is important to note all of the needs above since accessibility must allow for quick and effective maintenance at competition. In 2010, an accurate representation of the motor was created in CATIA. This model helped determined how the engine would fit into the monocoque as well as how the engine intake, chain guard, and other engine components would work with the chassis. A guide was made to show how much room a wrench would take up inside the chassis when adjusting parts and securing the engine. This was done so that the chassis would account for the bolts that are necessary to access and adjust. A visual of this model is shown below in Figure 13 where the pie-shaped figure is where the wrench would be placed and shows the range of motion necessary.

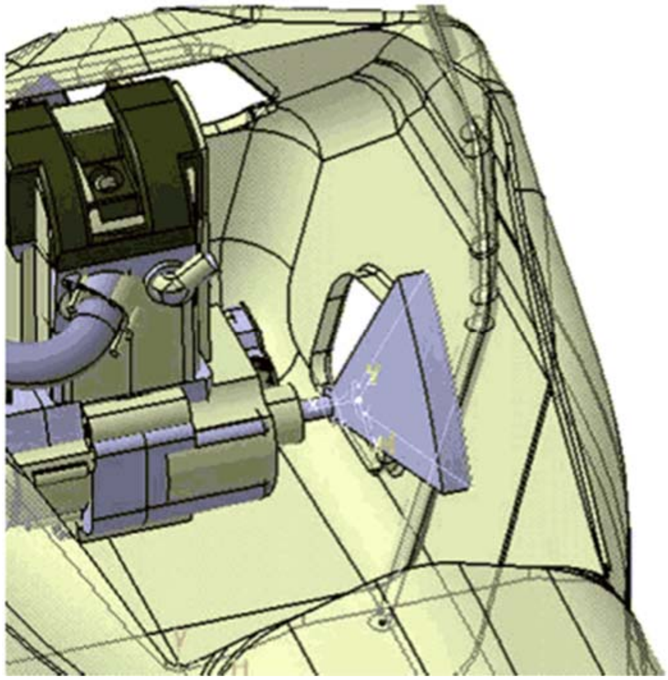


Figure 13 Wrench Guide

The necessary openings in the back of the chassis cause the section above the chain guard to be small and weak. The current chassis is strong enough, but during the 2010 season the car experienced a failure directly underneath the differential clevis in the back. Even with all the design and FEA tools available to the GFR team it is important to ensure the chassis is adequately strong to avoid similar issues. More specifics about the engine mounts are provided in the report and an FEA was performed to show the loading scenario of the engine weight as well as vibrations caused by the running motor. The pedals for the gas, brake, \the clutch are discussed and noted that it was “designed by OSU team members”. The detail is less than ideal and is an area that GFR continues to stress improvement on. The report mentions some driving factors of the chassis design such as Front A-Arms, WLAN router, impact attenuator and steering. The dashboard and steering wheel ergonomics are well defined in the report, unlike the 2009 report. At the end of the design report there is a mention of some of the things that were not considered at the beginning of the process but later changed. Included in this was: the raising of sides around the driver for more torsional stiffness, changing the bottom of the chassis for improved ergonomics, changing the cockpit rim, steering wheel, and headrest for better driver interface. These are the errors that GFR has learned from and worked out over the last four years but must also be careful that the team does not overlook previous mistakes.

d) Recent Design Process

More recent reports like the 2013 Chassis Design focus on specific parts of the chassis like hard points, joggle and material testing. There have been tests done on the carbon fiber weave and honeycomb core used in the current chassis and can be found in reports on the GFR chassis and composites website. In other reports there are breakdowns of chassis manufacturing time for the different parts of the car. A lower manufacturing time is a major consideration in the new chassis and one of the most measurable parameters available in the process. The manufacturing times from the 2011, 2013, and 2014 are shown below in Tables 1, 2, and 3 below.

Table 1 Manufacturing Time of Chassis Halves 2011 [5]

Carbon Layup Summary	C Car Hours	ECar Hours
upper half	258.6	162.25
lower half	413	292
TOTAL	671.6	454.25

Table 2 Manufacturing Time of Chassis 2013 [14]

Carbon Layup Summary	1st Car Hours	2nd Car Hours
Upper Outer Skin	176	150.25
Lower Outer Skin	272.5	209.25
Upper Inner Skin	108.75	91
Lower Inner Skin	182.5	165.75
TOTAL	739.75	616.25

Table 3 Manufacturing Time of first Chassis 2014 [5]

	hrs logged	percentage
Other	130.75	20.3%
Bagging cCar	89	13.8%
Layup cCar	194.5	30.2%
Bonding cCar	27.75	4.3%
Core cCar	202.75	31.4%
Sum	644.75	

Table 4 Joggle Timetable 2011 [5]

	C-Car monocoque	# of people	Corrected Hours	E-Car monocoque	# of people	Corrected Hours
+ post processing	40	1	40	40	1	40
+ joggle prep	12	3	36	10	3	30
+ initial bond	2	3	6	2	3	6
+ joggle layup	12	2	24	12	2	24
+ joggle bag	6	3	18	6	3	18
+ paint	8	3	24	8	3	24
Total Hours:			148			142

Table 5 Joggle Timetable 2013 [14]

Joint Summary	1st Car Hours	2nd Car Hours
Upper Outer Skin Joint Layup and Fitting	17.75	25.5
Lower Outer Skin Joint Layup and Fitting	41.75	36.75
Joint Prep and Bonding	56.25	21
TOTAL	115.75	83.25

e) 2015 and Future Design Process

Currently there are online documents, CATIA sketches, and conversations for the new chassis design. The drawings have been reviewed by the GFR 15 design team and comments have been posted to refine the designs. This is where it is possible for the design matrix to leave information that cannot be put in words. For developed chassis designs the matrix could be filled out and left for future design groups to have more concrete evidence and values of why certain design decisions were made.

i) Analysis of Current State

Strengths

- Have an existing and successful chassis already so we don't have to feel like we are starting from complete scratch
- The current team has familiarity with a monocoque chassis
- Leads and sub teams have dealt with struggles and successes of current chassis design and have good insight on what needs to be improved and what can remain the same.

Weaknesses

- Have not been able to experience effects of major chassis changes because of having the same chassis for four years.
- Full explanations of chassis selection and changes are not adequate in many design reports
- Hard to quantify or justify some chassis changes since some were done based on engineering intuition or a TA's judgment.

Opportunities

- Team members part of original monocoque and revisions over the years are still here and are a part of the 2015 design process.
- Decrease manufacturing time and difficulty
- Completely document entire design selection process
- Create a chassis that will also be adaptable to future rule or design changes

- Consider eCar

<u>Threats</u>

- Create an over designed chassis that doesn't have tolerances for changes
- Change parts of chassis that do not need to be changed just because change is desired.
- Over allocate time commitment to chassis development instead of current car completion

6) Benchmarking

It is important to benchmark the current state and set a standard for the design process. The primary parameter to be benchmarked is the manufacturing process and how it was documented in 2011, 2013 and 2014. As seen in the 2014 report, the differences in time breakdown for different layers and sections of the process are well documented. The time taken to construct the 2013 carbon fiber chassis upper and lower half increased from 2011. The increase in time from 2011 to 2013 could be from a lack of adequate direction from the 2011 team but was improved to an all-time low in 2014 which shows a step in the right direction. Every year the second chassis layup goes much faster than the first. This is due to the experience gained from manufacturing the first chassis and it is important for GFR to continue to improve the tutorials available in order to reduce the learning curve of chassis manufacturing and to have a fast production time for both the first and second layup. With a new chassis there will be no detailed tutorial, which makes the first construction team responsible for making an extremely accurate initial tutorial.

Another benchmarked process is the concept selection process. In 2009 the chassis concepts were presented in the report but no link or mention was made of the chassis in other documentation and did not elaborate on the rationale for ignoring some concepts and focusing on others. This year the CAD models on the sync drive include some 2015 chassis concepts in the same file and have a Google Document with the various models as well as links to a page with further explanation on the rationale for design changes.

7) Design Analysis

The decision matrix will help with the design process and with explaining the team's decision on specific chassis features and the overall design. The matrix will incorporate "design parameters" that have interactions with the chassis. It will relate these parameters with "selection criteria" that can be weighted in order to have a proper influence on the design matrix output. In order to produce a meaningful design matrix several techniques were analyzed.

a) Design Matrix Method 1

The first method considered for a design matrix is the one laid out in the Eppinger and Browning textbook. The "Design Structure Matrix Method" (DSM) [11] presented in the text can be used to analyze either a product, organization, or process. A product is considered to be one deliverable that could be as small as a single part or something made up of many parts. Analyzing an organization would involve studying the way the company shares information, interacts, makes decisions, and manages employees. A process would be the way in which all the parts of a project come together. Although this project focuses more narrowly on the single product design matrix method, the other two could be useful for the team. Evaluating the GFR organization as a whole, as well as the design process from the minute the last competition of the season ends, through senior design class, and through the remainder of the season could be a useful tool for the team.

The steps associated with making a Design Structure Matrix are to:

1) Decompose the product into its larger subsets

2) Identify the relationships among the systems elements

3) Analyze the relationships to understand the structural patterns and system behavior implications

4) Create a DSM that represents the entire product and highlights specific features of higher importance

5) Improve the product and DSM as priorities that need to be focused on and improved change.

The steps above are the overarching steps that should make for a successful design matrix. For the decomposition stage the product should be broken up into its modules and components. This includes listing all the elements interacting with the product as well as all the parts that make up the product itself. Depending on how in depth the analysis is will influence how many and how complex these components will be. The second step in decomposition is to assess how these components are implemented into the product and to assign interactions between the modules and components. Understanding the interactions help establish the boundaries of the product. The minimum allowed would be a chassis that performs equally well and is equally easy to manufacture as the current one while the maximum is constrained by cost, access to resources, rules, or the overall scope of GFR. After the product interactions and boundaries have been set it is important to start considering the interaction strength between the various criteria. With the interactions completed, the matrix is constructed with the same components and modules on the top and bottom, creating a square. Once the matrix is filled out and interactions are rated and recorded on it, the matrix can be re-organized in order to simplify the information. This process is called "clustering" [11] which is a technique of moving similar relationships into the same area in order to allow the DSM to show which parts of the product are most closely related. This time consuming process of clustering can be problematic for a matrix that is designed with the idea of being simple and quick to understand. Another problem with this technique is that it is meant for the preliminary design stages. It is extremely useful for relationship analysis and helping in creating designs instead of reflecting upon an already existing design.

The DSM process is confusing at first but with a relatively simple system it could be useful in recognizing problems or successes of a product. As a system becomes more and more complicated, however, the matrix becomes equally large. This difference in a simple and complex system can be seen in Figures 14 and 15. This strategy is not optimal when considering all the parameters associated with it. The DSM should be more seriously considered if a specific component was being analyzed. This project requires a simple matrix that can be quickly understood by each batch of new seniors and used to analyze the pros and cons of different chassis designs. I continued to look for a better design matrix method.

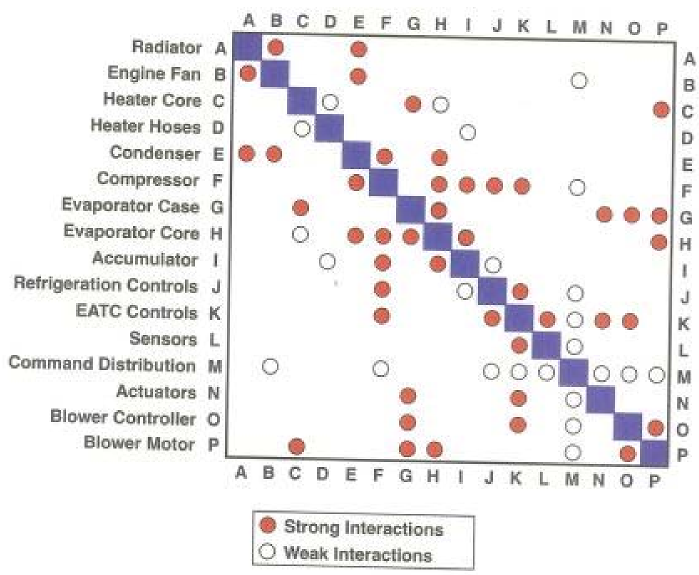


Figure 14 Simple DSM

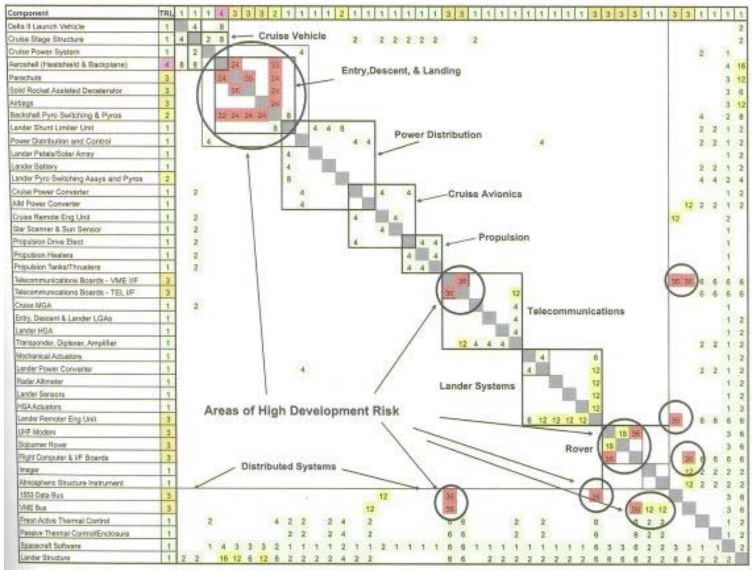


Figure 15 Clustered DSM

i) Matrix Method 1 Pros & Cons

Pros

- In depth comparisons possible for systems
- Can analyze system in two ways
    - How top component affects side component
    - How side component affects side component

Cons

- Doesn’t weight relationships between components well. Shows relationships but does not consider importance of different relationships which is necessary for the chassis.
- Confusing layout
- Designed more for specific parts and not for prioritizing in a whole chassis interfacing
- Takes time to cluster the matrix. The organization process after filling out matrix is not straightforward and the extra work is not optimal for the purpose of this design matrix.

b) Design Matrix Method 2

George Dieter’s book *Engineering Design* introduces a method similar to that presented in the book by Eppinger and Browning. Dieter calls this design method the “Theory of Inventive Problem Solving” or “TRIZ”. [13] This method lays out a “contradiction table” in the same way by keeping the square set up that has the same engineering requirements of a specific product on the side and top in the same order. On the top row the conditions are considered “undesired results” which means that the condition should be considered inadequate and the “features to improve” on the side are the parameters that relate to the undesired result and improve it. [13] This is difficult to explain in words but can be seen in the example in Figure 16.

	Undesired result / Feature to improve	1	2		9	10		38	39
		Weight of moving object	Weight of nonmoving object	. .	Speed	Force	. .	Level of automation	Productivity
	:								
8	Volume of nonmoving object		35,10 19,14			2,18 37			35,37 10,2
9	Speed	2,28 13,38				13,15 19,28		10 18	
	:								
27	Reliability	3,8 10,40	3,10 8,28			21,35 11,28		11,13 27	1,35 29,38
	:								
39	Productivity	35,26 24,37	28,27 15,3			28,15 10,36		5,12 35,26	

Figure 16 TRIZ Contradiction Table

In this matrix there are numbers inside the squares instead of a simple check, or interaction strength. The numbers represent different engineering parameters or inventive principles that are used in the TRIZ system. The numbers in the top row represent the relationship of engineering parameters in Figure 17 between the two parameters while the bottom row represents the inventive principles. The engineering parameters are product attributes that engineers are typically concerned with during production and analysis of a specific product or system. The inventive principles in Figure 18 are techniques for overcoming system conflicts and can help lead engineers to a more in depth understanding of how different parts of a product can be improved.

Engineering parameters commonly used in TRIZ

1. Weight of moving object	21. Power
2. Weight of nonmoving object	22. Waste of energy
3. Length of moving object	23. Waste of substance
4. Length of nonmoving object	24. Loss of information
5. Area of moving object	25. Waste of time
6. Area of nonmoving object	26. Amount of substance
7. Volume of moving object	27. Reliability
8. Volume of nonmoving object	28. Accuracy of measurement
9. Speed	29. Accuracy of manufacturing
10. Force	30. Harmful factors acting on object
11. Tension, pressure	31. Harmful side effects
12. Shape	32. Manufacturability
13. Stability of object	33. Convenience of use
14. Strength	34. Repairability
15. Durability of moving object	35. Adaptability
16. Durability of nonmoving object	36. Complexity of device
17. Temperature	37. Complexity of control
18. Brightness	38. Level of automation
19. Energy spent by moving object	39. Productivity
20. Energy spent by nonmoving object	

Figure 17 Engineering Parameters

The Inventive Principles of TRIZ

1. Segmentation	21. Rushing through
2. Extraction	22. Convert harm into benefit
3. Local quality	23. Feedback
4. Asymmetry	24. Mediator
5. Combining	25. Self-service
6. Universality	26. Copying
7. Nesting	27. An inexpensive short-lived object instead of an expensive durable one
8. Counterweight	28. Replacement of a mechanical system
9. Prior counteraction	29. Use of a pneumatic or hydraulic construction
10. Prior action	30. Flexible film or thin membranes
11. Cushion in advance	31. Use of porous material
12. Equipotentiality	32. Change the color
13. Inversion	33. Homogeneity
14. Spheroidality	34. Rejecting and regenerating parts
15. Dynamicity	35. Transformation of physical and chemical states of an object
16. Partial or overdone action	36. Phase transition
17. Moving to a new dimension	37. Thermal expansion
18. Mechanical vibration	38. Use strong oxidizers
19. Periodic action	39. Inert environment
20. Continuity of useful action	40. Composite materials

Figure 18 Inventive Principles

Similar to the DSM method, TRIZ is concerned more with the preliminary design process instead of the rating of an existing design. This matrix method goes into deeper depth than the DSM process which could add to the information from the matrix but is still confusing. This technique does not have a good way of quantifying the importance of some relationships over others, which is very important for to the formula chassis. The TRIZ method involves numerous parameters and inventive principles that should be memorized which makes a quick understanding of the matrix a needlessly time consuming task. For similar reasons as the first, the complexity and intricacies of this method are not optimal for the selection of the GFR chassis. The search for a successful design matrix structure continued.

i) Matrix Method 2 Pros & Cons

Since the layout of method two is similar to that of method one the pros and cons of this method are similar as well. The additional pros and cons are listed for this method below.

Pros

- Standardized Scoring system
- More detailed ranking of components
- Possibility of ranking inventive principles on importance level to weight components

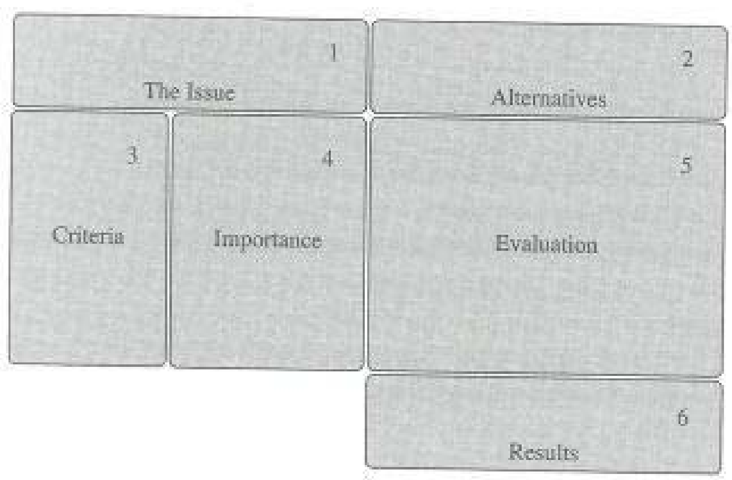
Cons

- The inventive principles are not tailored to chassis design well
    - Additional principles could be created but there is danger in making too many of your own principles because they can be overly or not specific enough and dilute the usefulness of the TRIZ matrix.
- Weighting adds an extra step to design matrix which does not allow for easy carry over or adaptability from one year to the next.
- Will take a while to read and reference each number in the boxes of the matrix and understand significance

c) Design Matrix Method 3

After finding two mediocre design matrix processes I used the knowledge of what didn't work and began looking for a matrix that can be easily read and provide a final number to help make hard decisions in the chassis selection. I continued my search in a book that was under my nose the whole time. I opened *The Mechanical Design Process* by OSU professor David Ullman. Dr. Ullman gives a description of Pugh's Method in detail and lays out the six sections of the design matrix. These include: Issue, Alternatives, Criteria, Importance, Evaluation, and Results the configuration of these sections are seen in Figure 19.

Figure 19 Decision Matrix Structure



1) **State the issue.** This project's issue is the selection of a new chassis.

2) **Select Alternatives to be compared.** This section is less straight forward than the first. There are some new full chassis designs that have been designed but it will not be as easy to have an alternative be an entire chassis and evaluate it that way. It will be necessary to break up the chassis into different subsystems and the alternatives within these subsystems and relate them with the scoring criteria to produce a useful matrix.

3) **Choose the Criteria for Comparison.** It is important to understand the basis on which the alternatives are to be compared with each other. This will be difficult in developing a limited, but wide enough, range of criteria to compare the alternatives meaningfully. This does allow for criteria to be separate from the alternatives and can remain in a different section of the matrix which will make the matrix easier to understand.

4) **Develop Relative Importance Weightings.** This step involves ranking the criteria in importance levels, independent of the alternatives, in order to help with the final “results” section. The importance levels will provide a weighting system that is much easier to implement than the previous two systems presented.

5) **Evaluate Alternatives.** This involves filling out the matrix that was created through the first four steps. Going through every cell and applying a value to the relationship based on the benchmark design. In this case, the benchmark would be the current chassis and every subsystem of the future chassis will be related to the 2014 Chassis. The recommended system of evaluation is to use values of -1, 0, +1 for designs that are worse, equal, or better than the current system. Another option to explore would be to increase the variability of this by increasing those values to -5, 0, +5, -10, 0, +10, or on a 0 - 10 scale.

6) **Compute the Satisfaction and Decide What to Do Next.** Multiply the evaluation value by the importance value of the design criteria and sum them up at the bottom in section six. Each alternative will have a separate value that will be better, worse, or the same as the design it is being compared to. This way it is much easier to identify, if the matrix is constructed correctly, which alternatives are better or worse than the current state? An example of a Pugh selection matrix is shown below in Figure 20.

Issue: Choose a MER wheel configuration		Baseline	Cantilevered Beam	Hub Switchbacks	Spiral Flexures	Multipiece
Mass efficiency	35	Datum	0	0	1	?
Manufacturability	10		0	−1	−1	?
Available internal wheel volume	20		1	1	1	?
Stiffness	35		1	1	1	?
	Total		2	1	2	?
	Weighted total		55	45	80	?

Figure 20 Example Pugh Decision Matrix

The decision matrix method laid out in Ullman's book seems to be the method that will be most successful in chassis analysis. There are parts of the matrix that will be difficult to quantify with an evaluation value and the alternatives will sometimes be hard to word so that there is a finite amount of quality alternatives. Other problems will be in ranking importance levels of the different criteria but this will come from conversations with the leads about the alternatives and the criteria. Those criteria and alternatives will be discussed later in the report.

i) Matrix 3 Pros & Cons

Pros

- Can weight selection criteria to put more emphasis on some qualities over others
- Simple layout which is easy to design, configure, and understand
- Easy to read. A total and weighted total results from every column for quick and easy analysis of chassis
- Easy to see how well each component of the chassis compares by the final value in the bottom.

Cons

- Dangers involved in improper weightings of selection criteria

- Problems could be deeper than just one criteria being miss weighted. Multiple weightings just slightly off could throw the matrix entirely.

8) Design Selected

a) Rationale for Selection

Pugh’s method was selected due to its variability, ease of use, and effective weighting process. The Pugh method will allow for extra design and selection criteria to be added, removed, and re-graded without having to reorganize the matrix like the other methods would require. This method allows for one, compact, visual representation of the grading criteria and results. There is a lot of adaptability in the matrix; in overall layout, importance weightings and evaluation parameters such as the difference in the basic sum and then the weighted sum to gain further insight into specific components of the chassis.

i) Initial Design Matrix Selection

Below is the preliminary design of the matrix. The scoring criteria are on the left side of the matrix and their respective importance weights are directly to the right of them. Each sub team has their own section that will have the design criteria tailored to that part of the chassis.

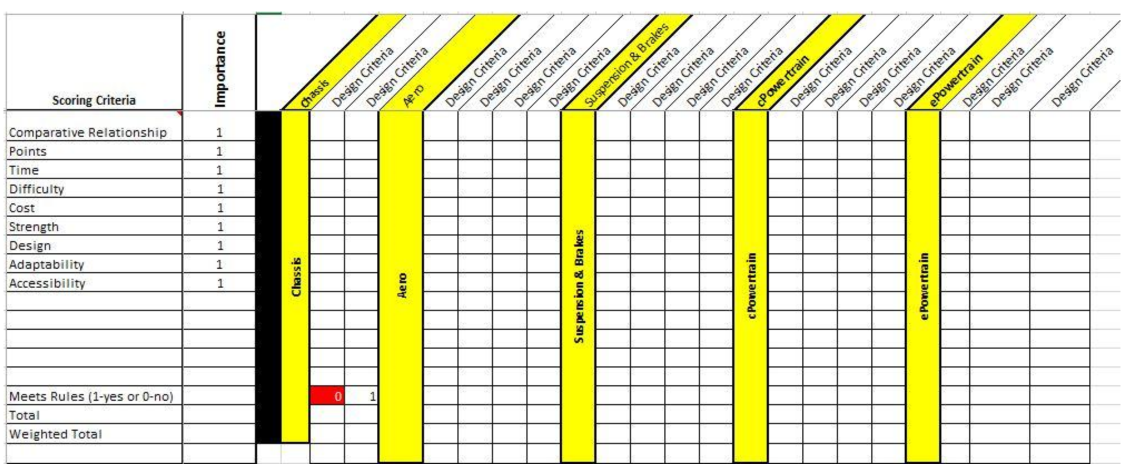


Figure 21 Initial Matrix Design

The matrix will be filled out by going through each design criteria and assigning a value to the box with corresponding scoring criteria. In some cases the scoring criteria may not relate to the design criteria, in which case it will be blacked out. If a lead does not have an educated opinion on a cell in the matrix that lead will leave the cell blank so that there are not unnecessary numbers in the matrix. The "Meets Rules" row is more of a check off section of the chassis design process. This is a double check type system that makes the person filling out the matrix think twice about if the component on the new design will meet the competition rules. The total is a sum of everything above and the weighted total is when the design criteria values in the individual boxes are multiplied by the importance values of the scoring criteria and then summed at the bottom. The person filling out this matrix can rate each part of chassis as they see fit but could also be split up between tech leads who would rate their respective sub section.

ii) Adapted Design Matrix Selection

One aspect that had not been considered until after the initial design was made and presented was the ability for all of the leads to have input on each part of the chassis. In the initial design the thought was that each lead would grade their own respective part. A lead could fill out their individual section and see how their subsection was affected to gain insight on how a few components would affect their sub team or could wait for all the leads to fill out their sections to see how the overall chassis stacks up. This is also where the problem comes in. The leads really only had one section to fill out on their sub team which is, theoretically, the location that they should have the most insight. But the other leads have their own ideas about other parts of the car and the chassis interfacing. In the previous design the leads did not have a good way to display their own thoughts about those sections. The matrix in Figure 22 was created to account for this.

Scoring Criteria	Importance	Chassis	Design Criteria	Design Criteria	Design Criteria	Design Criteria	Aero	Design Criteria	Design Criteria	Design Criteria	Design Criteria	Suspension & Brakes	Design Criteria	Design Criteria	Design Criteria	Design Criteria	cPowertrain	Design Criteria	Design Criteria	Design Criteria	Design Criteria	ePowertrain	Design Criteria	Design Criteria	Design C
Comparative Relationship	1																								
Points	1																								
Time	1																								
Difficulty	1																								
Cost	1																								
Strength	1																								
Design	1																								
Adaptability	1																								
Accessibility	1																								
Meets Rules (1-yes or 0-no)			0	0	1	1																			
Total																									
Weighted Total																									
Lead:	Chassis																								
Comparative Relationship	0.75																								
Points	0.75																								
Time	0.75																								
Difficulty	0.75																								
Cost	0.75																								
Strength	0.75																								
Adaptability	0.75																								
Accessibility	0.75																								
Lead:	Aero																								
Comparative Relationship	0.75		0																						
Points	0.75																								
Time	0.75																								
Difficulty	0.75																								
Cost	0.75																								
Strength	0.75																								
Adaptability	0.75																								
Accessibility	0.75																								
Lead:	Suspension																								
Comparative Relationship	0.75																								
Points	0.75																								
Time	0.75																								
Difficulty	0.75																								
Cost	0.75																								
Strength	0.75																								
Adaptability	0.75																								
Accessibility	0.75																								
Lead:	cPow																								
Comparative Relationship	0.75																								
Points	0.75																								
Time	0.75																								
Difficulty	0.75																								
Cost	0.75																								
Strength	0.75																								
Adaptability	0.75																								
Accessibility	0.75																								
Lead:	ePow																								
Comparative Relationship	0.75																								
Points	0.75																								
Time	0.75																								
Difficulty	0.75																								
Cost	0.75																								
Strength	0.75																								
Adaptability	0.75																								
Accessibility	0.75																								
Bottom Sum			0																						
Bottom Weighted Total			0																						
Final Sum			0																						
Final Weighted Total			0																						

Figure 22 Adapted Design Matrix

As seen above, the adapted matrix still has the initial layout on the top layer. This layer will still have the same function as the initial design. Each section will be filled out by the respective tech and then will be able to provide insight into the matrix in the lower layers of the matrix. Below the first level there are four more similar levels with blacked out sections. These blacked out sections are so the leads will not fill out the matrix for their particular sub team twice. Each lead has their own mini-matrix level to fill out. The importance levels of the lower levels are multiplied by a percentage so that they have less weight than the top level. The reason for this is so that the concerns of the leads on their respective sub teams are weighted more heavily than other leads' opinions on them. So, the lead will fill out the top layer matrix for their own sub team, proceed to their respective layer, and then continue to fill out that layer for all the horizontal sections. The totals for the top layer, bottom layer, and entire matrix will be calculated. The example is just for demonstration of how to fill out the matrix and the numbers are not representative. The example is as if the cPowertrain lead were to be filling out the design matrix.

Scoring Criteria	Importance	Chassis	Design Criteria	Design Criteria	Design Criteria	Design Criteria	Aero	Design Criteria	Design Criteria	Design Criteria	Design Criteria	Suspension & Brakes	Design Criteria	Design Criteria	Design Criteria	Design Criteria	cPowertrain	Design Criteria	Design Criteria	Design Criteria	Design Criteria	ePowertrain	Design Criteria	Design Criteria	Design C
Comparative Relationship	2																	3	1	5	-3				
Points	2																	2		2	-1				
Time	2																	4	2	2	1				
Difficulty	2																		-1		0				
Cost	2																		0						
Strength	2																	-2			-2				
Design	2																	1	2		0				
Adaptability	2																	2	2	1	-2				
Accessibility	2																	0	2		-1				
Meets Rules (1-yes or 0-no)			0	1	0	1		1	1	1	1		1	1	1	1		1	1	0	1		1	1	1
Total			0	0	0	0		0	0	0	0		0	0	0	0		10	8	10	-8		0	0	0
Weighted Total			0	0	0	0		0	0	0	0		0	0	0	0		20	16	20	-16		0	0	0
Lead:	Chassis																								
Comparative Relationship	1.5																								
Points	1.5																								
Time	1.5																								
Difficulty	1.5																								
Cost	1.5																								
Strength	1.5																								
Adaptability	1.5																								
Accessibility	1.5																								
Lead:	Aero																								
Comparative Relationship	1.5		0																						
Points	1.5																								
Time	1.5																								
Difficulty	1.5																								
Cost	1.5																								
Strength	1.5																								
Adaptability	1.5																								
Accessibility	1.5																								
Lead:	Suspension																								
Comparative Relationship	1.5																								
Points	1.5																								
Time	1.5																								
Difficulty	1.5																								
Cost	1.5																								
Strength	1.5																								
Adaptability	1.5																								
Accessibility	1.5																								
Lead:	cPow																								
Comparative Relationship	1.5		1	4	0	2		3	-2		2			-2	2	1							0	1	1
Points	1.5			2	0	-2		5	-2	2	1		-2	-1		1							0	1	-2
Time	1.5		2	-4		-1		1	-1	3	1		-2	-4									0	1	-2
Difficulty	1.5		3	-1	2	0		1	1	1	1		-1	5	2								0	1	-4
Cost	1.5				2	0			2	2			2	2	1	2							0	4	3
Strength	1.5		3	0	1	0		2		1			2	2	0	1							0	5	1
Adaptability	1.5		2	2	2	0		0			2				0	0							0	2	2
Accessibility	1.5		5		3						-3												0		
Lead:	ePow																								
Comparative Relationship	1.5																								
Points	1.5																								
Time	1.5																								
Difficulty	1.5																								
Cost	1.5																								
Strength	1.5																								
Adaptability	1.5																								
Accessibility	1.5																								
Bottom Sum			16	3	10	-1	0	12	-2	9	4	0	-1	2	5	5	0	0	0	0	0	0	0	15	-1
Bottom Weighted Total			24	4.5	15	-2	0	18	-3	14	6	0	-2	3	7.5	7.5	0	0	0	0	0	0	0	22.5	-1.5
Final Sum			16	4	10	0	0	13	-1	10	5	0	0	3	6	6	0	1	1	0	1	0	1	16	0
Final Weighted Total			24	4.5	15	-2	0	18	-3	14	6	0	-2	3	7.5	7.5	0	10	8	10	-8	0	0	22.5	-1.5

Figure 23 Example Matrix Filled out by cPowertrain Member

This example was done using a -5 to 5 scale. Using 0 as a mark that implies that the design criteria is normal while a -5 implies that it is terrible and a +5 is as good as it could possibly be. A blank space is left if a certain design criteria does not relate to the selection criteria. An example of this would be that the connection location of the aero packaging won't directly affect cost. This is the basic example of the layout and how the matrix can be used by all the leads in one compact place to analyze the chassis design. The specific definition and rationale behind each design and selection criteria are described in the next section.

iii) Rearranged Design Matrix

	Chassis	Weight (g)	Manufacturing	Carbon Weave Material	Honeycomb Material (N/mm)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)
Scoring Criteria	Importance						Importance	
Lead: Chassis			Lead: Chassis					
Comparative Relationship	1						1	
Points	1						1	
Time	1						1	
Difficulty	1						1	
Cost	1						1	
Strength	1						1	
Adaptability	1						1	
Accessibility	1						1	
Sum		0	0	0	0	0		0
Weighted Total		0	0	0	0	0		0
Lead: Aero	Importance			Lead: Aero			Importance	
Comparative Relationship	1						1	
Points	1						1	
Time	1						1	
Difficulty	1						1	
Cost	1						1	
Strength	1						1	
Adaptability	1						1	
Accessibility	1						1	
Sum		0	0	0	0	0		0
Weighted Total		0	0	0	0	0		0
Lead: Suspension	Importance			Lead: Suspension			Importance	
Comparative Relationship	1						1	
Points	1						1	
Time	1						1	
Difficulty	1						1	
Cost	1						1	
Strength	1						1	
Adaptability	1						1	
Accessibility	1						1	

Figure 24 Blank Redesigned Matrix

The Matrix was once again rearranged in order to increase the simplicity for the person filling the matrix out. This way there is not a box at the top to fill out and then a lead would move to their respective row section. A lead will start on the left and go right and does not have to change levels. The technique changed as well. If there is no information to input, the lead should continue to leave that cell blank or enter in “XXXX”. The ranking system has been changed to a 1-10 scale. This scale is used for better calculation from the matrix. A 1 means that a relationship between design and selection criteria is terrible and a 10 means that the relationship is as good as it could be.

b) Technical Specification

This section will be dedicated to describing the details of each selection and design criteria. It is important that this section be clear and concise so that each lead understands exactly what is being referred to when read on the matrix. If the leads all have different impressions of what the selection criteria or design criteria mean then the matrix will be ineffective.

i) Selection Criteria

The selection Criteria were initially selected by getting input from leads on their view of which criteria are most important.

Comparative Relationship

Basically a qualitative measure. From engineering intuition, previous experience, or looking at a part of the chassis and analyzing the effectiveness of the part of the car. This criteria was created in order to conserve the comparative nature of the Pugh method. Even though the matrix is designed to be objective, it is important for a comparative relationship to be established between current and future designs. This criteria allows the matrix to be influenced by the comparison between multiple designs but not completely controlled by that relationship.

Cost

GFR is fortunate enough to get a multitude of sponsors who will provided a discounted or waived cost for materials and services from carbon fiber and honeycomb to 5-axis CNC programming and machining and water jetting. For the parts that cannot be sponsored GFR still has a budget but if a part could not be sponsored and was expensive, getting enough product may prove difficult.

Points

How will a part of the chassis help us gain points?

Time

Refers to building/manufacturing time but could also be the time it takes to remove, replace, or perform maintenance on something.

Difficulty

Much like the time relation and mostly associated with manufacturing. Also could be difficulty interfacing with chassis.

Strength

The respective strength or stiffness of an area of the car.

Adaptability

How "changeable" is this chassis? If changes need to be made from year to year how easy will it be to adapt to those changing needs.

Accessibility

Will be related to maintenance mostly but also related could be related to a feature like the brakes. How accessible is the proposed chassis design?

iii) Design Criteria

Each design criteria is listed below in **bold** face. The first step in the design criteria is to quantify them as best as possible. This way, after a first glance, it can be understood what the measurement of design criteria should be of primarily concern. The units of the design criteria are just for reference and the relative ranking will be given by the opinion of the leads.

Chassis Design Criteria

Weight (g)

The weight of the base chassis including all carbon layers, honeycomb layers, and hard points.

Manufacturing (hours)

This is how hard and how long the layup will be of the chassis. Compared to the current chassis how many more, or fewer, hours will the chassis take. This is also related to how much relative care will have to be taken to avoid bridging in some areas or just chassis design that will increase the difficulty of layup or joining the two halves.

Carbon Weave Material

How does the stiffness of the proposed carbon weave compare to the current material?

Honeycomb Material (N/mm)

How does the material that is expecting to be used compare with the honeycomb material of the previous chassis? A report on testing is currently being done which will provide insight to superior honeycomb materials and density configurations.

Center of Gravity Height (mm)

This criteria is directly related to points in the point matrix. The consideration of the height of the center of gravity should be considered in the design process.

<u>Aero Design Criteria</u>

Aerodynamic Performance of Chassis (Drag N)

This is not an aerodynamic packaging concern but the actual aerodynamics of the chassis itself. Although it mostly is adapted by the aero packaging to make up for any lapses in streamlining of the chassis itself the chassis design should not be completely disregarded from the design process.

Chassis Width (cm)

The chassis width can directly relate to how the aero packaging can be attached and how useful that packaging can be in reducing drag and increasing drag force. How wide is the chassis and how does that help or hurt the aero packaging possible for the proposed chassis?

Front Aero wing connection (cm^2)

The front wing connection will work with, and around, the chassis front design and will be adapted to maximize aero effectiveness. How well can the front wing aero packaging be connected and utilized on the proposed chassis? The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Side Aero connection (cm^2)

This aero packaging depends not only on the chassis but on the cooler size and orientation. If the sides of the chassis are larger and flatter, like mentioned in suspension section, there can be more adaptability to configure the side pods. How well can the side aero packaging be connected and utilized on the proposed chassis? The "cm^2" does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Rear wing Aero connection (cm^2)

There have been changes made to how the rear aero is connected to the rest of the chassis in recent years. It has been moved to connect with the suspension instead of being connected directly to the chassis. Either way will affect the chassis design. This criteria is a measure of how well the proposed aero design can be connected to the proposed chassis design. The "cm^2" does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Brakes and Suspension Design Criteria

Kinematics (Stiffness)

The configuration of the wheel and shock locations and orientations can affect the drivability of the car. How does the kinematic predictions of the proposed chassis compare with that of the previous chassis?

Connection Surfaces (cm^2 & degree angle)

Connection surfaces are best when the area of the surface is maximized. Especially in the initial design of a chassis because this will provide an extra amount of variability. The "flatness" of the surface is important as well so that there are not ridges or angle changes in a surface so the connection locations can be effective, and variable if necessary. The "cm^2 & degree angle" does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Brake Wiring (cm^2)

This criteria is a factor that was stressed by multiple leads. Currently the side of the chassis uses one inch core and then is transitioned into half inch core on the bottom corner of the chassis so that there is a sort-of track for the wires to run out of the way. Having wires in the way of maintenance processes and especially foot operations in the pedals is bad. The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Foot and Pedal Area (cm^2)

Usually the tallest people who need the pedals pushed the furthest out have the largest feet. The current 2014 chassis tapers smaller towards the front of the chassis which is done for aerodynamic principles but also makes it harder for larger drivers to have comfortable room in the end of the pedal region. How well does the new chassis do in providing room in the foot and pedal area? The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Driver Ergonomics and Seat belt Configuration (cm^2)

This may be a more qualitative measurement. This will depend on the different drivers for the competition year and how they want the back insert to be configured for their driving style. The main concern will be how adaptable is the chassis for different ergonomic settings. This will be measured by an area because the more room for the different drivers the more adaptable it will be as well as how will the harness connection locations allow for a comfortable and safe seat belt that also meets the rules? The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

cPowertrain Design Criteria

Area required for Engine Removability (cm^2)

Although much of the maintenance for the combustion engine can be done when the car is inside the chassis it must be initially inserted and may need to be completely removed during competition. Although this is not a common occurrence it should be accounted for because in this situation at competition a quick removal will be very useful. The connection should be adaptable to moving the engine around in the future as well as having the strength and stiffness to support the engine through the wear of vibrations and forces of testing and competition. How does the chassis allow for the installment and connection of the combustion engine?

Engine Maintenance Access (cm^2)

One difficulty is the accessibility to the rear connections that are for the engine to the chassis. As seen in Figure 25 there is a vertical hole in the left side of the rear of the chassis but this is usually completely taken up due to the chain and chain guard filling the space. An idea is to add a small hole in the right side to increase accessibility but the design criteria relates to just the accessibility of those connection points with a wrench or the spark plug for rules check.

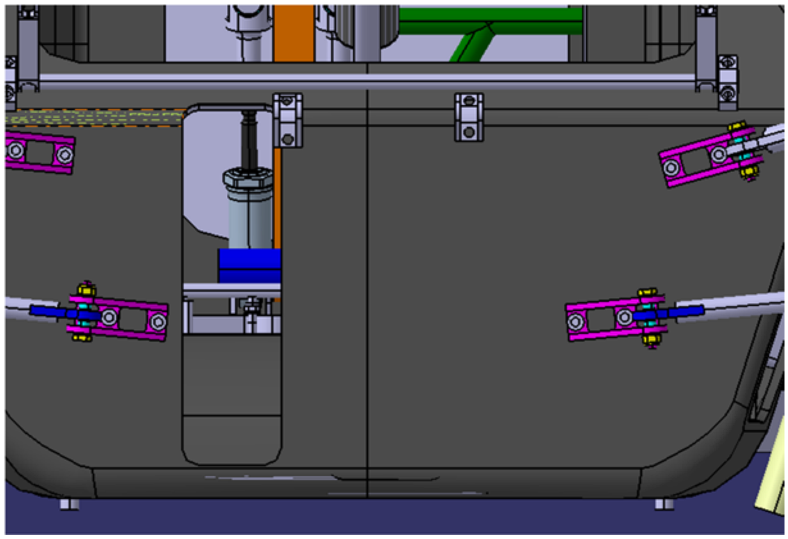


Figure 25 Rear of chassis

Radiator Mounting (cm^2)

This criteria is concerned with how the radiator will be interfaced with the chassis. How the chassis can be connected to the chassis. Again flat and large surfaces are helpful in this. This also relates to the location of mounting and how the cooling and oil tubes will come from inside the chassis and out the rear side holes to the radiator. The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Area for Wiring Interface (cm^2)

Similar to the wiring interface from Suspension Design Criteria section. It is important that the wires are out of the way in the powertrain to allow for easier maintenance as well as during removal that there are minimal wires in front of the motor that get in the way. The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

Side Access holes (cm^2)

Overall how do the access holes for the engine maintenance compare to previous chassis. There are a few holes that are required for basic operation (engine removability) or rules (spark plug measurement) that have been addressed specifically. This criteria is a relationship that considers as a whole how the access holes compare to the previous chassis. For example in Figure 26 the access hole for checking the oil cooler sensor level on the right side of the chassis. This criteria may have to become more specific but for current design stage the high level analysis motto for this matrix will remain. The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

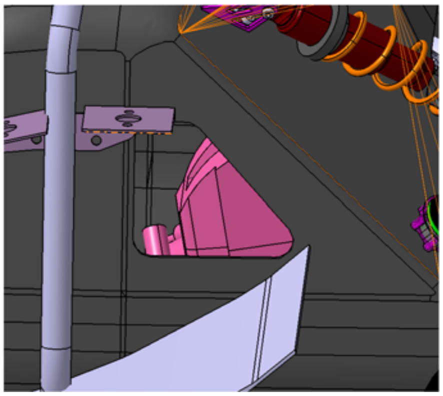


Figure 26 Oil Mounting sensor level check access

ePowertrain Design Criteria

Engine Maintenance Area (cm^2)

The electric motor and gearbox requires the ability to be removed and worked on outside the car. For this reason it is more important for the eCar engine to be removed than the cCar engine and needs to be relatively easy to remove and replace. Related to how the chassis allows for proper and quick engine maintenance.

Engine and Battery Mounting (cm^2)

The location of the mounting of the battery and engine. This can also relate to the orientation of the battery packs within the complete battery configuration but that is a more detailed issue. This is related to how the location and connection of the battery and engine interfaces with the chassis. Currently the hard points have been adapted to have a y-shaped extension to help with mounting of battery and engine. Also, this criteria will be concerned with how the shape and location of the battery can influence the width of the chassis. The “cm^2” does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

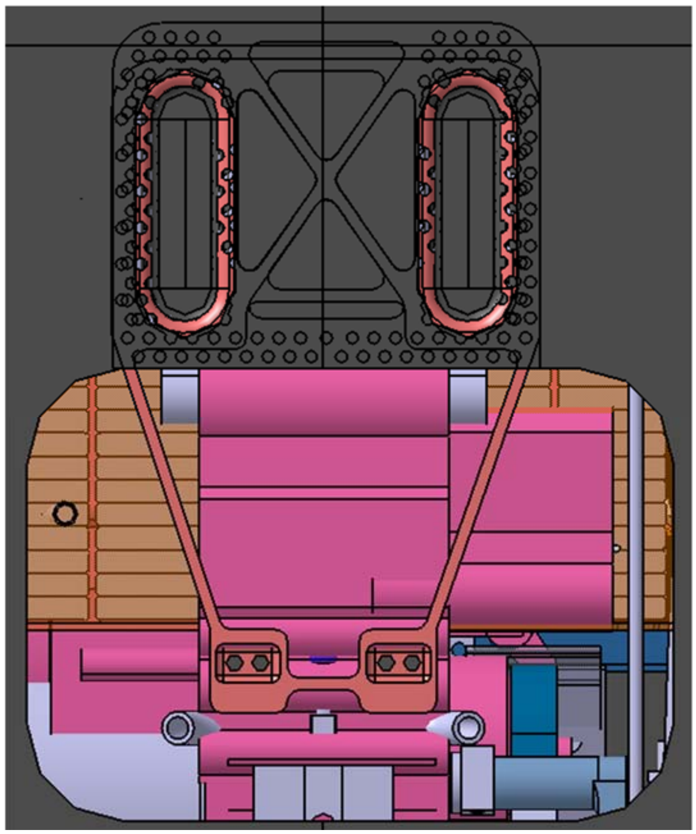


Figure 27 Lower Hard point on Bottom of Current Chassis

Rear close out fire panel configuration (cm^2)

The current seat harness is connected right above the close out panel but inside the chassis. There have been complaints that it is sometimes a problem with the close out panels and the convenience of the two part configuration with the top close out panel as well as the flat rear close out panel. This is more of a preference design criteria but can still be considered as how the rear close out fire panel relates to the accessibility to the engine and components in the rear of the chassis. The "cm^2" does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

eCar side impact Constraints

There are additional side impact constraints on the chassis stiffness requirements surrounding the battery components of the eCar. Previous chassis have been extremely close to, an may have not even of complied with, this rule so it is important to make sure our chassis is qualified for both competition rule subsets.

Wiring Interface (cm^2)

Similar to the wiring interface from Suspension Design Criteria section. It is important that the wires are out of the way in the powertrain to allow for easier maintenance as well as during removal that there are minimal wires in front of the motor that get in the way. The "cm^2" does not necessarily relate to simply having more area, but how the available area on the chassis design caters to the respective design criteria.

9) Implementation

a) Selection Criteria

The selection criteria were roughly the same throughout the entire design phase. The criteria were created from research, familiarizing myself with the car, rules, and asking team members about the struggles with the current car construction. The primary complaint was the sheer time required to design, produce and test the parts on the formula car. It is a well understood concept that constructing a competitive car from nothing is going to be a labor intensive process but many felt like the time required to construct various parts of the car could be drastically reduced, while maintaining the level of quality. Another point of emphasis was the points gained at competition. The car is being built to win and without a competitive car the hours required to complete the car are not worthwhile. The other criteria mentioned often were concerned about the difficulty of producing a part and the required strength of those parts. Many aero sub team members stressed the importance of adaptability of the car so that the aero package could have as much opportunity to utilize the chassis to its full advantage. The powertrain and brake/suspension sub teams were concerned with the ability to access bolt points chassis so that maintenance or tweaks could be made quickly at competition. Cost was also an issue that was reported from people in charge of obtaining sponsors or ordering parts and is included as a criteria. Those seven criteria of points, time, difficulty, strength, adaptability, cost, and accessibility started my list.

For the initial design the plan was to rate every criteria as a comparison to the current chassis. The 2014 chassis is what every team member knows best and have a solid understanding of its intricacies. The potential future design being scored in the matrix would be compared to the current chassis; if the matrix said it was better it would be a viable option, if not, then it should be adjusted or rejected. After discussions with Dr. Paasch, I was reminded that the students and leads change every year and to set up a matrix that compares a future design with the current one is not advisable. GFR currently has a very successful chassis and the plan is to continue that success but a problem lurks in the shadows if a chassis that is built in the future does not meet the team's expectations. In the future, using the design matrix in that scenario would be comparing options to a subpar current chassis. Better than not good enough is not a standard that is tolerable for a decorated and successful GFR team. For this reason the matrix was changed to be independent of the current chassis. The current chassis will still be scored using the matrix and the values in the matrix will be a good benchmark for the future chassis but the individual cells that are filled out are objective and unrelated to the current or previous chassis used. This is when a new selection criteria was added. Even though the whole matrix was not going to be related to an existing chassis there should be a criteria that allows the leads to compare the future chassis to what they currently know. For this reason the "Comparative Relationship" criteria was created. The relationship between past, present and future can still exist but will not dominate the matrix and be the reason for potentially misleading a design selection.

The criteria were selected and finalized to those eight and needed to be weighted. The weighting process involved getting input from the technical leads to see which criteria were most important to them. Figure 28 is the compiled numbers from the leads on their weighting and ranking of the selection criteria. The criteria were weighted from 1-10; 1 being an unimportant criteria that should not be considered heavily and 10 being an extremely important criteria that should be a major influence on the matrix. They were also ranked from 1-8; with 1 being the most important and 8 being least important criteria. The two different ranking systems were in case there was a major discrepancy on the weighting of the selection criteria. If there was a resounding agreement between leads on the weight of a criteria then the relative ranking could be looked at to aid in deciding which way to lean on the final weighting value. Dr. Hoyle provided a paper by Hazelrigg that also provided with tools to help resolve these sorts of disputes. [17]

	Weighting							
	Trevor (Suspension)	Phil (Aero)	Sam (ePow)	Jay (cPow)	Paul (Chassis)	Average	Stan Dev	Rounded
Comparative	8	5	4	7	1	5.0	2.74	5.0
Points	4	10	5	10	7	7.2	2.77	7.0
Time	8	8	10	8	9	8.6	0.89	9.0
Difficulty	10	8	7	8	7	8.0	1.22	8.0
Cost	3	3	5	1	2	2.8	1.48	3.0
Strength	3	2	4	1	5	3.0	1.58	3.0
Adaptability	6	10	6	5	5	6.4	2.07	6.0
Accessibility	6	7	8	10	6	7.4	1.67	7.0
	Rankings							
	Trevor (Suspension)	Phil (Aero)	Sam (ePow)	Jay (cPow)	Paul (Chassis)	Average	Stan Dev	Rounded
Comparative	3	6	8		8	6.3	2.36	6.0
Points	6	2	6		3	4.3	2.06	4.0
Time	2	3	1	1	2	1.8	0.84	2.0
Difficulty	1	4	2	3	1	2.2	1.30	2.0
Cost	8	7	7		7	7.3	0.50	7.0
Strength	7	8	5		4	6.0	1.83	6.0
Adaptability	4	1	3	4	3	3.0	1.22	3.0
Accessibility	5	5	4	3	5	4.4	0.89	4.0

Figure 28 Matrix Weighting Calculations

As seen in the weighting table, there are selection criteria that have large standard deviations. This means that different leads had much different opinions on how important a specific criteria was to the chassis design. For example, the comparative relationship, points and adaptability all have standard deviations above 2. With respect to a scale of ten, that is a large standard deviation. It was important to understand the reason behind the large differences in opinions between the technical leads. For these criteria I went and engaged in a conversation between the leads that had big variance from the average. The comparative relationship criteria was not fully understood by some leads but was accepted at a weight of 5 since that is an appropriate middle of the road weighting that would signify it being compared to last year. For points, some leads took that as involving a specific sub team's ability to influence points compared to other teams. The criteria was created to judge the importance of competition points, which should be a definite focus of the GFR chassis design. The adaptability criteria was harder to resolve the discrepancy of weighting values since each sub team has a different need for accessibility. It was resolved by discussing possible final weighting values and deciding on one that was close to the average but not rounding up from that average, due to the large variation.

The criteria of cost, strength, and accessibility all had standard deviations that were more than desired but also were not too large to expect the average to be unrepresentative of the proper weight. The final two criteria of time and difficulty were both agreed upon on being important criteria. This is expected because one of the main reasons for the re-designed chassis is reducing the manufacturing time and difficulty of it. The difficulty criteria may not have been as defined as it should have been and could be the reason for the higher standard deviation than the time criteria. It is important to stay in an open dialog between the matrix designer and the technical leads to ensure that the data being received is, indeed, in agreement with the philosophy and view of the team.

b) Design Criteria

Selecting design criteria was a process that took more consideration to produce meaningful criteria. A conversation was had with each lead on their respective subsystem of the car. They would run through everything that they deemed important, showing it visually on CATIA and why it was important to them. This provided plenty of ideas of what was important and should be considered in the matrix but the problem lied in the fact that there were too many "important" parts of every subsection of the car. The design matrix is a high level overview of the chassis that should not deal too much with specifics. An excess of design criteria would make the matrix a long and tedious task that would probably be treated as a spreadsheet that should be filled out as fast as possible just to get through it. With too many criteria there is also the danger of over defining the matrix and having less important columns influence the final outcome from the matrix. Too few criteria could cause the matrix to be ineffective and lead to something that an educated team member could discern in a glance.

The process that was taken to reduce design criteria were to write down everything for each sub team and put it on paper. It was then a matter of striking and combining different criteria to the point where it was acceptable. There was a goal of having 4-6 criteria for each sub team. This range fits the “not too many but not too few” theory in order to fully consider each subsection of the car. The first step in refining the design criteria is to combine smaller criteria into a larger, broader, criteria. For example, cPowertrain has a lot of interaction with the back of the car like having openings large enough for the exhaust pipe, chain guard, air intake, etc. as well as being able to perform maintenance on the engine. Instead of having multiple requirements for individual parts that need access to the rear access hole the criteria of “Access Holes” was created to encompass these needs. If a criteria is a non-essential individual need and cannot be grouped with other criteria then it should be taken off the list of criteria. On cPowertrain the engine being attached properly to the chassis would be an essential individual need that needs to be considered but the desire for a larger maintenance hole may have to be considered post matrix. The smaller criteria can still be considered once the basic chassis has been established but it cannot be selected due to having several uniquely beneficial parts.

c) Overall Design

The functionality and use of the design matrix has stayed the same but a layout change has been made due to a recommendation by Dr. Hoyle. The process of having a lead fill out their respective section on the top and then moving down to a row that has a black box sitting in the middle of it was confusing and had the potential for error. The matrix was rearranged so that each lead only has to fill out their own row. The row has an individual weighting associated with each sub team section on the matrix and the lead’s respective subsection has a full weighting while the other sections are corrected so that their opinion is slightly less important than another lead in their respective section. A visual of this can be seen below in Figure 29. This is just the upper left corner of a template matrix that has hidden columns and is for the purpose of displaying the weighting system. The first set of rows is for the chassis lead, the second set of rows for aero and the third set for suspension lead. For their respective sections, the weight being applied to their sections is full power but in the other sections it is multiplied by a factor, in this example that value is ¾.

	Chassis	Weight (g)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)	Rear Wing Aero Connection (cm^2)	Suspension & Brakes
Scoring Criteria	**Importance**	Relative		**Importance**			**Importance**
Lead: Chassis							
Comparative Relationship	5			3.75			3.75
Points	8			6			6
Time	9			6.75			6.75
Difficulty	8			6			6
Cost	2			1.5			1.5
Strength	3			2.25			2.25
Adaptability	6			4.5			4.5
Accessibility	7			5.25			5.25
Sum		0	0		0	0	
Weighted Total		0	0		0	0	
Lead: Aero	**Importance**			**Importance**			**Importance**
Comparative Relationship	3.75			5			3.75
Points	6			8			6
Time	6.75			9			6.75
Difficulty	6			8			6
Cost	1.5			2			1.5
Strength	2.25			3			2.25
Adaptability	4.5			6			4.5
Accessibility	5.25			7			5.25
Sum		0	0		0	0	
Weighted Total		0	0		0	0	
Lead: Suspension	**Importance**			**Importance**			**Importance**
Comparative Relationship	3.75			3.75			5
Points	6			6			8
Time	6.75			6.75			9
Difficulty	6			6			8
Cost	1.5			1.5			2
Strength	2.25			2.25			3
Adaptability	4.5			4.5			6
Accessibility	5.25			5.25			7

Figure 29 Final Design Matrix Weighting

With the weights and layout of the matrix established, the process of filling out the matrix was examined more closely. With the amount of rows and columns in the matrix there were 400 individual cells that were supposed to be filled out by a lead. This is overly daunting and, since some of the selection and design criteria do not relate to each other, it was possible to go through and distinguish certain cells as non-important. To do this the irrelevant boxes were filled with "XXXX". Black highlight could also be used but the text would have to be made colored or else an errant keystroke could throw off the data. Many leads feel that their knowledge is not substantial enough to enter a value into a cell anyways so there may be additional blocked out boxes in different sections, depending on which lead is filling out the matrix. The matrix with preliminary marked boxes is shown below in Figure 30.

	Chassis	Weight (g)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)	Rear Wing Aero Connection (cm^2)	Suspension & Brakes
Scoring Criteria	**Importance**	Relative		**Importance**			**Importance**
Lead: Chassis							
Comparative Relationship	5			3.75			3.75
Points	8			6			6
Time	9		XXXXX	6.75			6.75
Difficulty	8			6			6
Cost	2		XXXXX	1.5	XXXXX	XXXXX	1.5
Strength	3		XXXXX	2.25	XXXXX	XXXXX	2.25
Adaptability	6	XXXXX	XXXXX	4.5			4.5
Accessibility	7	XXXXX	XXXXX	5.25	XXXXX	XXXXX	5.25
Sum		0	0		0	0	
Weighted Total		0	0		0	0	
Lead: Aero	**Importance**			**Importance**			**Importance**
Comparative Relationship	3.75			5			3.75
Points	6			8			6
Time	6.75		XXXXX	9			6.75
Difficulty	6			8			6
Cost	1.5		XXXXX	2	XXXXX	XXXXX	1.5
Strength	2.25		XXXXX	3	XXXXX	XXXXX	2.25
Adaptability	4.5	XXXXX	XXXXX	6			4.5
Accessibility	5.25	XXXXX	XXXXX	7	XXXXX	XXXXX	5.25
Sum		0	0		0	0	
Weighted Total		0	0		0	0	
Lead: Suspension	**Importance**			**Importance**			**Importance**
Comparative Relationship	3.75			3.75			5
Points	6			6			8
Time	6.75		XXXXX	6.75			9
Difficulty	6			6			8
Cost	1.5		XXXXX	1.5	XXXXX	XXXXX	2
Strength	2.25		XXXXX	2.25	XXXXX	XXXXX	3
Adaptability	4.5	XXXXX	XXXXX	4.5			6
Accessibility	5.25	XXXXX	XXXXX	5.25	XXXXX	XXXXX	7

Figure 30 Final Design Matrix with Blocked Out Boxes

10) Testing

Two chassis have been analyzed. The current (2014) chassis and the 2015 chassis design. The matrices feature a sum at the very bottom and an overall average in the bottom right corner. These final five numbers give insight to the matrix, but there are two whose value are more important because of the weighting. With the input of the leads on the two chassis, the final value from the design matrix confirms the initial thoughts of the leads on the new chassis.

Final Sum	75
Final Average Sum	22
Final Weighted Total	400
Average Weighted Per Cell	32
Final Average Weighted	120
	Final Average

Figure 31 2015 Design Matrix Results

Final Sum	64
Final Average Sum	19
Final Weighted Total	344
Average Weighted Per Cell	26
Final Average Weighted	100
	Final Average

Figure 32 2014 Design Matrix Results

The parameters listed on the left side are defined as follows:

Final Sum: Average of the sum of all values imputed but not multiplied by weight in a section.

Final Average Sum: Average (unweighted) sum of one column in the matrix

Final Weighted Total: Average weighted sum of a section of the matrix

Average Weighted Per Cell: Cells weighted, added and then divided by number of cells that were filled out in a column.

Final Average Weighted: Average Weighted value of a column in the matrix

The results from this show that the 2015 chassis is a definite improvement from the 2014 chassis according to the leads and the design matrix. The final sum is the average sum of each sub team section. The 2015 chassis has been designed to be functional in the ways that the leads see fit so it is understandable that the 2015 chassis should score better, but it is also proof the chassis that has been designed to be better than the 2014 chassis. By individually ranking pieces of the chassis in a design matrix it is more difficult to let a bias influence the outcome. On an overall scale a person may think the chassis will be better, but when scoring each subsection individually it will provide a less biased result. I was strongly advised not to switch around weighting values in order to get the desired result and, in this case, that practice was thankfully avoided. The weights that were obtained from the weighting process were correct the first time. After the results had been calculated the weights were changed around slightly to see what would happen. The difference between the two chassis changed but the 2015 chassis consistently outscored the 2014 chassis.

a) 2015 Design Matrix

GFR 15 Chassis	Chassis	Weight (g)	Manufacturing (hours)	Carbon Weave Material	Honeycomb Material (N/mm)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)	Chassis Width (cm)	Front Aero Wing Connection (cm^2)	Side Aero Connection (cm^2)	Rear Wing Aero Connection (cm^2)	Suspension & Brakes	Kinematics	Connection Surfaces (cm^2 & angle)	Brake Wiring (cm of clearance)	Foot and Pedal Area (cm^2)	Ergon Se Con (
Selection Criteria	Importance	Importance Factor	0.75				Importance						Importance					
Lead: Chassis			Lead: Chassis							Lead: Chassis								
Comparative Relationship	5	8	8	6	7	5	3.75	2	5	6	7	3	3.75	5	8	7	7	
Points	8	8	9	5	5	5	6	2	2	6	5	3	6	5	XXXXX	XXXXX	XXXXX	
Time	9	5	8	7	7	XXXXX	6.75	2	2	3	8	3	6.75	XXXXX	8	XXXXX	XXXXX	XXXX
Difficulty	8	5	8	7	6	5	6	2	2	3	8	3	6	8	8	5	6	
Cost	2	7	XXXXX	5	7	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Strength	3	6	XXXXX	6	7	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	8	XXXXX	XXXXX	XXXX
Adaptability	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	1	1	6	7	3	4.5	6	7	6	7	
Accessibility	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	8	8	7	XXXX
Sum		39	33	36	39	15		9	12	24	35	15		24	47	26	27	
Weighted Total	1012	221	248	217	221	105	504.75	49.5	60.75	123.75	189.75	81	722.25	123.75	223.5	125.25	130.5	
Lead: Aero	Importance			Lead: Aero			Importance			Lead: Aero			Importance					
Comparative Relationship	3.75	6	7	5	6	5	6	5	7	6	8	5	3.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Points	6	8	7	5	6	6	8	6	4	4	7	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Time	6.75	9	6	6	6	XXXXX	9	5	5	5	7	5	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Difficulty	6	6	8	6	7	6	8	5	4	4	7	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Cost	1.5	5	XXXXX	5	5	XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Strength	2.25	6	XXXXX	5	6	XXXXX	3	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	4	5	6	8	5	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Sum		40	28	32	36	17		25	25	25	37	25		0	0	0	0	
Weighted Total	741.75	188.25	156.75	144	162	90.75	974	182	174	175	263	180	0	0	0	0	0	
Lead: Suspension	Importance			Lead: Suspension			Importance			Lead: Suspension			Importance					
Comparative Relationship	3.75	5	10	9	9	6	3.75	XXXXX	4	7	8	XXXXX	5	5	6	7	6	
Points	6	7	XXXXX	XXXXX	XXXXX	6	6	XXXXX	4	XXXXX	XXXXX	XXXXX	8	5	XXXXX	XXXXX	XXXXX	XXXX
Time	6.75	9	9	XXXXX	9	XXXXX	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	9	XXXXX	6	XXXXX	XXXXX	
Difficulty	6	XXXXX	9	XXXXX	8	XXXXX	6	XXXXX	XXXXX	XXXXX	8	XXXXX	8	8		9	7	
Cost	1.5		XXXXX	XXXXX	5	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Strength	2.25	8	XXXXX	XXXXX	7	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	3	XXXXX	7	XXXXX	XXXXX	XXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	XXXXX	XXXXX	XXXXX		XXXXX	6	8	8	9	7	
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX	8	9	8	XXXX
Sum		29	28	9	38	12		0	8	7	16	0		26	35	34	28	
Weighted Total	549.75	139.5	152.25	33.75	165.75	58.5	143.25	0	39	26.25	78	0	946	177	209	224	184	
Lead: ePow	Importance			Lead: ePow			Importance			Lead: ePow			Importance					
Comparative Relationship	3.75	7	8	7	7	6	3.75	5	5	6	5	6	3.75	6	7	6	6	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Time	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Difficulty	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXX
Sum		7	8	7	7	6		5	5	6	5	6		6	7	6	6	
Weighted Total	131.25	26.25	30	26.25	26.25	22.5	101.25	18.75	18.75	22.5	18.75	22.5	120	22.5	26.25	22.5	22.5	
Final Sum	93	115	97	84	120	50	58	39	50	62	93	46	65	56	89	66	61	
Final Average Sum	23	29	24	21	30	13	16	13	13	16	23	15	22	19	30	22	20	
Final Weighted Total	487	575	587	421	575	276.75	345	250.25	292.5	347.5	549.5	283.5	358	323.25	458.75	371.75	337	297.5
Average Weighted Per Cell	35	34	49	30	32	31	28	23	23	29	42	26	37	36	38	41	37	33
Final Average Weighted	121.7	143.8	146.8	105.3	143.8	69.2	95.1	83.4	73.1	86.9	137.4	94.5	119.2	107.8	152.9	123.9	112.3	99.2
	Average						Average						Average					

Figure 33 2015 Design Matrix

GFR 15 Chassis	CPowertrain	Engine Connection and Removability (cm^2)	Engine Maintenance Access (cm^2)	Area for Wiring Interface (cm^2)	Side & Rear Access Holes (cm^2)	Radiator Mounting (cm^2)	ePowertrain	Engine Matinence Acess (cm^2)	Engine and Battery Location/ Mounting (mm)	Rear Close out Fire Panel Configuration	eCar Side Impact Constraints	Area for Wiring Interface	
Selection Criteria													
Lead: Chassis	Importance				Lead: Chassis		Importance				Lead: Chassis		
Comparative Relationship	3.75	6	7	6	6	7	3.75	4	6	XXXXX	7	5	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	7	5	XXXXX	6	7	6.75	5	7	XXXXX	5	XXXXX	
Difficulty	6	7	5	8	4	8	6	5	7	XXXXX	6	5	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	5	1.5	XXXXX	XXXXX	XXXXX	5	XXXXX	
Strength	2.25	8	XXXXX	XXXXX	5	XXXXX	2.25	XXXXX	5	XXXXX	4	XXXXX	
Adaptability	4.5	5	6	5	6	8	4.5	5	8	XXXXX	7	5	
Accessibility	5.25	8	6	5	5	5	5.25	2	4	XXXXX	XXXXX	5	
Sum		41	29	24	32	45		21	37	0	34	20	
Weighted Total	834.75	194.25	148.5	119.25	151.5	221.25	533.25	111.75	180	0	144	97.5	
Lead: Aero	Importance				Lead: Aero		Importance				Lead: Aero		
Comparative Relationship	3.75	XXXXX	5	XXXXX	XXXXX	6	3.75	5	5	XXXXX	XXXXX	XXXXX	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	6	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	XXXXX	6	XXXXX	XXXXX	6	6.75	6	5	XXXXX	XXXXX	XXXXX	
Difficulty	6	XXXXX	6	XXXXX	XXXXX	6	6	6	5	XXXXX	XXXXX	XXXXX	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	5	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX		XXXXX	XXXXX	XXXXX	
Adaptability	4.5	XXXXX	5	XXXXX	XXXXX	7	4.5	5	5	XXXXX	XXXXX	XXXXX	
Accessibility	5.25	XXXXX	6	XXXXX	XXXXX	6	5.25	6	5	XXXXX	XXXXX	XXXXX	
Sum		0	28	0	0	42		28	25	0	0	0	
Weighted Total	364.75	0	149.25	0	0	205.5	280.5	149.25	131.25	0	0	0	
Lead: Suspension	Importance				Lead: Suspension		Importance				Lead: Suspension		
Comparative Relationship	3.75	5	4	6	5	7	3.75	4	7	XXXXX	8	6	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	5	4	XXXXX	XXXXX	7	6.75	XXXXX	7	XXXXX	7	XXXXX	
Difficulty	6	5	3	XXXXX	7	XXXXX	6	XXXXX	7	XXXXX	8	5	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	5	XXXXX	
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	6	XXXXX	5	XXXXX	
Adaptability	4.5	XXXXX	3	5	8	8	4.5	8	8	XXXXX	8	XXXXX	
Accessibility	5.25	XXXXX	XXXXX	XXXXX	5	5	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Sum		15	14	11	25	27		12	35	0	41	11	
Weighted Total	459.75	82.5	73.5	45	123	135.75	448.5	51	165	0	180	52.5	
Lead: ePow	Importance				Lead: ePow		Importance				Lead: ePow		
Comparative Relationship	3.75	7	7	6	6	5	5	6	6	6	8	6	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	8	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	9	5	6	6	7	XXXXX	
Difficulty	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	8	5	6	5	5	7	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2	XXXXX	XXXXX	XXXXX	6	XXXXX	
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	3	XXXXX	7	XXXXX	8	XXXXX	
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	5	7	7	5	6	
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	5	5	7	5	6	
Sum		7	7	6	6	5		26	37	31	44	25	Average of Totals
Weighted Total	116.25	26.25	26.25	22.5	22.5	18.75	1033	180	230	215	244	164	
Final Sum	73	63	78	41	63	119	85	87	134	31	119	56	75
Final Average Sum	21	21	20	14	21	30	29	22	34	31	40	19	22
Final Weighted Total	353	303	397.5	186.75	297	581.25	459	492	706.25	215	568	314	400
Average Weighted Per Cell	28	30	27	27	27	31	33	29	32	43	30	31	32
Final Average Weighted	101.4	101.0	99.4	62.3	99.0	145.3	162	123.0	176.6	215.0	189.3	104.7	120
	Average						Average						Final

Figure 34 2015 Design Matrix continued

b) 2014 Design Matrix

GFR 14 Chassis	Chassis	Weight (g)	Manufacturing	Carbon Weave Material	Honeycomb Material (N/mm)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)	Chassis Width (cm)	Front Aero Wing Connection (cm^2)	Side Aero Connection (cm^2)	Rear Wing Aero Connection (cm^2)	Suspension & Brakes	Kinematics	Connection Surfaces (cm^2 & angle)	Brake Wiring (cm of clearance)	Interior Foot and Pedal Area (cm^2)	Driver Ergonomics and Seat Belt Configuration (cm^2)
Selection Criteria	Importance	Importance Fac	0.75				Importance						Importance					
Lead: Chassis			Lead: Chassis							Lead: Chassis								
Comparative Relationship	5	6	5	6	4	5	3.75	2	5	5	4	5	3.75	7	6	6	6	7
Points	8	7	7	5	5	5	6	2	5	6	4	4	6	7	XXXXX	XXXXX	XXXXX	XXXXX
Time	9	5	4	7	6	XXXXX	6.75	2		6	2	4	6.75	XXXXX	5	XXXXX	XXXXX	7
Difficulty	8	3	4	7	6	5	6	2	5	4	3	5	6	6	5	3	6	4
Cost	2	5	XXXXX	5	5	XXXXX	1.5	XXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	3	3	XXXXX	6	4	XXXXX	2.25	XXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	8	XXXXX	XXXXX	XXXXX
Adaptability	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	1	4	5	5	5	4.5	5	8	5	4	1
Accessibility	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	7	5	4	XXXXX
Sum		29	20	36	30	15		9	19	26	18	23		25	39	19	20	19
Weighted Total	829	174	149	217	184	105	503.25	49.5	96.75	141.75	93	122.25	592.5	126.75	177	89.25	97.5	102
Lead: Aero	Importance			Lead: Aero			Importance			Lead: Aero			Importance					
Comparative Relationship	3.75	5	7	5	6	5	5	3	4	5	6	5	3.75	XXXXX	XXXXX	XXXXX	6	XXXXX
Points	6	10	7	5	6	6	8	3	3	4	5	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75	9	10	6	6	XXXXX	9	3	3	4	2	5	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Difficulty	6	8	9	6	7	5	8	2	3	3	2	5	6	XXXXX	XXXXX	XXXXX	7	XXXXX
Cost	1.5	7	XXXXX	5	5	XXXXX	2	XXXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25	2	XXXXX	5	6	XXXXX	3	XXXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	2	2	6	3	5	4.5	XXXXX	XXXXX	XXXXX	6	XXXXX
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	6	XXXXX
Sum		41	33	32	36	16		13	15	22	18	25		0	0	0	25	0
Weighted Total	783	202.5	189.75	144	162	84.75	656	94	107	153	122	180	123	0	0	0	123	0
Lead: Suspension	Importance			Lead: Suspension			Importance			Lead: Suspension			Importance					
Comparative Relationship	3.75	5	7	5	5	5	3.75	XXXXX	5	4	3	XXXXX	5	5	3	5	6	5
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	8	5	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75	XXXXX	4	XXXXX	XXXXX	XXXXX	6.75	XXXXX	XXXXX	4	4	XXXXX	9	5	4	XXXXX	XXXXX	5
Difficulty	6	XXXXX	4	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	5	3	XXXXX	8	3	5	5	6	5
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXXX	XXXXX	XXXXX	XXXXX	XXXXX	3	XXXXX	5	XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	XXXXX	XXXXX	4	4	XXXXX	6	3	4	3	3	5
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX	XXXXX	3	5	XXXXX
Sum		5	15	5	5	10		0	5	17	14	0		21	21	16	20	20
Weighted Total	182.25	18.75	77.25	18.75	18.75	48.75	183	0	18.75	90	74.25	0	657	152	130	104	131	140
Lead: ePow	Importance			Lead: ePow			Importance			Lead: ePow			Importance					
Comparative Relationship	3.75	7	5	5	XXXXX	7	3.75	5	3	5	5	5	3.75	6	5	5	4	4
Points	6	5	XXXXX	2	XXXXX	6	6	XXXXX	3	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75	5	5	4	XXXXX	XXXXX	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Difficulty	6	5	5	4	XXXXX	5	6	XXXXX	3	XXXXX	XXXXX	XXXXX	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Cost	1.5	5	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25	6	XXXXX	7	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5	XXXXX		XXXXX	XXXXX	XXXXX	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Sum		33	15	22	0	18		5	9	5	5	5		6	5	5	4	4
Weighted Total	413.25	141	82.5	97.5	0	92.25	122.25	18.75	47.25	18.75	18.75	18.75	90	22.5	18.75	18.75	15	15
Final Sum	83	108	83	95	71	59	51	27	48	70	55	53	54	52	65	40	69	43
Final Average Sum	22	27	21	24	24	15	14	9	12	18	14	18	17	17	22	13	17	14
Final Weighted Total	442	536	499	477	365	331	293	162	270	404	308	321	293	301	326	212	367	257
Average Weighted Per Cell	30	28	36	27	28	30	22	15	21	27	21	29	28	30	27	24	28	29
Final Average Weighted	116	134	125	119	122	83	81	54	67	101	77	107	91	100	109	71	92	86
	Average						Average						Average					

Figure 35 2014 Design Matrix

GFR 14 Chassis	CPowertrain	Engine Connection and Removability (cm^2)	Engine Maintenance Access (cm^2)	Area for Wiring Interface (cm^2)	Side & Rear Access Holes (cm^2)	Radiator Mounting (cm^2)	ePowertrain	Engine Matinence Acess (cm^2)	Engine and Battery Location/ Mounting (mm)	Rear Close out Fire Panel Configuration & Removability	eCar Side Impact Constraints	Area for Wiring Interface	
Selection Criteria													
Lead: Chassis	Importance				Lead: Chassis		Importance				Lead: Chassis		
Comparative Relationship	3.75	7	7	6	6	4	3.75	4	4	5	4	4	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	5	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	7	5	XXXXX	6	4	6.75	5	6	4	6	XXXXX	
Difficulty	6	7	5	8	4	4	6	5	6	4	6	6	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX		XXXXX	
Strength	2.25	6	XXXXX	XXXXX	5	XXXXX	2.25	XXXXX		XXXXX		XXXXX	
Adaptability	4.5	3	6	5	6	6	4.5	5	6	4	3	5	
Accessibility	5.25	7	6	5	5	5	5.25	2	4	4	XXXXX	4	
Sum		37	29	24	32	28		21	26	21	19	19	
Weighted Total	747.75	179.25	148.5	119.25	151.5	149.25	569.5	111.75	139.5	108.75	105	94.5	
Lead: Aero	Importance				Lead: Aero		Importance				Lead: Aero		
Comparative Relationship	3.75	XXXXX	4	XXXXX	5	7	3.75	4	XXXXX	XXXXX	XXXXX	XXXXX	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	XXXXX	5	XXXXX	4	4	6.75	5	XXXXX	XXXXX	XXXXX	XXXXX	
Difficulty	6	XXXXX	4	XXXXX	4	3	6	4	XXXXX	XXXXX	XXXXX	XXXXX	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Strength	2.25	XXXXX	XXXXX	XXXXX	5	XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Adaptability	4.5	XXXXX	5	XXXXX	5	4	4.5	5	XXXXX	XXXXX	XXXXX	XXXXX	
Accessibility	5.25	XXXXX	4	XXXXX	4	5	5.25	4	XXXXX	XXXXX	XXXXX	XXXXX	
Sum		0	22	0	27	23		22	0	0	0	0	
Weighted Total	356.25	0	116.25	0	124.5	115.5	116.25	116.25	0	0	0	0	
Lead: Suspension	Importance				Lead: Suspension		Importance				Lead: Suspension		
Comparative Relationship	3.75	6	7	5	5	3	3.75	2	3	XXXXX	4	6	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	5	7	XXXXX	4	2	6.75	XXXXX	5	XXXXX	4	XXXXX	
Difficulty	6	5	8	4	4	3	6	XXXXX	5	XXXXX	5	5	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	5	XXXXX	
Strength	2.25	5	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX	5	XXXXX	5	XXXXX	
Adaptability	4.5	4	4	XXXXX	5	3	4.5	5	4	XXXXX	5	XXXXX	
Accessibility	5.25	3	6	XXXXX	5	5	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Sum		28	32	9	23	16		7	22	0	28	11	
Weighted Total	546	131.25	171	42.75	118.5	82.5	300	30	104.25	0	113.25	52.5	
Lead: ePow	Importance				Lead: ePow		Importance				Lead: ePow		
Comparative Relationship	3.75	7	7	5	5	4	5	3	2	4	6	5	
Points	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	8	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Time	6.75	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	9	4	5	5	4	XXXXX	
Difficulty	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	8	4	5	5	3	4	
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
Strength	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	3	XXXXX	4	XXXXX	7	XXXXX	
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6	5	5	3	3	6	
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	4	4	4	2	5	
Sum		7	7	5	5	4		20	25	21	25	20	Final Average
Weighted Total	105	26.25	26.25	18.75	18.75	15	728	141	165	151	143	128	
Final Sum	72	72	90	38	87	71	61	70	73	42	72	50	64
Final Average Sum	20	24	23	13	22	18	21	18	24		24	17	19
Final Weighted Total	351	337	462	181	413	362	341	399	409	260	361	275	344
Average Weighted Per Cell	25	26	29	26	23	21	25	23	26	26	23	28	26
Final Average Weighted	96	112	116	60	103	91	116	100	136	130	120	92	100
	Average						Average						

Figure 36 2014 Design Matrix continued

c) Discussion

It is important to understand the results of the matrices and use the information to influence possible refinements to the chassis design. One way in which it can be useful is confirming that a key factor for the redesign of the chassis is addressed. For this chassis the manufacturing time of the chassis was extremely important to the team. The manufacturing time, according to the design matrix, will be greatly improved for the 2015 chassis. Although the improvement may be able to be increased, it still represents a verified improvement and reason to continue with this particular design concept. The design matrix can also be used to spot potential lapses in design of a subsection as a whole.

For example, in the 2014 Chassis the front, side, and rear wing aero connection received a score of 27, 21, and 29, respectively, for average weighted score. The 2015 chassis received scores of 29, 42, and 26 in the same, respective, categories. This shows that the new chassis has a much better relationship with side aero connections, slightly better front connections, and inferior connections for the rear aerodynamic abilities than the 2014 chassis. This result is useful in identifying a possible area of the chassis that should be looked at again. Although there is a large increase in the side connections, the unimpressive results from the rest of the aerodynamic connections may outweigh the improvements to the side. If it is reexamined and the side connections will make the car much better despite the other areas of aero, then the design is okay and does not have to be refined. It is possible that some small adjustments to the front and rear connection points could be changed in order to increase the overall effectiveness of the aerodynamics, instead of just the side.

Another example of the design matrix being able to provide insight to a certain aspect of the car is the information shown in the cPowertrain section. The engine maintenance access criteria for the 2015 chassis is ranked lower than the 2014, the area for wiring interface, side & rear access holes are only slightly better for the 2015 chassis and the radiator mounting criteria is noticeably better than the 2014 chassis. The fact that there is not much of an improvement from last year to this year in the cPowertrain section could indicate a variety of things about the future design. It could be that the powertrain section of the chassis did not need improvement from the past years or that even if it didn't need improvement, the improvement to cPowertrain was less important than improving other sections of the car. Another possibility is that the improvement to the cPowertrain is lacking and that there needs to be more improvement in the future design. Whatever the reason is, it is important to realize this potential issue and look at that section of the car.

11) Conclusion

a) Final Matrix

The Design matrix is posted below and includes the final layout with selection and design criteria as well as the weighting of the selection criteria and the cells with unrelated criteria. A lead may still "XXXX" out a cell if he or she feels that they cannot provide an educated value into the matrix or, if in their mind, the selection and design criteria are unrelated.

GFR Chassis Selection Matrix Template	Chassis	Weight (g)	Manufacturing	Carbon Weave Material	Honeycomb Material (N/mm)	Center of Gravity Height (mm)	Aero	Aerodynamic Performance of Chassis (Drag N)	Chassis Width (cm)	Front Aero Wing Connection (cm^2)	Side Aero Connection (cm^2)	Rear Wing Aero Connection (cm^2)	Suspension & Brakes	Kinematics	Connection Surfaces (cm^2 & angle)	Brake Wiring (cm of clearance)	Foot and Pedal Area (cm^2)	Driver Ergonomics and Seat Belt Configuration (cm^2)
Scoring Criteria	Importance	Importance Factor	0.75				Importance						Importance					
Lead: Chassis			Lead: Chassis							Lead: Chassis								
Comparative Relationship	5						3.75						3.75					
Points	8						6						6		XXXXX	XXXXX	XXXXX	XXXXX
Time	9					XXXXX	6.75						6.75	XXXXX		XXXXX	XXXXX	
Difficulty	8						6						6					
Cost	2		XXXXX			XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	3		XXXXX			XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX		XXXXX	XXXXX	XXXXX
Adaptability	6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5						4.5					
Accessibility	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX				XXXXX
Sum		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Lead: Aero	Importance			Lead: Aero			Importance			Lead: Aero			Importance					
Comparative Relationship	3.75						5						3.75					
Points	6						8						6		XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75					XXXXX	9						6.75	XXXXX		XXXXX	XXXXX	
Difficulty	6						8						6					
Cost	1.5		XXXXX			XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25		XXXXX			XXXXX	3	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX		XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	6						4.5					
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX				XXXXX
Sum		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lead: Suspension	Importance			Lead: Suspension			Importance			Lead: Suspension			Importance					
Comparative Relationship	3.75						3.75						5					
Points	6						6						8		XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75					XXXXX	6.75						9	XXXXX		XXXXX	XXXXX	
Difficulty	6						6						8					
Cost	1.5		XXXXX			XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25		XXXXX			XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	3	XXXXX		XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5						6					
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	7	XXXXX				XXXXX
Sum		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lead: cPow	Importance			Lead: cPow			Importance			Lead: cPow			Importance					
Comparative Relationship	3.75						3.75						3.75					
Points	6						6						6		XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75					XXXXX	6.75						6.75	XXXXX		XXXXX	XXXXX	
Difficulty	6						6						6					
Cost	1.5		XXXXX			XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25		XXXXX			XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX		XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5						4.5					
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX				XXXXX
Sum		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Lead: ePow	Importance			Lead: ePow			Importance			Lead: ePow			Importance					
Comparative Relationship	3.75						3.75						3.75					
Points	6						6						6		XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75					XXXXX	6.75						6.75	XXXXX		XXXXX	XXXXX	
Difficulty	6						6						6					
Cost	1.5		XXXXX			XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	1.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Strength	2.25		XXXXX			XXXXX	2.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	2.25	XXXXX		XXXXX	XXXXX	XXXXX
Adaptability	4.5	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	4.5						4.5					
Accessibility	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	5.25	XXXXX				XXXXX
Sum		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0		0	0	0	0	0
Final Sum																		
Final Average Sum																		
Final Weighted Total																		
Average Weighted Per Cell																		
Final Average Weighted																		
	Average						Average						Average					

Figure 37 Final Matrix Design

GFR Chassis Selection Matrix Template	CPowertrain	Engine Connection and Removability (cm^2)	Engine Maintenance Access (cm^2)	Area for Wiring Interface (cm^2)	Side & Rear Access Holes (cm^2)	Radiator Mounting (cm^2)	ePowertrain	Engine Matinence Acess (cm^2)	Engine and Battery Location/ Mounting (mm)	Rear Close out Fire Panel Configuration	eCar Side Impact Constraints	Area for Wiring Interface
Scoring Criteria												
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75			XXXXX			6.75					XXXXX
Difficulty	6						6					
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX		1.5	XXXXX	XXXXX	XXXXX		XXXXX
Strength	2.25		XXXXX	XXXXX		XXXXX	2.25	XXXXX		XXXXX		XXXXX
Adaptability	4.5						4.5					
Accessibility	5.25						5.25				XXXXX	
Sum		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0
Lead: Aero	Importance				Lead: Aero		Importance				Lead: Aero	
Comparative Relationship	3.75						3.75					
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75			XXXXX			6.75					XXXXX
Difficulty	6						6					
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX		1.5	XXXXX	XXXXX	XXXXX		XXXXX
Strength	2.25		XXXXX	XXXXX		XXXXX	2.25	XXXXX		XXXXX		XXXXX
Adaptability	4.5						4.5					
Accessibility	5.25						5.25				XXXXX	
Sum		0	0	0	0	0		0	0	0	0	0
Weighted Total	0	0	0	0	0	0	0	0	0	0	0	0
Lead: Suspension	Importance				Lead: Suspension		Importance				Lead: Suspension	
Comparative Relationship	3.75						3.75					
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75			XXXXX			6.75					XXXXX
Difficulty	6						6					
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX		1.5	XXXXX	XXXXX	XXXXX		XXXXX
Strength	2.25		XXXXX	XXXXX		XXXXX	2.25	XXXXX		XXXXX		XXXXX
Adaptability	4.5						4.5					
Accessibility	5.25						5.25				XXXXX	
Sum		0	0	0	0	0		0	0	0	0	0
Weighted Total	0	0	0	0	0	0	0	0	0	0	0	0
Lead: cPow	Importance				Lead: cPow		Importance				Lead: cPow	
Comparative Relationship	5						3.75					
Points	8	XXXXX	XXXXX	XXXXX	XXXXX		6	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	9			XXXXX			6.75					XXXXX
Difficulty	8						6					
Cost	2	XXXXX	XXXXX	XXXXX	XXXXX		1.5	XXXXX	XXXXX	XXXXX		XXXXX
Strength	3		XXXXX	XXXXX		XXXXX	2.25	XXXXX		XXXXX		XXXXX
Adaptability	6						4.5					
Accessibility	7						5.25				XXXXX	
Sum		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0
Lead: ePow	Importance				Lead: ePow		Importance				Lead: ePow	
Comparative Relationship	3.75						5					
Points	6	XXXXX	XXXXX	XXXXX	XXXXX		8	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX
Time	6.75			XXXXX			9					XXXXX
Difficulty	6						8					
Cost	1.5	XXXXX	XXXXX	XXXXX	XXXXX		2	XXXXX	XXXXX	XXXXX		XXXXX
Strength	2.25		XXXXX	XXXXX		XXXXX	3	XXXXX		XXXXX		XXXXX
Adaptability	4.5						6					
Accessibility	5.25						7				XXXXX	
Sum		0	0	0	0	0		0	0	0	0	0
Weighted Total		0	0	0	0	0		0	0	0	0	0
Final Sum												
Final Average Sum												
Final Weighted Total												
Average Weighted Per Cell												
Final Average Weighted												
	Average						Average					

Figure 38 Final Matrix Design continued

b) Analysis

The GFR design process has evolved greatly since the design of the first carbon fiber chassis. The current process is being documented in a more concise fashion in order to guide future teams. This progress is important in order to help GFR continue its excellence in competition and with the engineering education. The Pugh style design matrix will help document this design process.

The design matrix confirms that, as an overall product, the 2015 design will be a better chassis for the GFR team. The lower score of rear aero interfacing mentioned above is one of the few cases where the 2014 chassis scored better than the 2015 design. Every sub team section of the 2015 chassis has a higher weighted score than the 2014 chassis which proves that the technical leads hopes of creating a better chassis moving forward is a realistic possibility and is confirmed by the design matrix. The design matrix proved to be successful in comparing the 2014 and 2015 chassis designs. Although the 2015 chassis has not been built or driven yet the design is one that sacrifices little but gains time and convenience. This extra time and lack of difficulty will allow for extra track time and therefore more tests and improvements to the car. The 2015 chassis will prove to be a step up for the GFR team in the future.

The advantage of the design matrix is that it is able to discern which parts of the chassis are better or worse than other options and to what degree they are different. As discussed above in the testing section, the aero section had an overall better score for the 2015 chassis. There are, however, specific parts of the aero section that are not as big of improvements as desired and should be re-evaluated. Also, the cPowertrain section does not show a large improvement from last year. This may be an acceptable result from the new chassis design, but if not, this is an area of the chassis that should be re-evaluated. These situations are the ones where the design matrix is helpful to display the improvement of a sub team's ability to improve performance, even though specific parts of that sub team may be worse than before. Analyzing the relative increases between sub team sections is one way that the design matrix can show the relationship between the 2014 and 2015 chassis. The suspension section shows an improvement of 9 points average per weighted cell while the combustion powertrain shows an increase of only 3 points. Is the greater increase in suspension side worth the smaller increase in the cPow sub team? The answer may be yes, but the matrix aids in the raising the question that may otherwise not be posed. The chassis sub team shows an increase of only 5 points on average weighted per cell but shows an increase of 13 points for manufacturing time, a major factor for the new chassis design. Although the overall increase of the chassis subtend section is not as large as what may be expected, the increase in the specific criteria relevant to the time taken for construction shows tremendous increase.

This raises a problem with the current status of the design matrix. The meaning of the relative scores between chassis is currently undefined. Saying that there is an increase in points between the two chassis does not have a tangible or established value. This is what will come from continued testing of chassis designs with the matrix and the construction of those designs. It is obvious that an increase of 10 is better than an increase of 5 but the question of how beneficial an increase of 10 points is to the GFR team remains. With the completion of the 2015 chassis these point values may be able to be better established. By having hands on experience with a new chassis design it will be easier to understand the true meaning of an increase in value in the matrix. It is the ultimate goal to understand the meaning between an increase in matrix value and a gain in points. If this relationship could be established, the matrix could prove to be invaluable. To understand that an increase of “x” in the matrix could lead to an increase of “y” amount of points would help the GFR team optimize the chassis to increase points in competition. Although the results of the average of the averages is shown above, it is important to be cautious in using this final number as the guiding number. It is a good indication of the overall performance of a chassis design and a good place to look to get an overview, but should be used with caution since an average of so much information can be misleading.

Another downfall of this project is the limited number of chassis available to test with the matrix. The 2015 chassis design is the result of many different iterations and combinations of different chassis. Because of this, the technical leads do not have ample experience with each individual chassis iteration to provide an educated opinion about many of the other options. Since the 2015 chassis has been narrowed down, there are no other well developed chassis designs that are available. The leads have the most knowledge of the 2014 chassis and have dealt with it firsthand. They have encountered the struggles and intricacies of the chassis. Even with a developed concept of the 2015, chassis the level of detail in some areas is not as specific as one might hope while filling out a design matrix. Fortunately, this design matrix is high level and does not depend on the intricacies a completely finalized chassis design.

The design project and thesis report has shown me how an engineering design project, and the research associated with it, can benefit the team. Through the research I have learned that there are many different ideas and concepts for engineering design matrices. Some that may prove useful for design analysis and others that would not. One thing that has become clear through this process is how easy it can be to over define a project and create a product that will not be useful. Creating a product that is designed to be used in the future cannot be overly specific so that it can adapt to change. A change in philosophy or opinion could spur the need to redefine or change parts of an overly defined matrix.

Another lesson learned from this project is the necessity of communication throughout the design and development process. This project relied on the combination of the technical lead's ideas. It was my job to simply gather those ideas and put them into a format that could benefit the team. This made it imperative to communicate with them and make sure that the matrix that was being built reflected the views of the leads. At times I felt extremely connected and on the same page with them, and at other times I felt as if there was a disconnect. Much of this came throughout the weeks prior to the Michigan competition when the team is very busy preparing the car and there is not too much concern but the production of next year's car. If there was ever a problem or misunderstanding, the longer I would wait to talk to the leads, the longer I would go without working on the matrix. The reason for some of these misunderstandings was the lack of clarity in some of the directions given to the tech leads. When I asked them to weight the different criteria it became clear that each TA had a slightly different understanding of the criteria and weighted them differently than if they fully understood what was being asked of them. Another example is when I asked the leads to fill out the matrix I gave them information on the way to score each cell (with a value of 1-10). They came across cells that did not have any meaning to them (the ones that were eventually filled with “XXXX”) and got confused when they were being prompted to provide a score for it. The research involved in this project demonstrated the need for clear and concise instructions while maintaining a constant stream of communication.

From reflecting upon the mistakes made throughout the process it triggers the question of what I would do differently if I were to start this whole process over. The first thing I would do is lock down the selection and design criteria earlier in the process. With those criteria established the definitions of them could be refined so that it is extremely clear what is meant by certain selection or design criteria and explain that to the leads. Also, I should have foreseen how busy the leads would get around competition time and gotten them to fill it out much sooner in the process to understand some of the difficulties they would have. Earlier in the year there was not such a well-defined 2015 chassis design. It was still in its early stages and having the leads fill out the matrix on one of those early designs as well as the more finalized design would have helped in understanding and refining the design matrix results. Overall the process and project proved to be successful and will continue to prove valuable to the GFR team with continued use of the design matrix.

c) Suggestions for Future Efforts

The chassis design matrix has been constructed after much thought, refinement, and experimentation but there is room for the GFR team to continue to develop it. The best way to continue the design matrix is to test it on new chassis designs in the future. Currently, there are two chassis that have been scored. The current (2014) chassis has been extremely successful in competition for the GFR team and, according to the design matrix created, the 2015 will be better. This cannot be proven until the new chassis has been built, tested, and competed in SAE events. If the new chassis proves to be successful then it will be a step closer in solidifying the validation of the matrix. If the new chassis proves to be inferior to the previous design then the matrix weighting values should be re-evaluated. Even though this is not an expected outcome of the new chassis it is still a possibility that may need to be addressed.

Another area capable of future research would be the creation of a design matrix for more specific parts of the car. It is not advised to make a highly detailed matrix on a large part of the car. If a more detailed matrix were to be made for the chassis the matrix would be too large for filling. If matrices were made for sub teams of the car, on the other hand, it could provide powerful insight to some specifics of those sub teams. To analyze a location or function of the car more specifically could help the team refine parts of the car that are not up to the quality or expectation as the rest of the car without having to do a complete re-design. Although the DSM and TRIZ methods are presented as studied methods for specific parts of a product the Pugh method is again recommended. The Pugh method is a simple style to create and understand that can be passed along through GFR documentation successfully. Overall, engineering design matrices can prove to be an important part of continuously improving the GFR team.

12) Bibliography

[1] "2013 Chassis Manufacturing." *GFR Google Site*. Global Formula Racing, Web. 28 Jan. 2014.<https://sites.google.com/a/ba-racing-team.de/body-team/project-groups/Composites/reports/2013-chassis-manufacture>.

[2] "An Abridged History of SAE." *An Abridged History of SAE*. Web. 29 Jan. 2014. <http://www.sae.org/about/general/history/>.

[3] "GFR About Us." *Global Formula Racing*. Oregon State University, Web. 28 Jan. 2014. <http://www.global-formula-racing.com/>.

[4] "Global Formula Racing." Web. 29 Jan. 2014. <http://waldner-karriere.over-blog.de/categorie-11881300.html>.

[5] Neuber, Nico. "OSU Bond Joint Testing Report." *2014 Senior Projects*. GFR14, Web. 28 Jan.2014.<https://docs.google.com/a/ba-racing-team.de/document/d/1w5kedBZF_M_E2w0KY2-gSGB8-tPbKyOYk73rZBxd4so/edit>.

[6] "2014 Formula SAE Rules." *SAE International*. Society of Automotive Engineers, n.d. Web. 28 Jan. 2014. <http://students.sae.org/cds/formulaseries/rules/2014_fsae_rules.pdf>.

[7] "Global Formula Racing Private Home." *Global Formula Racing*. N.p., n.d. Web. 20 Feb. 2014. <https://sites.google.com/a/ba-racing-team.de/global-formula-racing-

general/home>.

[8] "2008 FSAE Chassis." *Oregon State GFR*. GFR Google Site, n.d. Web. 22 Feb. 2014. <https://docs.google.com/a/ba-racing-team.de/file/d/0Bz4LssEMLkkEZjQ1OEVVVVF2WVU/edit>

[9] "2009 Body Monocoque Design." *GFR Website*. N.p., n.d. Web. 23 Feb. 2014. <https://docs.google.com/a/ba-racing-team.de/file/d/0Bz4LssEMLkkER3lOT3lZbDl4U0E/edit>.

[10] "2010 Monocoque Design and Ergonomics." *GFR Website*. N.p., n.d. Web. 23 Feb. 2014. <https://docs.google.com/a/ba-racing-team.de/file/d/0Bz4LssEMLkkEQUZBdzJQZFJZZ1k/edit>

[11] Eppinger, Steven D., and Tyson R. Browning. "Introduction to Design Structure Matrix Methods." *Design Structure Matrix Methods and Applications*. Cambridge, MA: MIT, 2012. N. pag. Print.

[12] Ullman, David G. "Concept Evaluation and Selection." *The Mechanical Design Process*. New York: McGraw-Hill, 1992. N. pag. Print.

[13] Dieter, George Ellwood. "Concept Generation and Evaluation." *Engineering Design*. Boston: McGraw-Hill Higher Education, 2009. N. pag. Print.

[14] Rojan, Anna-Lena. "OSU Bond Joint Testing Report." *2014 Senior Projects*. GFR14, Web. 28 Jan.2014.<https://docs.google.com/a/ba-racing-team.de/document/d/1DHASSvbH1j-92uyZptqzHzFrZ_bNVxnuKPEnnfd7gUc/edit>.

[15] Hendricks, Aaron. "Testing of Honeycomb Materials." *GFR*. Google, n.d. Web. 18 Mar. 2014. <https://docs.google.com/a/ba-racing-team.de/document/d/1adPq4AwxPVoz-NBYIjaK33kh_44AGsB5EG_BHYR3E58/edit>.

[16] Varela ,Nicholas. "Steering Column Report." *GFR*. Google, n.d. Web. 18 Mar. 2014. <https://docs.google.com/a/ba-racing-team.de/document/d/1zWI8jGvCkMQaaj9C_084Dkc0lNLXk97rfWEWJU0_77A/edit>.

[17] Hazelrigg, George A. "Validation of Engineering Design Alternative Selection Methods." *Engineering Optimization* 35.2 (2003): 103-20. *Taylor & Francis Group*.