DESIGN OF A FRAMEWORK TO FACILITATE DISTRIBUTED CONCURRENT ENGINEERING WITH GT MOTORSPORTS

In the context of ME 6102 & ME 6170

ME 6102 Final Project Report

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May 2, 2000

Abridged February 20, 2002

ABSTRACT

This document is a compilation of my learning for the spring semester of ME 6102: Designing Open Engineering Systems. My goals for this semester are to outline the structure for my Master's research (to develop a framework to facilitate Distributed Concurrent Engineering) and tie-in the principal elements of ME 6102: **O**pen **E**ngineering **S**ystems (OES) and the **D**ecision **S**upport **P**roblem (DSP) Technique. As a case study, I've chosen to focus on the activities of the **G**eorgia **T**ech **M**otor**S**ports (GMTS) team and their task to design, build and race a mini-formula racecar in the Formula SAE® competition. Not only will I leverage knowledge gained this semester in ME 6102, I will also draw upon my previous experiences and learning from ME 6170 (Engineering Design).

ACKNOWLEDGMENTS

I gratefully acknowledge the contributions of the following individuals:
Brandon Taylor and the GTMS team for their assistance in the development and verification of the design models, Gabriel Hernandez and Farrokh Mistree of the Systems Realization Laboratory for orchestrating my learning of Open Engineering Systems and the DSP Technique, and Dr. Mark Hale for his comments and direction with Decision Support Matrices.

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CHAPTER 1

PROJECT OVERVIEW, MOTIVATION AND REPORT ORGANIZATION

In this chapter I explain the reasons I enrolled in ME 6102 and what goals I plan to accomplish with this report. I also describe how this report is structured and why I chose this format.

1.1 COURSE AND PERSONAL OBJECTIVES

1.1.1 Statement of Course Objectives

This report was produced as a final project for ME6102: Designing Open Engineering Systems, a graduate design course. This work represents a comprehensive examination of concepts presented and goals set forth in class within the context of a design and manufacturing setting. My objective is to create a framework for the GTMS team to efficiently make use of available resources to design and build a complete racecar from raw materials in the timeframe of two academic semesters. Specifically, I completed the design process of one of the substructures of the GTMS vehicle and formulated a framework to facilitate the design of the other substructures. Through successful completion of this project, I feel that both the objectives of the class and the needs of the GTMS team have been satisfied.

1.1.2 Statement of Personal Objectives

My major objective within the scope of this course is to answer the question for the semester: "*how should the Decision Support Problem Technique be leveraged to better support the realization of Open Engineering Systems?*" Further, I want to formulate the structure of my Master's Thesis; the study of Distributed-Concurrent Engineering. I want to hone my technical skills, but more importantly I want to acquire the skills necessary to actively and effectively guide the course of my own learning. In short, I want to learn how to learn and improve my critical thinking skills.

1.2 PROJECT OBJECTIVES AND EXPECTATIONS OF GTMS

1.2.1 Introduction to GTMS

GTMS was established in 1986 as an active source of hands on experience for Georgia Tech students as well as a resource for furthering the engineering mindset and thought process. GTMS is a student-run organization dedicated to designing and building an open wheeled Formula SAE prototype car for competition purposes in the annual Formula SAE event. GTMS has produced eight award winning cars since its beginning in 1986 and is currently producing its ninth. GTMS prototypes are built from scratch every year sizing up to a half-scale Indy car. They are primarily meant for amateur/professional autocrossing events. Every Summer, GTMS sets its sights on the upcoming year by setting team and engineering goals to begin the design of a new Formula SAE car. Every Fall, those designs are transformed from computer design to aluminum and steel incarnations by students in machine shops across campus. Every Spring, 20 team members, a 27 ft trailer, and one finely-tuned machine depart for Detroit to face similar efforts from 100 other schools. All of this is made possible entirely through intense student efforts including fund raising, research, design, time/project/people management, fabrication, and fierce system tuning.

1.2.2 How is GTMS involved in Distributed Concurrent Engineering?

I am interested in developing a framework to promote collaborative distributed engineering. As the laboratory instructor for ME 4041 (Interactive Computer Graphics and Computer-aided Design), I teach 45 students every semester how to build CAD models and conduct a finite element analysis using CAE tools. I also provide instruction and technical support in the CAD/CAE area to GTMS. There have been significant overlapping of the two activities: GTMS members occasionally take ME 4041 and ME 4041 students occasionally use GTMS as projects as part of the course [The ME 4041 Web page]. I want to develop a tighter integration between ME 4041 and GTMS. To ME 4041 students, this means being more involved in the design aspect of GTMS; making decisions that affect the function, layout and manufacture of the racecar and its components. For GTMS, this is an opportunity to make better use of CAD/CAE/CAM (C3) tools, to work more efficiently and faster. Students in ME 4041 and GTMS utilize computer clusters in the MRDC and A. French buildings (see Figure 1.2.1). There are also C3 software installed in the GTMS lab and students have personal copies of software installed in their dorms and at home. How do we coordinate all of this information in the distributed environment to arrive at the same goal of building a racecar?

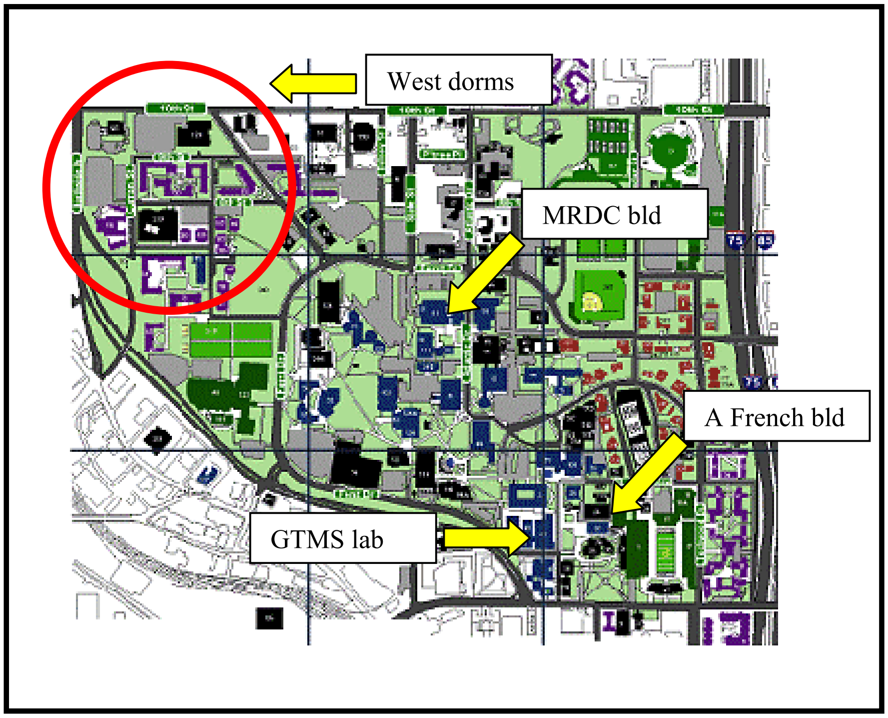


Figure 1.2.1 - The Distributed computer environment at Georgia Tech.

1.2.3 How is GTMS an Open Engineering System? A Product Family?

GTMS is an extra-curricular, multi-disciplinary, "volunteer" student organization. The students are faced with the monumental task of coordinating their busy academic and personal schedules to collaborate on the project and design/build/race a car in two academic semesters. An open engineering approach can help GTMS accomplish their task by imbedding the qualities of Robustness, Modularity and Mutability into their activities. The Formula SAE® competition requires that GTMS builds a "new" car every year. A "new" car is classified as a car with a frame that has not been used in a Formula SAE® competition. However, there is no restriction on the number of parts and components from previous years' cars that can be reused. With a history of cars dating back to 1986, the GTMS racecar is essentially a product family architecture in which existing components can be reused and new components introduced in response to changes in:

- customer requirements (i.e., new Formula SAE® rules)
- existing resources (i.e., lab equipment, computer software), and
- technology (i.e., new composite materials, Methanol fuels instead of Gasoline).

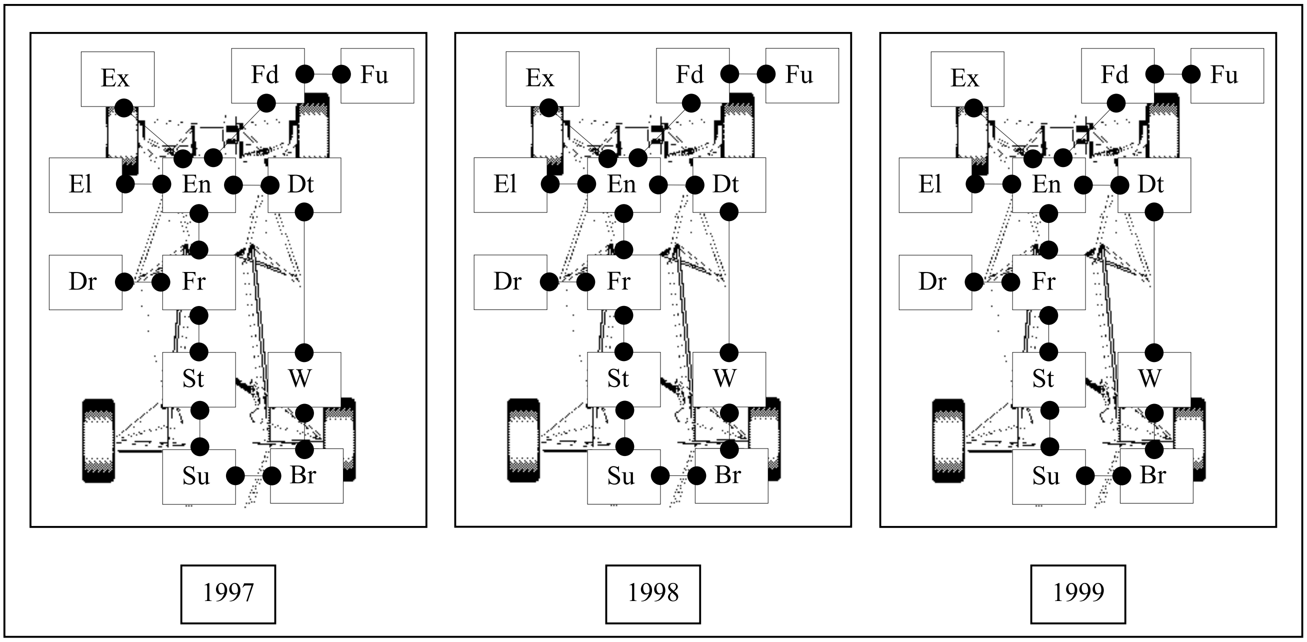


Figure 1.2.2 - GTMS substructures.

GTMS has maintained design robustness out of convenience and by accident. As illustrated in Figure 1.2.2, the essence of the racecar design remains the same from year to year. For example from 1997-1999, the racecar was essentially made of 12 major substructures:

1. Ex - Exhaust System
2. El - Electrical System
3. En - Engine
4. Ig - Ignition System
5. Fu - Fuel
6. Dt - Drivetrain
7. Dr - Driver and Safety Equipment
8. Fr - Frame
9. St - Steering
10. Su - Suspension System
11. Br - Brakes
12. Wh - Wheels & Tires

It is the particular details of each substructure that distinguishes one car from another.

	Substructure	1997	1998	1999
Ex	Exhaust			
El	Electrical			
En	Engine	Honda CBR600F2	Honda CBR600F3	
Ig	Ignition System	Gas Injection	M85 Injection	
Fu	Fuel	Gas	M85	
Dt	Drivetrain			
Dr	Driver/Safety			
Fr	Frame			
St	Steering			
Su	Suspension	outboard damper-coilovers		inboard damper-coilovers
Br	Brakes			
Wh	Wheels & Tires			

Table 1.2.1 - Changes in GTMS substructure from 1997 to 1999.

For example, Car 13 (1999) was an overall iteration of Car 85 (1998). The new frame was build from 1998's design and most of the components were reused in the 1999 racecar. To improve the car's handling and endurance, changes were made to the car's suspension system redesigning it from an outboard coilover damper to an inboard coilover setup as illustrated in Table 1.2.1. It is my belief that the DSP Technique can evolve GTMS from a trial-and-error OES to a structured OES through the implementation of DBD process planning and management tools.

1.3 ORGANIZATION OF THE REPORT

1.3.1 Approach to the Problem

Use of Data Management Software

Two major benefits of my work to GTMS are the creation of a framework to facilitate Distributed Concurrent Engineering and a repository of past design decisions. As the first step towards accomplishing these tasks, I have installed Metaphase (by Structural Dynamics Research Corporation (SDRC)) in the CAD laboratory of the A. French building. Metaphase is a web-centric Product Information Manager (PIM) software that provides the information infrastructure for engineers to control, configure, and connect product-related intellectual data into collaborative processes that can be quickly initiated and continuously improved. Metaphase is integrated with a wide range of authoring tools and product realization applications, including systems that perform mechanical design, electrical design, word processing, presentation preparation, spreadsheet generation, and enterprise resource planning. Metaphase manages product information as reusable intellectual capital. For example, Metaphase will enable GTMS to check their most valuable product information into a centrally managed meta-repository that subsequently can be accessed by diverse users, from remote locations.

Use of Pahl and Beitz and the DSP Technique

If Metaphase can be used to share electronic data, how do we manage the interactions and dependencies between the data (design variables)? For example, a student working on part B may be dependent on data from part A. I believe that the Pahl & Beitz method augmented by the Decision Support Problem (DSP) Technique is the answer. The Pahl and Beitz Method is a systematic approach to engineering design in which the design process is broken down, first into phases and then into distinct steps, each with its own working methods. This systematic approach provides an effective way to rationalize the design and production processes necessary to build the racecar. Structuring the problem and task makes it easier to recognize application possibilities for established solutions from previous projects and to use design catalogs.

The DSP Technique is an application of Decision Based Design (DBD). It is codeable providing the means for modeling decisions encountered in design through domain specific mathematical models (templates). The power of the computer can be harnessed to iterate through a multitude of scenarios much quicker than an unaided human can. Also, since most of our information will be transferred and stored electronically, codeability is a very important asset. The DSP Technique is capable of conducting multiobjective mathematical programming through the use of the Decision Support Problems [Bras and Mistree]. Using DSPs, an engineer can deal with coupling between dissimilar variables and determine the values of design variables which satisfy a set of constraints while achieving a set of conflicting goals as well as possible.

I propose to:

1. Create an infrastructure to share information across a distributed environment using the Metaphase PDM software.
2. Create a legacy database that future GTMS students can draw upon to build a car.
3. Create templates by which to make decisions of coupled design variables.

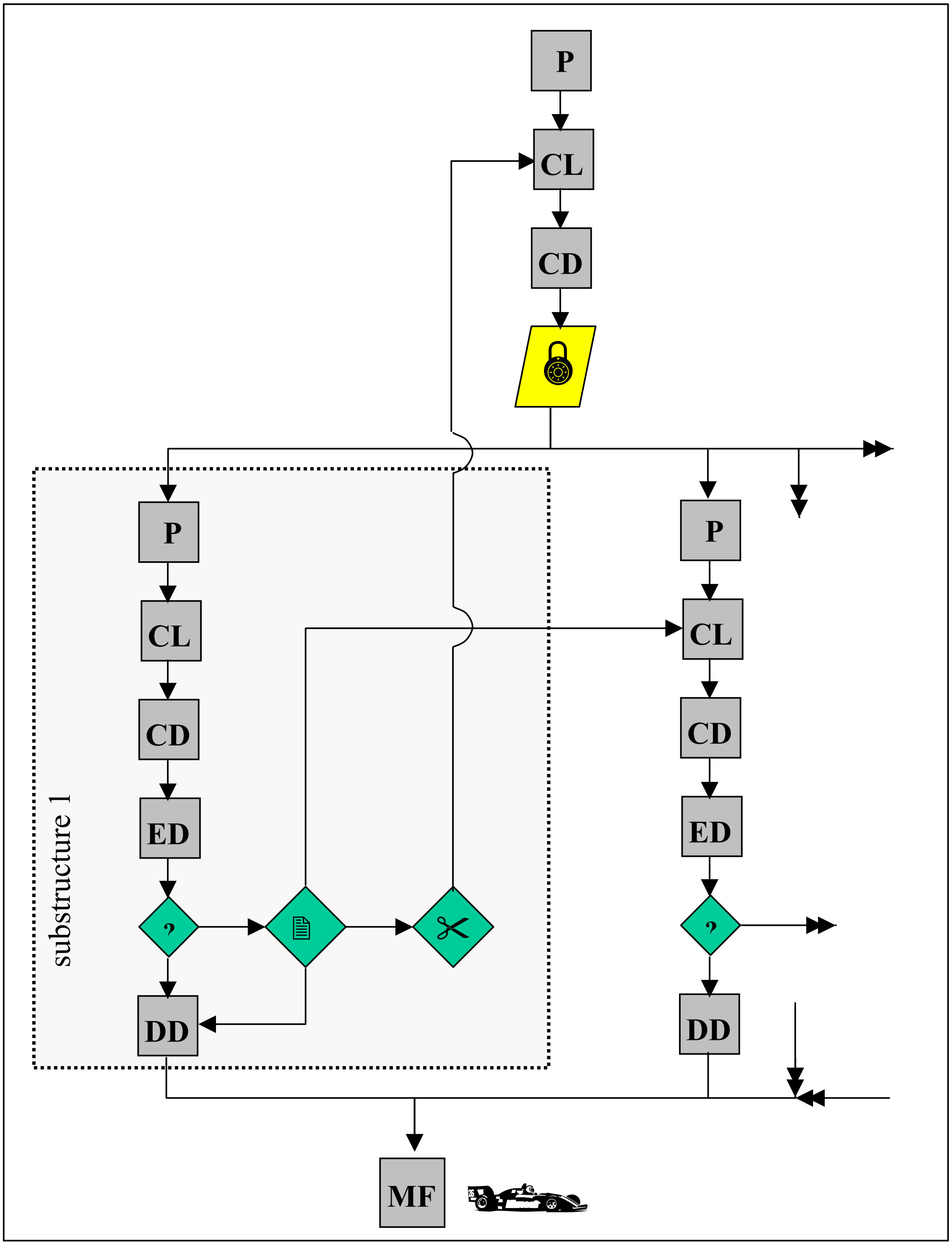


Figure 1.3.1 - The proposed GTMS design process.

I envision the design process to proceed as depicted in Figure 1.3.1:

- The first step (**P**) is the **P**lanning phase in which the team leaders set objectives for the new model year, develop a PEI (**P**hase-**E**vent-**I**nformation) diagram and model the design process using the DSPT Palette.
- In the **Cl**arification of Task (**CL**) phase, the entire team investigate the competition rules and they apply to previous years' designs.
- In the **C**onceptual **D**esign (**CD**) phase the entire team decides on the major substructures of the vehicle, how they are interdependent and what are the governing constraints ( ) between substructures.

At this point the team separates into smaller teams based on substructures, each performing the 4 steps of the Pahl & Beitz method (augmented by the DSP Technique) in the context of the constraints that link the substructures. For example:

- In the **P**lanning (**P**) phase of substructure 1, the team sets objectives, develops a PEI (**P**hase-**E**vent-**I**nformation) diagram and models the design process using the DSPT Palette.
- In the **Cl**arification of Task (**CL**) phase, the team investigates the governing constraints ( ) and how they apply to previous years' designs.
- The **C**onceptual **D**esign (**CD**) phase may not be fully conducted because the team is doing adaptive or variant design, but a short review of new/other technologies is performed.
- In the **E**mbodiment **D**esign (**ED**) phase, the team determines the construction structure (overall layout) of the substructure in line with the governing constraints ( ).Selection DSP(s) or Compromise DSP(s) may be formed here to evaluate design choices.
    - ♦ If the output ? results in a design that does not violate the governing constraints ( ), the team proceeds to the **D**etail **D**esign (**DD**) phase.
    - ♦ If the output ? results in a design that does violate the governing constraints ( ):
        - If the output results in a change of variables, then the variables must be reported to the affected substructure team. A coupled Compromise DSP could be used to enable multiple teams to work concurrently.
        - If the output results in a change of concept (i.e., instead of bolts use welds), then all of the teams must regroup and return to the **Cl**arification of Task (**CL**) phase to decide how these changes affect the entire design process.
- In the **D**etail **D**esign (**DD**), the arrangement, forms, dimensions and surface properties of all the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated and all the drawings and other production documents produced. [Pahl & Beitz pg. 69]
- The **M**anu**f**acturing (**MF**) phase involves the transformation of the design into a physical artifact.

1.3.2 Organization of the Report

This report was organized to answer the question for the semester: "*how should the Decision Support Problem Technique be leveraged to better support the realization of Open Engineering Systems?*"

- ✓ In Chapter 1 I set the context in which the question for the semester will be answered.
- ✓ In Chapter 2 I lay the foundation for my Master's Thesis by outlying the framework in which GTMS can design a racecar utilizing DBD.
- ✓ In Chapter 3 I perform an in-depth investigation of the design of one substructure (the frame) of the racecar by applying the Pahl & Beitz Method augmented by the DSP Technique.
- ✓ In Chapter 4 I summarize my learning by answering the question for the semester.
- ✓ Appendix A contains descriptions of the cross-sections of the GTMS racecar.
- ✓ Appendix B contains graphs of the Response Surface Models.
- ~~✓ Appendix C is a compilation of assignments from this semester.~~
- ~~✓ Appendix D is a compilation of learning essays from this semester.~~
- ~~✓ Appendix E contains the mid-term presentation slides.~~
- ~~✓ Appendix F contains the final presentation slides.~~
- ~~✓ Appendix G contains the final grading for this semester.~~
- ✓ The Report ends with the References section.

1.3.3 Graphical Outline of the Report

Figure 1.3.2 is a graphical representation of how this report was planned and constructed using a PEI (**P**hase-**E**vent-**I**nformation) diagram. This diagram has been useful to depict the information flow in the design process and for scheduling the necessary tasks. It is a living document that has undergone many updates as necessitated by changes to the design process.

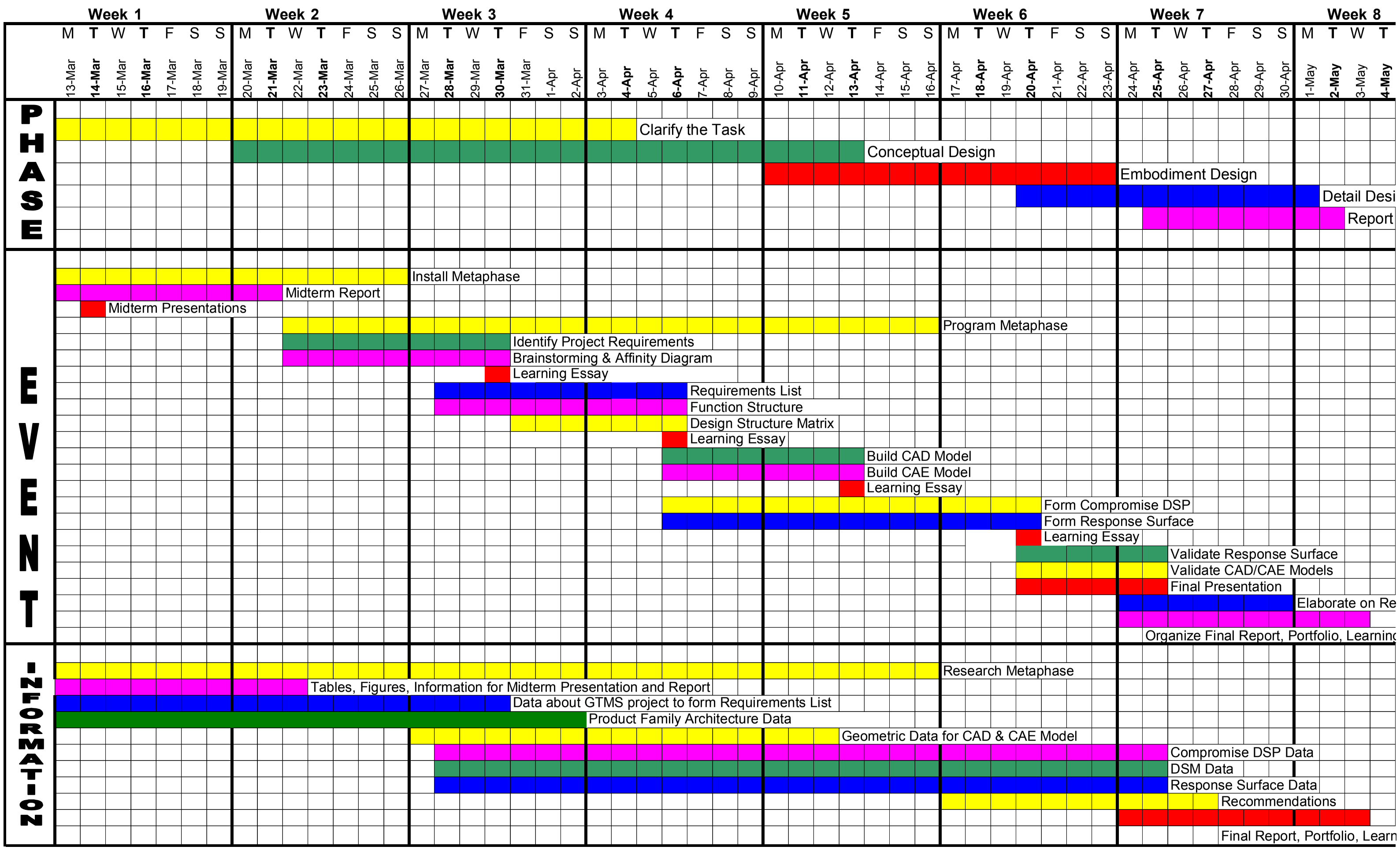


Figure 1.3.2 - PEI Diagram of the report construction.

1.4 SUMMARY

In this chapter I have set the context in which the question for the semester will be answered. I have explained why I chose GTMS as a focus to illustrate my learning in ME6102. I have outlined how I plan to apply the Pahl & Beitz method augmented by the DSP Technique to GTMS.

CHAPTER 2

DESIGNING THE DESIGN PROCESS

In this chapter, the first 3 phases of the design process of GTMS is designed and explored in the context of the Pahl & Beitz method augmented by the DSP Technique.

2.1 PRODUCT PLANNING

2.1.1 Meta-Design of the Design Process

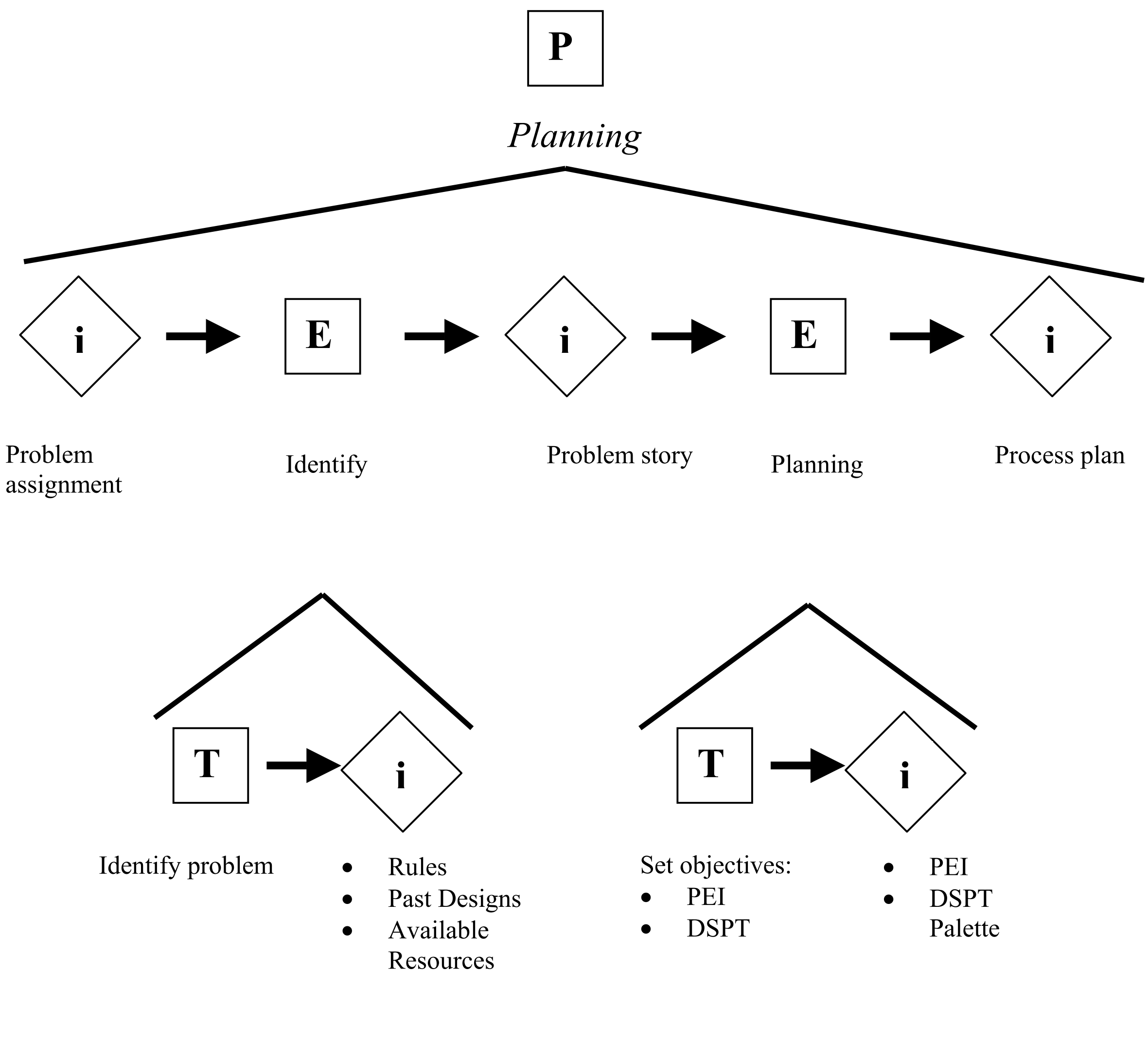


Figure 2.1.1 - The Planning phase of GTMS.

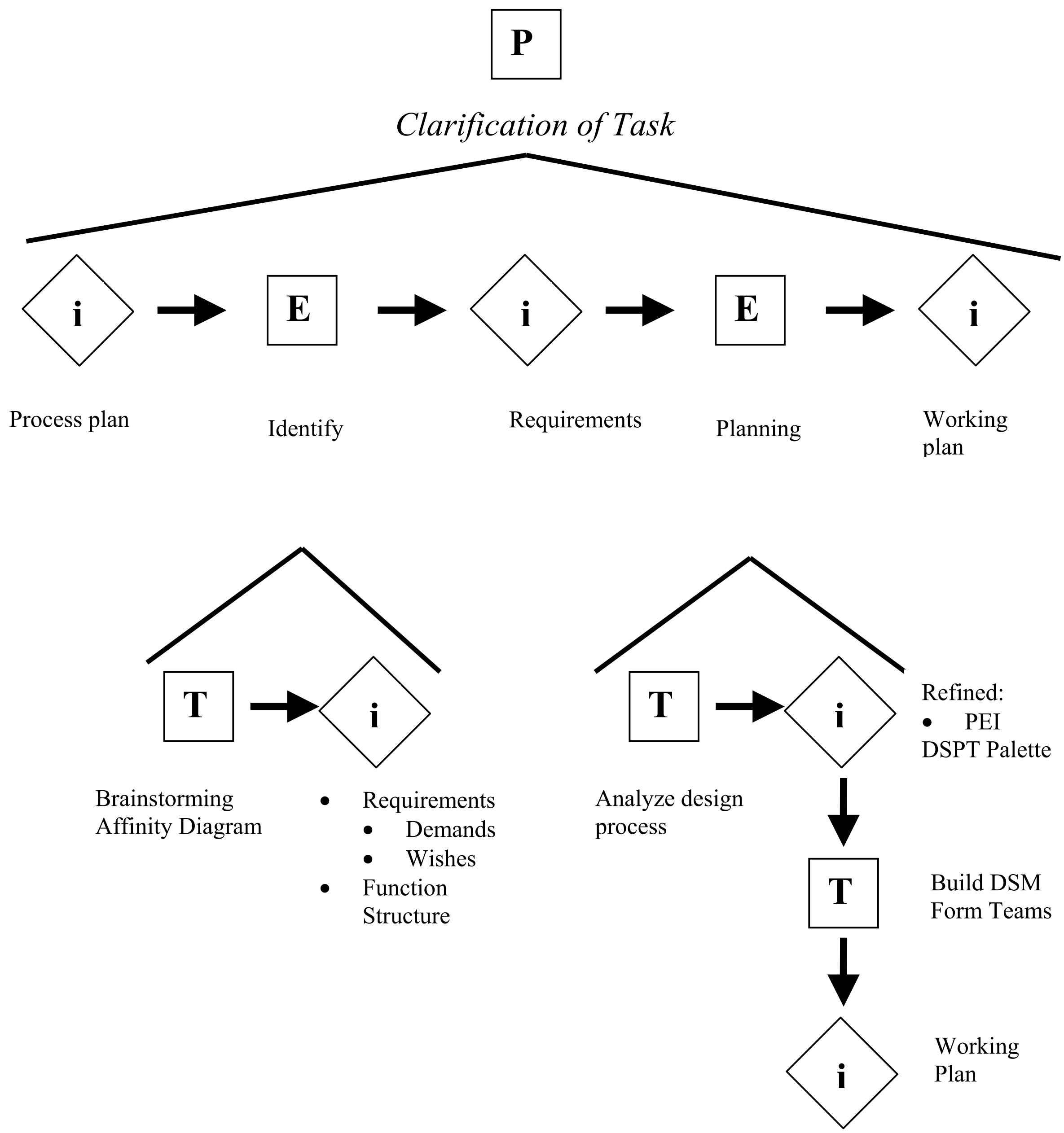


Figure 2.1.2 - The Clarification of Task phase of GTMS.

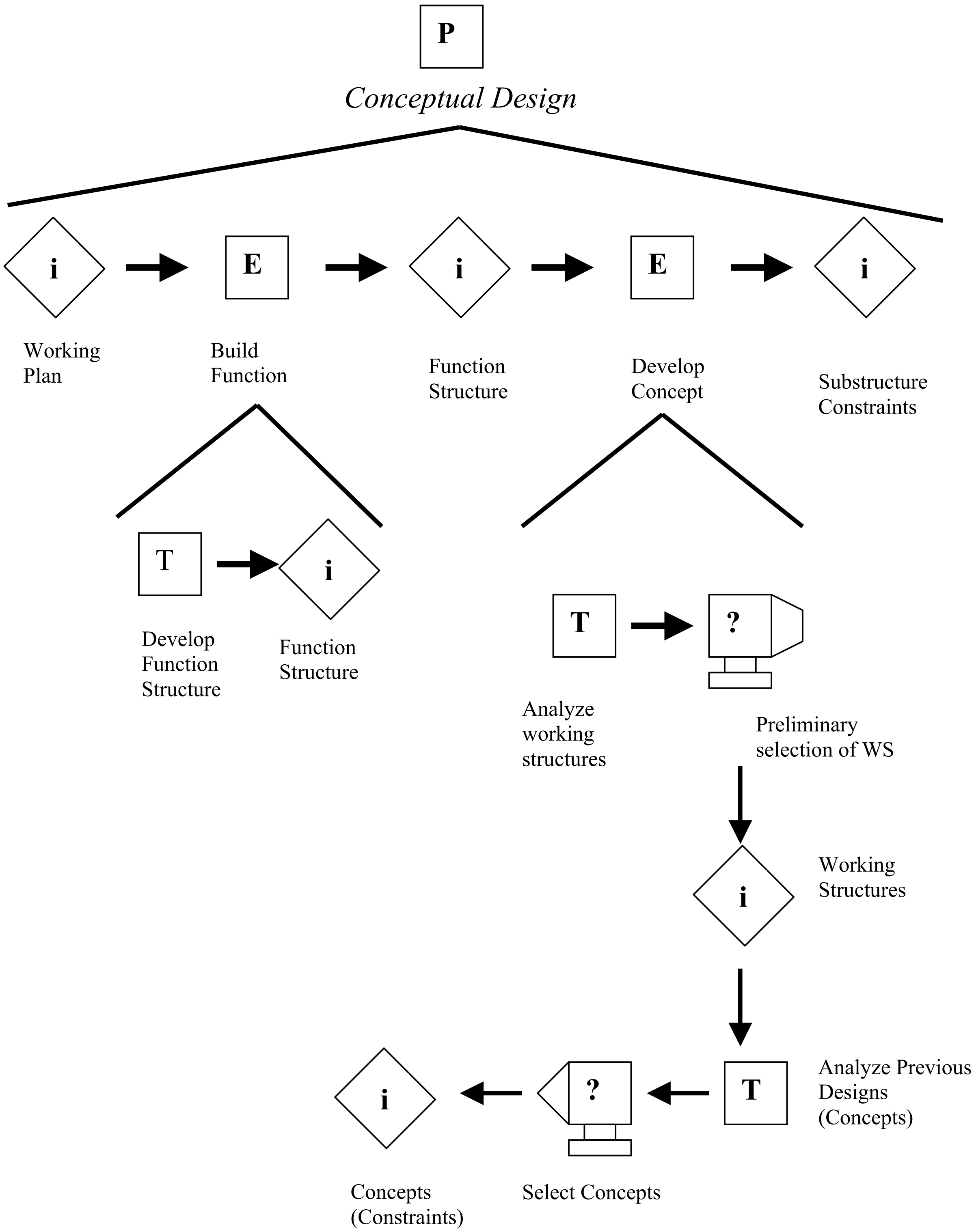


Figure 2.1.3 - The Conceptual Design phase of GTMS.

2.1.2 Explanation of the Design Process

Planning phase (see Figure 2.1.1)

i - a new set of rules and regulations are received from Formula SAE®
E - Identify the Problem
  T - team leaders identify key changes between last years' and this year's rules
    team leaders identify successes and failures from previous years
    team leaders inventory available resources (including people)
  i - rules, past designs, and available resources are gathered
i - the Problem Story is formulated
E - Planning
  T - the objectives of the team are set, the PEI diagram and DSPT palette are built
  i - PEI diagram and DSPT palette
i - the Process Plan is available

Clarification of Task phase (see Figure 2.1.2)

i - the Process Plan is executed
E - Identify
  T - team performs Brainstorming and Affinity Diagram activities
  i - Requirements List and Functions Structure are formed
i - the Requirements are identified
E - Planning
  T - the team analyzes the design process and refines the PEI diagram and DSPT palette
  i - PEI diagram and DSPT palette
  T - the **D**ecision **S**upport **M**atrix (DSM) is formed and the team decomposes into sub-teams
  i - a plan of action is formulated
i - the Working Plan is available

Conceptual Design phase (see Figure 2.1.3)

i - the Working Plan is executed
E - build Function Structure
  T - team builds Function Structures for car substructures
  i - Function Structures are formed
i - Function Structures
E - Develop Concepts
  T - the team analyzes the working structures from previous designs
  ? - a preliminary selection of working structures
  i - Working Structures
  T - the team analyzes the previous substructure designs and how they interact
  ? - substructure designs are selected (Concepts)
  i - inter-Substructure Constraints are specified
i - inter-Substructure Constraints (sub-teams begin work)

2.2 CLARIFICATION OF TASK

2.2.1 GTMS Objective:

The objective of GMTS and the Formula SAE® competition is to conceive, design, fabricate, and compete with small formula-style racing cars. For the purpose of the competition, the students assume that a manufacturing firm has engaged them to produce a prototype car for evaluation as a production item. The intended sales market is the nonprofessional weekend autocross racer. Therefore, the car must have very high performance in terms of its:

- acceleration
- braking
- handling

The car must be:

- low in cost
- easy to maintain
- reliable

In addition, the car's marketability is enhanced by other factors such as:

- aesthetics
- comfort
- use of common parts

The manufacturing firm is planning to produce four (4) cars per day for a limited production run and the prototype vehicle should actually cost below $30,000. The challenge to the design team is to design and fabricate a prototype car that best meets these goals and intents. Each design is compared and judged with other competing designs to determine the best overall car.

2.2.2 Assumptions

Based on discussions with GTMS, I formulated the following assumptions upon which we will operate:

- GTMS can reuse the existing frame design (the present frame meets or exceeds rules requirements) for many years as long as a new one is fabricated each year.
- The existing frame design will accomplish the required tasks of protecting the driver and integrating the subcomponents without any modifications to structure, layout or material.
- Subcomponents attach to the frame using conventional insertion methods (i.e., bolts and rivets).
- Components from previous years can be reused without restrictions by Formula SAE® rules.
- Previous years' off-the-shelf components are still available for purchase.
- GTMS laboratory facilities still have the capability to remanufacture components used in previous years' cars.

2.2.3 Directed graph of racecar substructures

The Formula SAE® competition requires that GTMS build a "new" car every year. A "new" car is classified as a car with a frame that has not been used in a Formula SAE® competition. Assuming that GTMS can reuse the existing frame design (the present frame meets or exceeds rules requirements) for many years as long as a new one is fabricated each year, we will focus on the subcomponents that make-up the race car and the relationships between them, the frame and each other. Essentially we are doing Adaptive or Variant Design to the super and sub structures of the racecar, no further modification is necessary. When we break the system down to the component level, we will have the possibility of performing Original Design.

In Figure 2.2.1, I have graphically depicted the racecar substructures and interdependencies. In the center of the figure is the frame, the component I have chosen to focus on in Chapter 3. The arrows indicate not only the relationship between structures, but also which direction information flows. For example:

- dimensions from the engine, front and rear suspensions drive the dimensions of the frame.
- the frame drives placement of the steering, the driver's seat and seatbelts.

Solid arrows indicate a strong relationship that cannot be ignored.

- dimensions of the suspensions (rear and front) drive the brakes, wheels and tires.
- the engine parameters drive the exhaust, ignition system and electrical system

Dashed arrows indicate a weak relationship of parameters that can easily be changed.

- The frame drives placement of the battery, but the placement of the battery is very flexible.
- The exhaust may interfere with the ignition system but is flexible and can be rerouted.

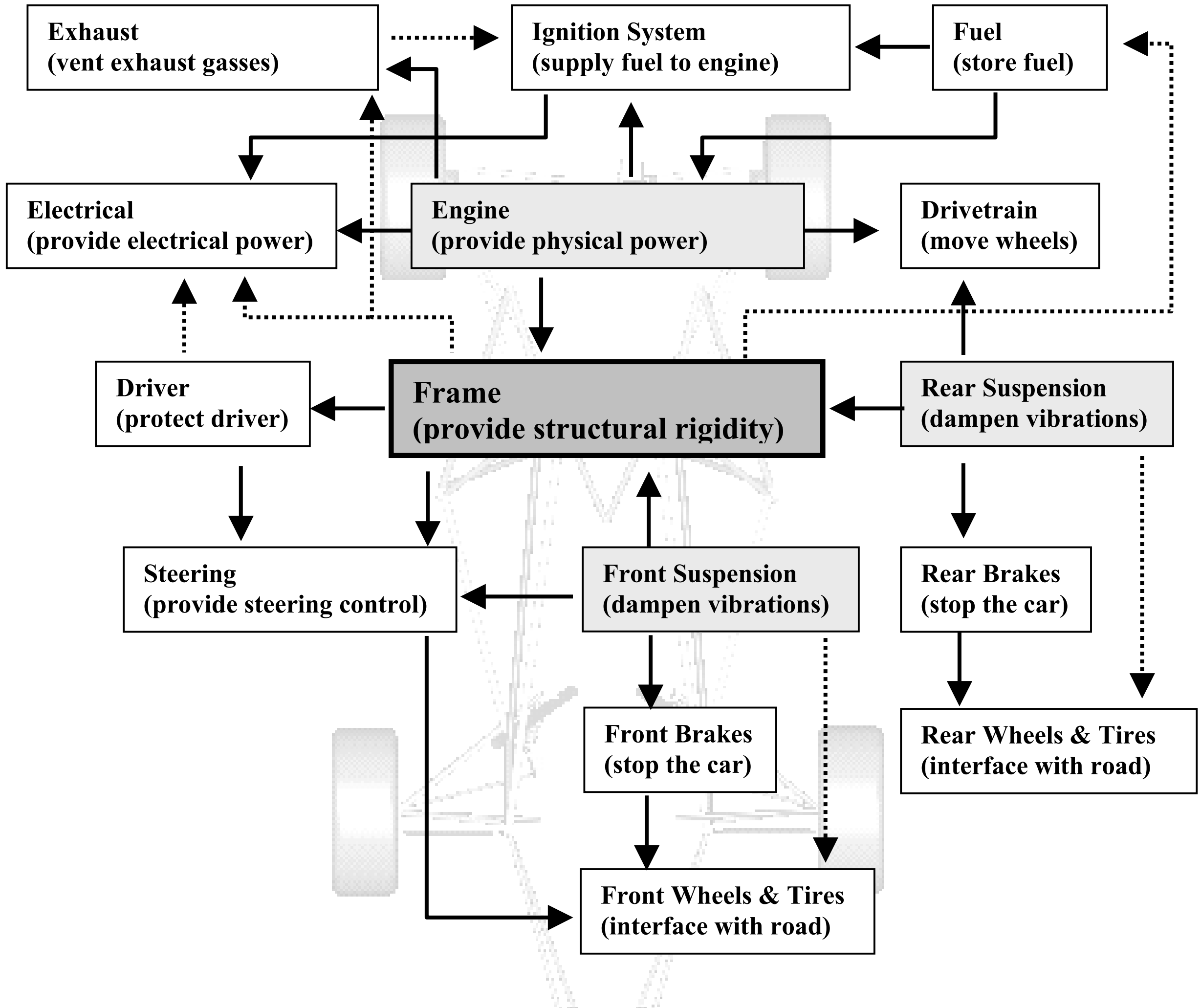


Figure 2.2.1 - Directed Graph of GTMS substructures.

2.2.4 Breakdown of racecar substructures

This is how the official Formula SAE® rules influence the design of the substructure of the GTMS racecar:

Exhaust
(vent exhaust gasses)
- four-cycle piston engine
  - 610 cc displacement per cycle or less
- 1-8 cylinder engine
- water cooled only

Ignition System
(supply fuel to engine)
- fuel injected
- carbureted
- turbo-charged
- super-charged
- throttle body
- restrictor

Fuel
(store fuel)
- Unleaded Gasoline
  - less than 7.57 liters (2 U.S. gallons)
  - aluminum, steel, stainless steel tank
- M85
  - 13.25 liters (3.5 U.S. gallons)
- stainless steel tank

Electrical
(provide electrical power)
- brake light of at least 15 watts
- Master cutoff switch
- 12 volts
- 6 volts
- battery type?

Driver
(protect driver)
- restraint harness
  - five or six-point
  - Nylon
  - Dacron polyester
- safety helmet
- fire extinguisher
- fire resistant suit, gloves, shoes
- rear-view mirrors
- head restraint

Steering
(provide steering control)
- must affect at least two wheels
- must have positive steering stops
  - which prevent the steering linkages from locking up
- Steering Wheel
  - Circular Shape - Required

Quick Disconnect - Required
Rack and Pinion
steering free play will be limited to 7 degrees total
measured at the steering wheel

Suspension
(dampen vibrations)
front and rear, fully-operational suspension system
shock absorbers
usable wheel travel of at least 50.8 mm (2 inches)
25.4 mm (1 inch) jounce
25.4 mm (1 inch) rebound

Brakes
(stop the car)
braking system that has two independent hydraulic circuits
acts on all four wheels
operated by a single control

Wheels & Tires
(interface with road)
wheels must be 203.2 mm (8.0 inches) or more in diameter
tires can be any size or type
Wheel base must be at least 1525 mm (60 inches) measured between
center of ground contact between front and rear wheels
with wheel pointed straight ahead.
must have four wheels that are not in a straight line

Exhaust
(vent exhaust gasses)
less than 113 dBA
less than 60 cm behind centerline of rear axle

Drivetrain
(move wheels)
Automatic transmission
4 or 5 speed stick shift

2.2.5 Decision Support Matrix

In my Masters' Thesis, I will develop a mechanism to ensure and facilitate communication between design teams. To do this I must first identify the information flow in a project and determine where and when communication must occur. I began this task by reading the paper "Managing the Integration Problem in Concurrent Engineering" by Eppinger and McCord. The authors assert that manufacturing firms have embraced concurrent engineering in an effort to bring new products to market faster and with higher quality. Large complex operations, such as the automotive or computer industries, involve hundreds of people organized into many small interdependent teams. For example, the engineers working on motherboards at a computer company are dependent on information of microchip configuration from the CPU team. The challenge to management is to foster communication between teams. The authors introduce the Design Structure Matrix as a tool to manage the interaction between system teams.

Working from the digraph in Figure 2.2.1, the relationships between substructures and what variables/parameters must be transferred between substructures are stated in Table 2.2.1.

row	Priority	Sub 1	Sub 2	Interaction	Variables
1	L	Ex (Exhaust)	Ig (Ignition System)	possible clearance	
2	H	En (Engine)	Ex	vent gasses from engine	exhaust port geometry bolting locations
3	L	Fr (Frame)	Ex	possible clearance	hose clamp to frame bolting locations?
4	H	Fu (Fuel)	Ig	transmit fuel	fuel type inlet geometry
5	L	Ig	El (Electrical System)	fuel gauge fuel pump	voltage amperage
6	H	En	Ig	deliver fuel to engine	intake port geometry bolting locations
7	H	Fu	En	deliver fuel	fuel type
8	L	Fr	Fu	attach fuel tank	fuel tank geometry bolting locations
9	H	En	El	power starter sensors, coil	voltage amperage
10	L	Dr (Driver)	El	gauge locations	ability to see gauges
11	L	Fr	El	attach battery attach gauges	battery geometry gauge locations
12	H	En	Dt (Drivetrain)	power driveshaft	shaft diameters shaft torque
13	H	En	Fr	support engine	bolting locations structural
14	H	Fsu (Front Suspension)	En	support suspension	bolting locations structural
15	H	Fr	St (Steering)	support steering	bolting locations structural
16	H	Rsu (Rear Suspension)	Dt	support drive axle	axle geometry
17	H	Dr (Driver)	Fr	support driver seatbelts protect driver	bolting locations bolting locations structural
18	H	Fr	Dr	interface with driver	steering location
19	H	RSu	Fr	support suspension	bolting locations structural
20	L	Rsu	RWh (Rear Wheels & Tires)	ride height	geometry
21	H	Fsu	Fr	support suspension	bolting locations structural
	H	Dr	St	clearance	steering location
22	H	Rsu	RBr (Rear Brakes)	support brakes	bolting locations structural
23	H	RBr	RWh	support wheels stop wheels	bolting locations structural
24	H	FBr (Front Brakes)	FWh (Front Wheels & Tires)	support wheels stop wheels	bolting locations structural
25	L	FSu	FWh	ride height	geometry
26	H	St	FWh	steer wheels	geometry
27	H	FSu	FBr	support brakes	bolting locations structural
28	H	FSu	St	support steering	bolting locations structural

Table 2.2.1 - GTMS substructure realtionships.

In the first row of Table 2.2.1 there is a relationship between the Exhaust and Ignition Systems. This relationship is rated LOW because there may be possible clearance issues, but the Exhaust System is flexible can be bent/maneuvered around the obstacle.

In the second row of Table 2.2.1, there is a relationship between the Exhaust System and Engine. This relationship is rated HIGH because the Exhaust System must bolt to the Engine and vent exhaust gasses. Parameters from the Engine drive the size and configuration of the Exhaust outlet.

The information in Table 2.2.1 is inserted into a Design Structure Matrix and depicted in Figure 2.2.2.

	Ex	Ig	Fu	El	En	Dt	Dr	Fr	RSu	RBr	RWh	FWh	FBr	FSu	St
Ex					H			L							
Ig	L		H		H										
Fu								L							
El		H			H		L	L							
En			H												
Dt					H				H						
Dr								H							
Fr					H				H					H	
RSu															
RBr									H						
RWh									L	H					
FWh													H	L	H
FBr														H	
FSu															
St							H	H						H	

Figure 2.2.2 - DSM of substructure interaction.

The DSM is an attention-directing tool to identify coupling between tasks (teams) and help facilitate information transfer between design teams [The MIT Design Structure Matrix - DSM - Home Page]. Using the DSM, an engineer can:

- Provide a visual image of important relationships in a product development project.
- Capture and display a process.
- Reveal key information flows.
- Show people where they fit in a design process.
- Discover previously unknown patterns: product architecture & organizational architecture

The DSM is not a symmetric matrix. It is formed by reading across rows and identifying subsystems that feed variables/parameters into the current subsystem. For example, following the row of the Frame (Fr) we see that it is directly driven by variables/parameters from the Front Suspension (FSu), Rear Suspension (RSu) and Engine (En). Following down the column of the Frame we find that it directly drives the Exhaust (Ex), Fuel (Fu), Electrical (El), Drivetrain (Dt) and Steering (St) subsystems. The idea is to swap rows and columns of the matrix, forming dense "blocks" of marks along the diagonal. This is an indication of where the highest level of information flow is required and where is appropriate to form teams. One algorithm formulated to condense the DSM matrix is called DeMAID (The **De**sign **M**anager's **A**id for **I**ntelligent **D**ecomposition) which I obtained from Dr. Mark Hale of the Aerospace Department of Georgia Tech [Welcome to Image!].

From the DSM, we can see that most of the activities of GTMS are concentrated along the diagonal. GTMS is a small team of 20 students and consists of 14 substructures, several of which can be combined into one. I experimented with several algorithms in an attempt to condense the GTMS DSM, none produced results better than what is presented in Figure 2.2.2. The DSM is still useful to GTMS to identify coupling between substructures were coupled Compromise DSPs will be needed to facilitate Concurrent Engineering.

2.3 SUMMARY

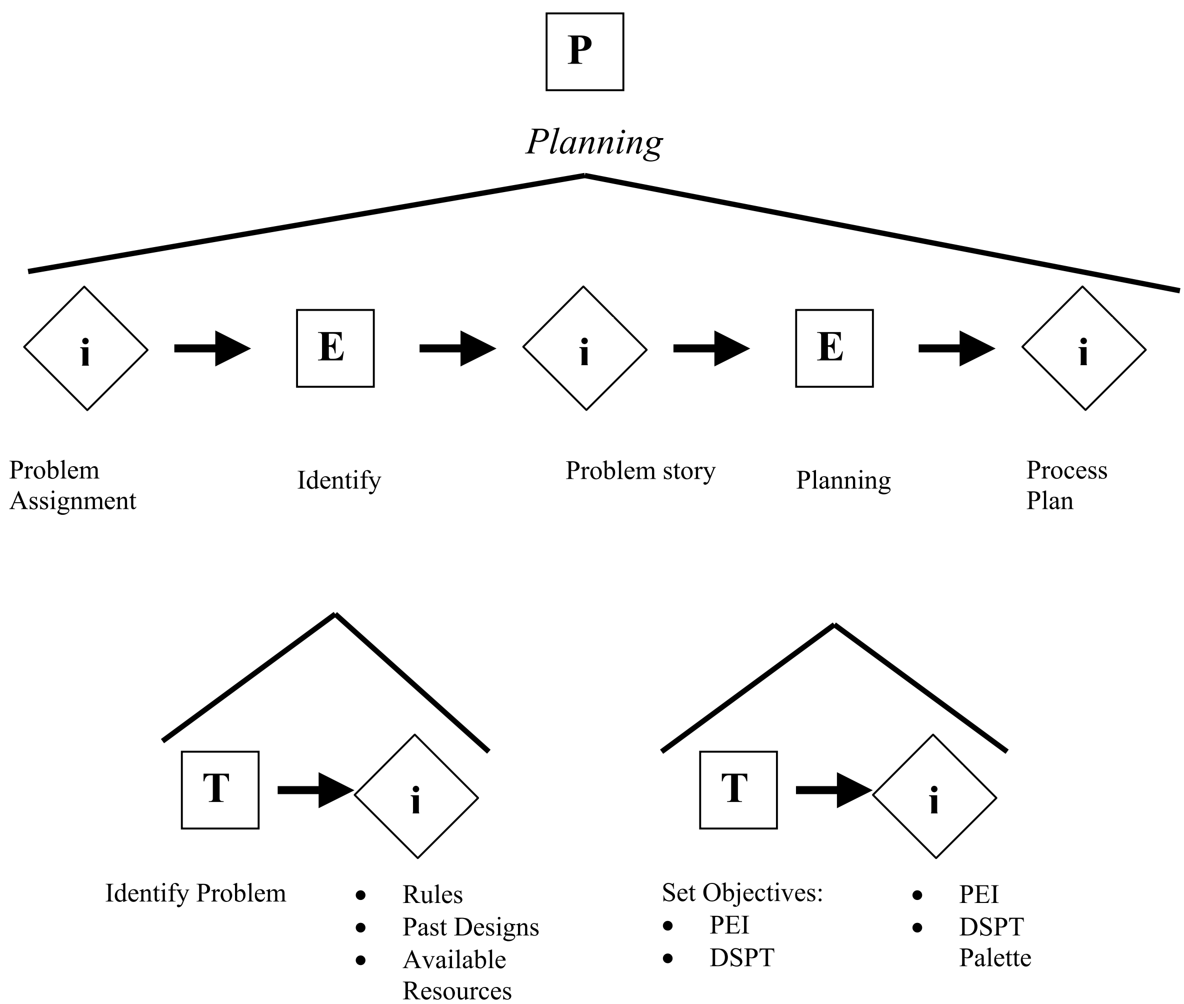
Although GTMS is a small team of less than 25 students, it is very important that the entire team convene to discuss and design the design process before any work is done on the substructures. This is because there is coupling between substructures that must be identified in-order for effective concurrent engineering to occur. The nice part of being a small team is that the designer is also the manufacturer and keenly aware of the relationships between the two phases. I've illustrated why the GTMS racecar can be considered a family of products. By adapting a structured method to engineering design, GTMS can make maximum use of limited resources and time.

CHAPTER 3

DESIGNING THE FRAME

In this chapter, I apply the Pahl & Beitz Method augmented by the DSP Technique to one substructure of the car: the frame.

3.1 PLANNING



3.1.1 Meta-Design of the Design Process

Figure 3.1.1- The Planning phase of the GTMS frame.

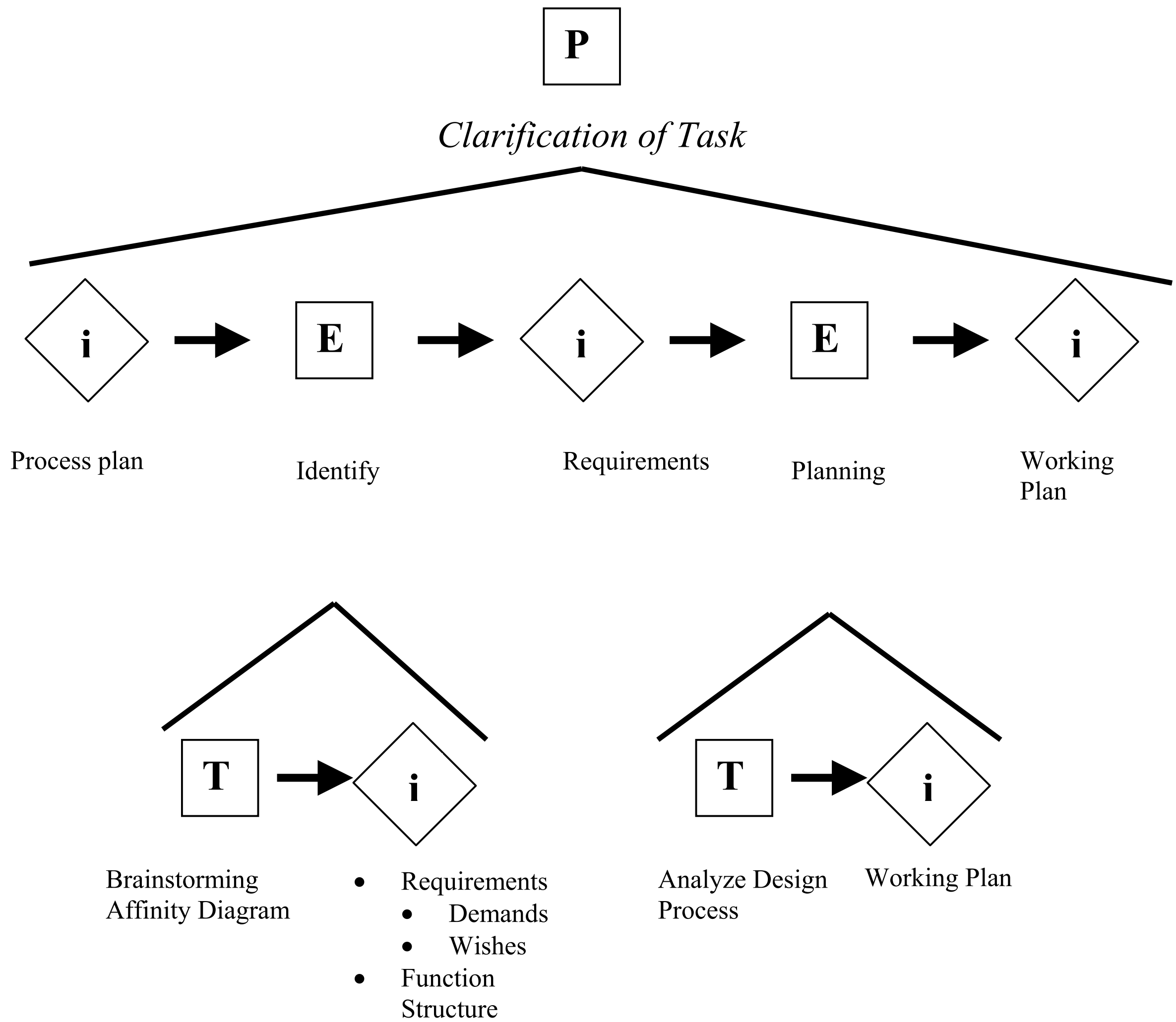


Figure 3.1.2 - The Clarification of Task phase of the GTMS frame.

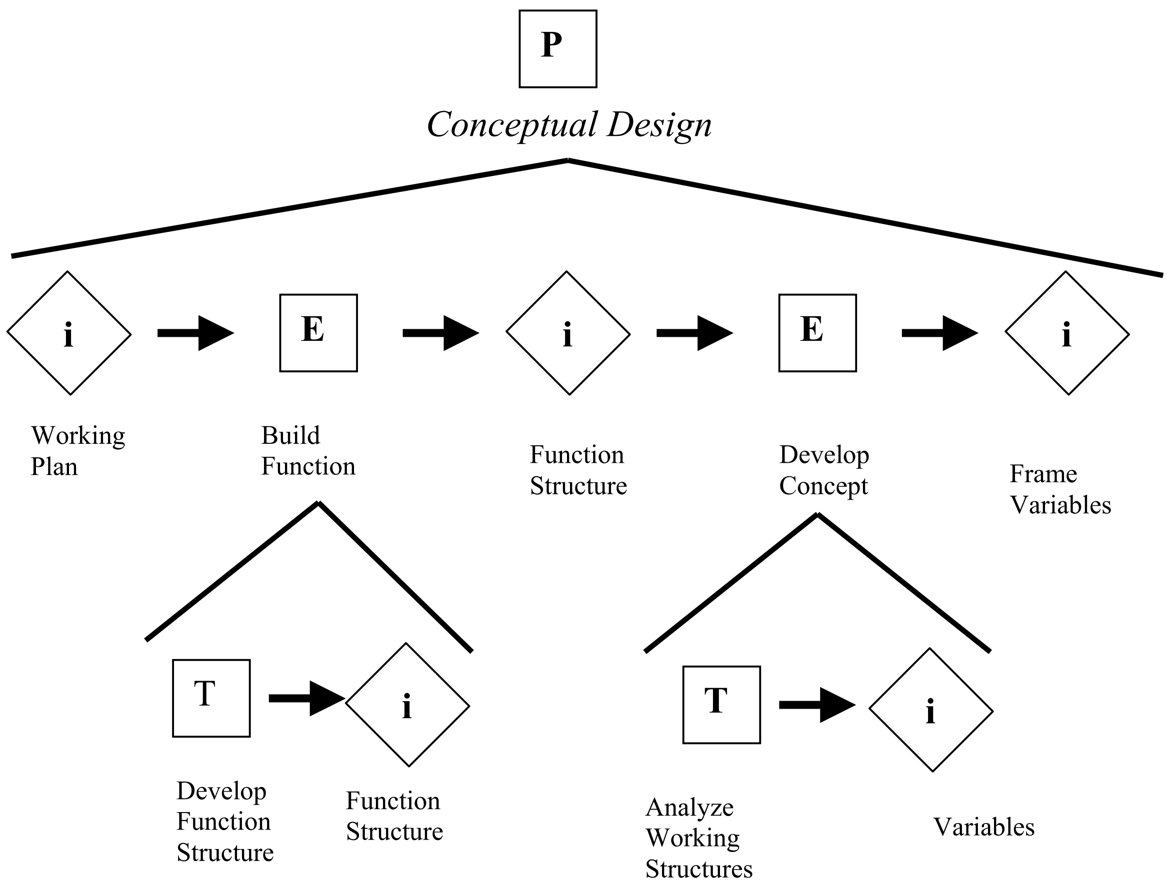


Figure 3.1.3 - The Conceptual Design phase of the GTMS frame.

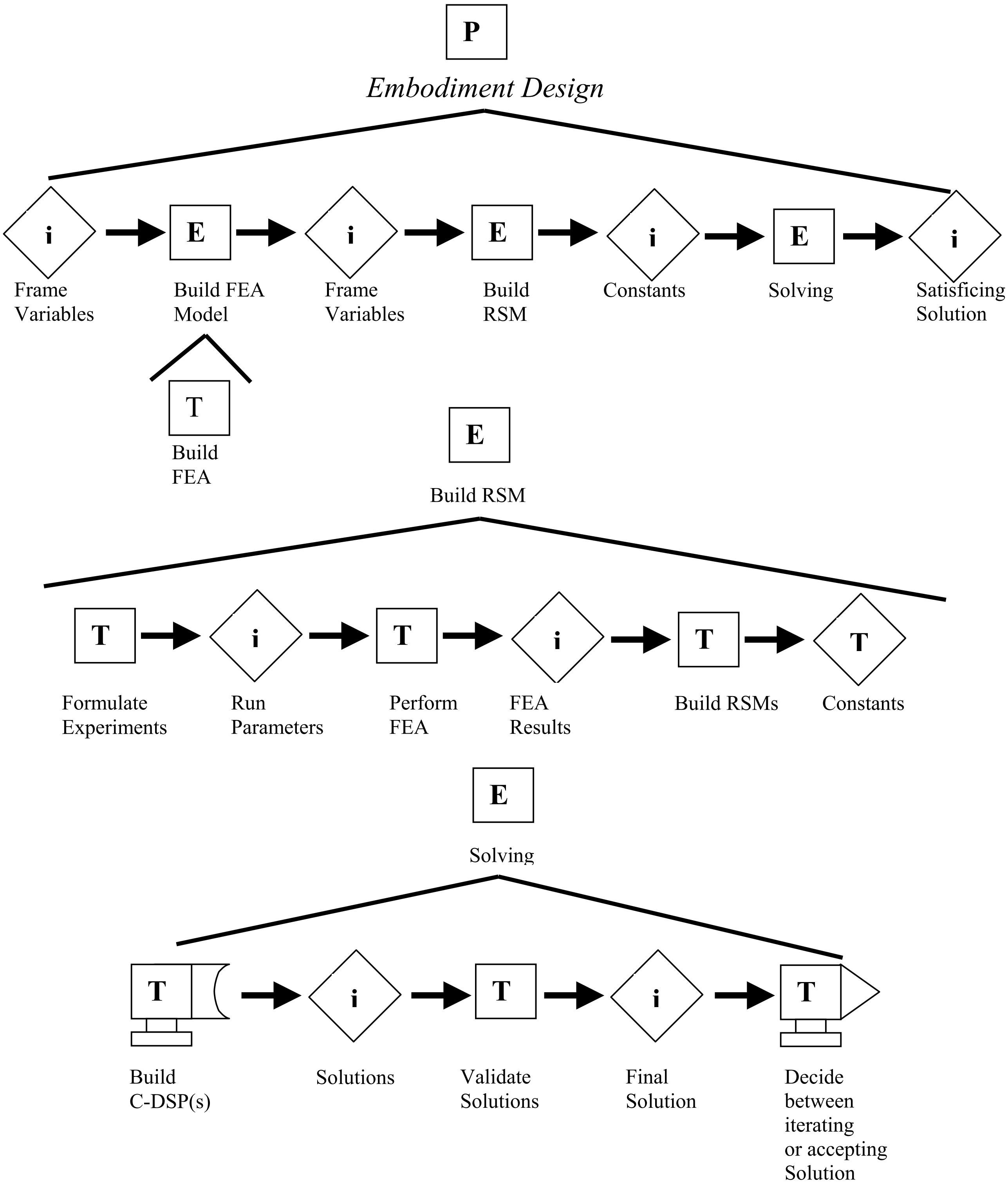


Figure 3.1.4 - The Embodiment Design phase of the GTMS frame.

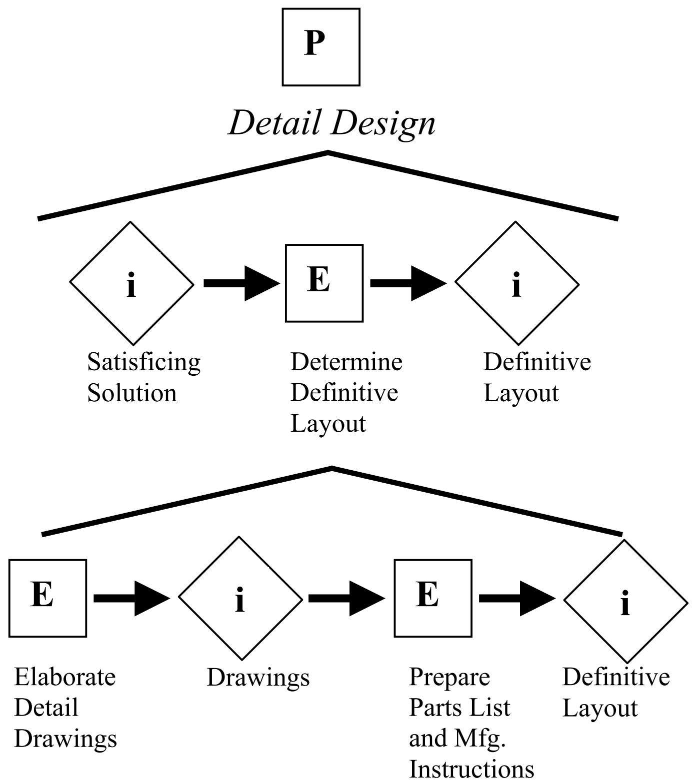


Figure 3.1.5 - The Detail Design phase of the GTMS frame.

3.1.2 Explanation of the Design Process

Planning phase (see Figure 3.1.1)

i - the Problem is assigned from the main team body
E - Identify the Problem
  T - frame team identify key changes between last years' and this year's rules
    frame team identify successes and failures from previous years
    frame team leaders inventory available resources (including people)
    frame team leaders identify interrelationship with other substructures
  i - rules, past designs, and available resources are available
i - the frame Problem Story is formulated
E - Planning
  T - the objectives of the frame team are set, the PEI diagram and DSPT palette are built from the main team's PEI diagram and DSPT palette
  i - frame team PEI diagram and DSPT palette
i - the frame Process Plan is available

Clarification of Task phase (see Figure 3.1.2)

i - the frame Process Plan is executed
E - Identify
  T - frame team performs Brainstorming and Affinity Diagram activities
  i - Requirements List and Functions Structure are formed
i - the Requirements are identified
E - Planning
  T - the frame team analyzes the Design Process
  i - a plan of action is formulated
i - the Working Plan is available

Conceptual Design phase (see Figure 3.1.3)

i - the Working Plan is executed
E - build Function Structure
  T - frame team builds Function Structures for frame
  i - the frame Function Structure is formed
i - Function Structure
E - Develop Concepts
  T - the team Analyzes the Working Structures from previous designs and how they fit constraints to determine changeable variables & parameters
  i - Variables & parameters
i - Frame Variables & parameters

Embodiment Design phase (see Figure 3.1.4

i - Frame Variables & parameters
E - Build FEA Model
  T - frame team builds FEA Model

i - Frame Variables & parameters e
E - Build RSM
    T - the frame team Formulates Experiments
    i - experiment parameters
    T - the FEA experiments are run
    i - FEA results
    T - RSM are built and evaluated
    i - RSM Constants
i - Constants calculated from the RSM
E - Solving
    T - build Compromise DSP(s)
    i - C-DSP solutions
    T - Validate C-DSP solutions with FEA
    i - Final Solution
    T - Decide between iterating or accepting Solution
i - Satisficing Solution

Detail Design phase (see Figure 3.1.5)

i - Satisficing Solution
E - Determine Definitive Layout
    T - dimensions and surface properties of all the individual parts are drawn and laid down
    i - Drawings
    T - materials are specified, production possibilities assessed, costs estimated and all other production documents produced
    i - Definitive Layout
i - Definitive Layout

3.2 CLARIFICATION OF TASK

Goals

- Minimize weight
- Minimize complexity
- Provide efficient load paths for all suspension inputs
- Minimize fabrication complexity
- Provide outstanding front, side, and roll-over protection
- Provide integral suspension pick-up points

Brainstorming

To form the requirements list, we conducted a brainstorming exercise based on the Formula SAE® competition rules to determine issues affecting the design of the frame. The brainstorming exercise (conducted with GTMS team leaders) is shown in Figure 3.2.1.

(AA) stamping
(AB) single piece
(AC) firewall
(AD) ground clearance
(AE) steering mounts
(AF) suspension mounts
(AG) inventory
(AH) drivetrain mounts
(AI) fuel tank
(AJ) battery/electrical system
(AK) jacking points
(AL) brake lights
(AM) geometrical layout
(AN) bulkhead/crush
(AO) machining
(AP) tubing X section
(AQ) welding
(AR) engine support
(AS) torsion
(AT) seat driver
(AU) exhaust/muffler mounts
(AV) body shell
(AW) simplicity
(AX) interface w/ existing components
(AY) coolant mounts
(AZ) assembly ease
(BA) weight
(BB) seatbelts
(BC) clearance holes
(BD) suspension
(BE) screws
(BF) snap fit
(BG) rollover
(BH) structural
(BI) wheelbase
(BJ) mfg. process
(BK) impact
(BL) fire extinguisher
(BM) satisficing
(BN) flexibility
(BO) robustness
(BP) mutability
(BQ) material
(BR) cost
(BS) FEA model
(BT) CAD model

Figure 3.2.1 - The frame Brainstorming exercise.

Affinity Diagram

The issues identified from the brainstorming exercise were grouped under common headings forming an Affinity Diagram (see Figure 3.2.2). Although the heading are numbered, the numbers do not indicate a ranking only a means of ordering the categories.

1. Geometric constraints

- (AF) suspension mounts
- (AE) steering mounts
- (AI) fuel tank
- (AH) drivetrain mounts
- (AJ) battery/electrical
- (AK) jacking points
- (BC) clearance holes
- (AY) coolant mounts
- (BI) wheelbase
- (BB) seatbelts
- (AC) firewall
- (AD) ground clearance
- (AL) brake lights
- (AM) geometrical layout
- (AU) exhaust/muffler mounts
- (BL) fire extinguisher
- (AV) body shell
- (AN)

2. Driver

- (AT) seat

3. Structural

- (BG) rollover
- (AB) single piece
- (BS) FEA model
- (AS) torsion
- (BQ) material
- (BH) structural
- (BD) suspension
- (BK) impact
- (BT) CAD model
- (AR) engine support

4. Manufacturing

- (AW) simplicity
- (BJ) mfg. process
- (AQ) welding
- (AO) machining
- (AA) stamping
- (BE) screws
- (BF) snap fit
- (AZ) assembly

5. Quality/Cost goals

- (AX) interface w/ existing
- (BP) mutability
- (BM) satisficing
- (BN) flexibility
- (BO) robustness
- (BR) cost
- (AG) inventory
- (AP) tubing X
- (BA) weight

Figure 3.2.2 - The frame Affinity Diagram.

Requirements List

The categories from the Affinity Diagram were transformed into a requirements list and identified as wishes or demands by team members (see Figure 3.2.3).

<u>1. Geometric constraints</u> – the frame must provide rigid mounting locations for

- front suspension
- rear suspension
- steering
- fuel tank
- jacking points
- seat and seatbelts (house driver)

The following items may or may not be attached to the frame, they can be attached via non-rigid means (i.e., velcro, wire ties):

- muffler
- body (shell) & firewall
- brake lights
- coolant reservoir
- battery & electrical system

The drivetrain is usually supported by the engine and suspension. Ground clearance is usually achieved by adjusting the suspension.

<u>2. Driver</u> – the frame must completely encapsulate the driver.

<u>3. Structural performance</u> – the frame must protect the driver from impact and rollover, it should be designed and analyzed using CAD/CAD tools, it must support and protect the engine.

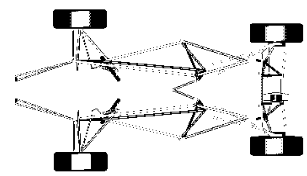
<u>4. Manufacturing</u> – the frame should simple to assemble by students with minimal training using existing lab equipment (welding, stamping, machining) and off-the-shelf fasteners.

<u>5. Quality/Cost Goal</u> – the frame must have a flexible design which can be mutated to hold existing substructures in various configurations, it should be made of inexpensive materials (i.e., no space-age materials that are difficult to get and costs more than the comparable amount of metal), the frame must use existing inventory of parts (tubing), if we can minimize the weight of the frame it will require less engine power.

ME 6102	Requirements List for Racecar Frame	Issued on: April 12, 2000

Problem Statement:

Ideally, a single frame of the GTMS racecar for the Formula SAE® competition should serve as the base for all present and future racecar designs. Analyze the frame to facilitate attaching present (and future) substructures.



Changes	D W	Requirements	Resp.
		1. Geometric constraints:	
	D	attach front suspension	
	D	attach rear suspension	
	D	attach steering	
	D	attach fuel tank	
	W	attach drivetrain	
	D	attach seat and seatbelts (house driver)	
	W	attach muffler	
	W	attach body (shell) & firewall	
	W	attach brake lights	
	W	provide ground clearance	
	W	attach coolant reservior	
	W	attach battery & electrical system	
	D	provide jacking points	
		2. Driver:	
	D	must house driver	
		3. Structural performance:	Tord
12-Apr-00	D	protect the driver from impact, rollover	&
	D	can be designed and analyzed using CAD/CAD tools	GTMS
	D	support engine	
		4. Manufacturing:	
	W	simple to assemble	
	D	use off-the-shelf fasteners	
	D	can be mfg with existing equipment (welding, stamping, machining)	
		5. Quality/Cost Goal:	
	D	flexible design, can be mutated to hold substructures in various configurations	
	D	inexpensive material	
	D	interface with existing substructures	
	D	use existing inventory of parts (tubing)	
	W	minimize weight	

Figure 3.2.3 - The frame Requirements List.

3.3 CONCEPTUAL DESIGN

Working from the Requirements List, we develop the function structure of the frame by analyzing the basic functions proposed by each requirement (see Table 3.3.1).

Requirements	**Description**	**Function**
Geometric constraints	the frame must provide rigid mounting locations for • front suspension • rear suspension • steering • fuel tank • jacking points The following items may or may not be attached to the frame, they can be attached via non-rigid means (i.e., velcro, wire ties): • muffler • body (shell) & firewall • brake lights • coolant reservoir • battery & electrical system The drivetrain is usually supported by the engine and suspension. Ground clearance is usually achieved by adjusting the suspension.	the frame must provide rigid mounting locations for substructures
Driver	the frame must completely encapsulate the driver	the frame must completely encapsulate the driver
Structural performance	the frame must protect the driver from impact and rollover, it should be designed and analyzed using CAD/CAD tools, it must support and protect the engine.	the frame must protect the driver from impact and rollover
Manufacturing	the frame should simple to assemble by students with minimal training using existing lab equipment (welding, stamping, machining) and off-the-shelf fasteners.	no function
Quality/Cost Goal	the frame must have a flexible design which can be mutated to hold existing substructures in various configurations, it should be made of inexpensive materials (i.e., no space-age materials that are difficult to get and costs more than the comparable amount of metal), the frame must use existing inventory of parts (tubing), if we can minimize the weight of the frame it will require less engine power.	no function

Table 3.3.1 - Frame functions.

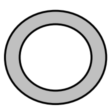
From the basic functional requirements shown in Table 3.3.1, we can abstract that the function of the frame is to:

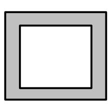
Attach substructures and protect and contain the driver.

3.4 EMBODIMENT DESIGN

3.4.1 Build FEA

The frame is modeled as a beam mesh using the I-DEAS software package by SDRC (**S**tructural **D**ynamics **R**esearch **C**orporation). The present frame is a truss structure of 65 tubes, 2 cross-section shapes (circular and square) and 8 cross section dimensions as illustrated in Table 3.4.1. Tubing cross-sections are identified in Appendix A.





Shape	D/W (in)	wall t (in)	A (sq in)	length (in)	vol (cub in)	weight (lbf)
Pipe	1	0.065	0.395134	75.952	30.01120359	8.485
Pipe	1	0.049	0.300333	68.229	20.49142818	5.794
Pipe	1	0.028	0.173466	304.533	52.82617618	14.935
Pipe	0.875	0.035	0.188574	130.536	24.61570859	6.960
Pipe	0.625	0.035	0.133596	113.085	15.1077294	4.271
Box	1	0.049	0.095599	70.438	6.733802362	1.904
Box	1	0.035	0.068775	129.894	8.93345985	2.526
Box	0.875	0.049	0.083349	263.067	21.92637138	6.199
						51.074 lbf total

mild steel (4130)

3.00E+07 psi	Elastic Modulus
0.29	Poisson's Ratio
7.32E-04 lbf s^2/in^4	density
1.16E+07 psi	Shear Modulus
3.60E+04 psi	Yeild Stress

Table 3.4.1– Frame parameters and variables.

The total weight of the frame is approximately 51 pounds. The material of all the tubes is a generic 4130 mild steel. After discussing the structural performance of the frame with GTMS members, we decided that for the first iteration we would like to analyze:

- head-on impact (ranging from 400-3600 lbf axial loading).
- restraints at the suspension points.

The boundary conditions are illustrated in Figure 3.4.1. Other boundary conditions (i.e., roll-over, side impact) will be analyzed at a later date. We do not have the means to conduct a physical test and verify the results from our FEA, but we are comfortable with the results as long as the stresses and strains stay in the linear region of the stress-strain curve for 4130 steel.

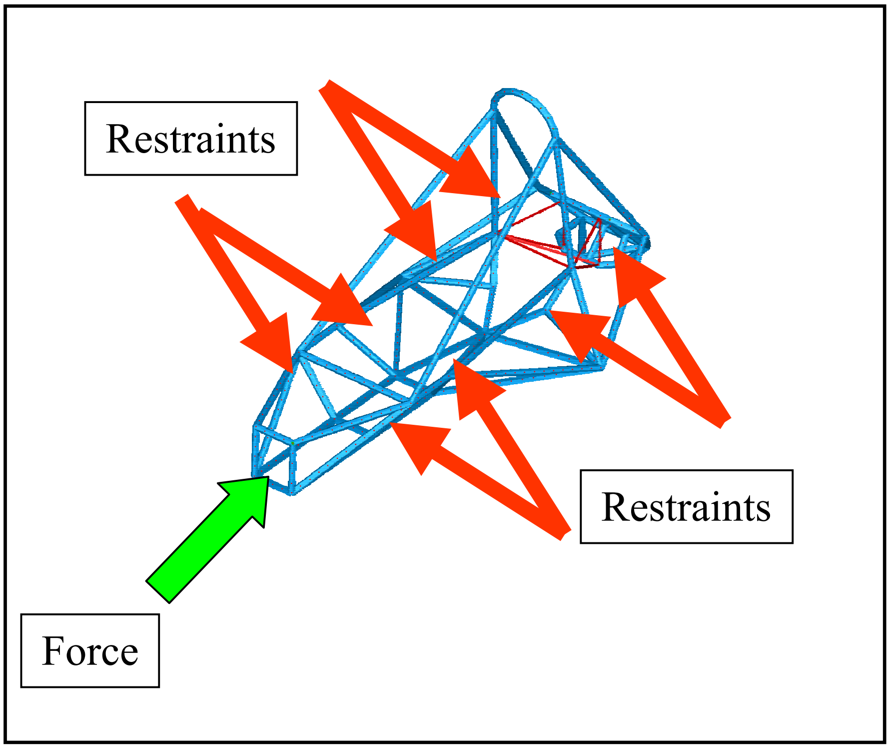


Figure 3.4.1 - GTMS frame and substucture mounting points.

3.4.2 Build Response Surface

Our goal is to minimize the number of cross-sections used in the frame while maximizing its performance. The original design of the frame was developed over 3 years ago and many modifications have been made to the cross-sections to "beef-up" certain. The actual centerline geometry of the beams has not changed. One alternative is to modify every beam to one cross-section, perform the FEA and then repeat for the other 7 cross-sections and compare the results. This only allows us to compare 8 cross-sections, what if we want to evaluate the multitude of other commercially available tubing sizes?

Using the allowable strain and stress of mild steel as constrains, I would like to formulate a Compromise DSP to minimize the weight of the frame by iterating through the available tubular cross-sections. The 15 truss members highlighted in Figure 3.4.2 are always made of a box cross-section (diameter = 0.875 in, wall thickness = 0.049 in) due to the competition rules.

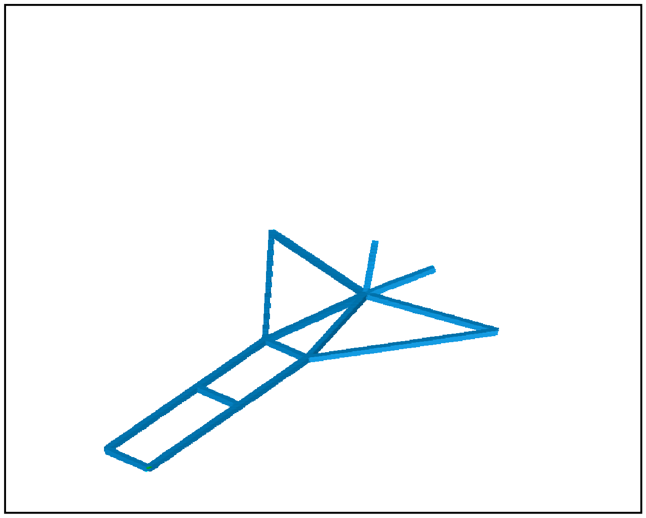


Figure 3.4.2 - Truss members where cross-sections cannot be changed.

With Gabriel's help, I formulated a strategy to analyze the frame by changing the cross-section of all of the changeable members to one cross-section and building a linear composite **R**esponse **S**urface **M**odel (**RSM**).

In the first analysis, the box cross-section variables were normalized between -2 and 2 as shown in Table 3.4.2.

box	-2	-1	0	1	2
diameter	0.8125	0.8750	0.9375	1.0000	1.0625
thickness	0.0280	0.0350	0.0420	0.0490	0.0560
force	100.0000	300.0000	500.0000	700.0000	900.0000

Table 3.4.2 - Box cross-section normalization.

8 screening runs were made and the FEA model was run to determine the maximum deflections, Von Mises stress and Von Mises strain developed.

Run	Diameter	Thickness	Axial Force	Deflection	Stress	Strain
1	-1	-1	-1	1.079E-02	1.103E+04	1.834E-04
2	1	-1	-1	1.029E-02	8.724E+03	2.111E-04
3	-1	1	-1	1.023E-02	8.194E+03	1.336E-04
4	1	1	-1	9.832E-03	6.431E+03	1.112E-04
5	-1	-1	1	2.517E-02	2.573E+04	4.280E-04
6	1	-1	1	2.400E-02	2.036E+04	3.584E-04
7	-1	1	1	2.388E-02	1.912E+04	3.118E-04
8	1	1	1	2.294E-02	1.501E+04	2.596E-04

Table 3.4.3 - Box cross-section runs.

For example, in row 1 of Table 3.4.3, all of the changeable members of the frame were set to a width of 0.875 inches and a thickness of 0.035 inches. The axial load was set to 300 pounds and the FEA was run. The maximum deflections, Von Mises stress and Von Mises strain developed in the entire frame were recorded. This exercise was repeated 7 times for the other criteria. Using the MiniTab software package, residuals of high accuracy (99.9%, 97% and 96.2% for the deflection, stress and strain respectively) were determined. Graphs of the response surfaces are shown in Appendix B.

For the circular cross section, a completely different picture emerged. The pipe cross-section variables were also normalized between -2 and 2 as shown in Table 3.4.4.

pipe	-2	-1	0	1	2
diameter	0.4375	0.6250	0.8125	1.0000	1.1875
thickness	0.0095	0.0280	0.0465	0.0650	0.0835
force	100.0000	300.0000	500.0000	700.0000	900.0000

Table 3.4.4 - Pipe cross-section normalization.

The 8 runs developed 4 models where stresses are higher than the yield stress (see highlighted regions in Table 3.4.5) and yielded residuals of 82%, 87.8% and 88.6% for the deflection, stress and strain respectively. Expanding the experiment to 15 runs increased the residual accuracy to 93.1%, 94.1% and 93.4% (for the deflection, stress and strain respectively) but there are now 7 runs with stresses beyond the elastic limit.

Run	Diameter	Thickness	Axial Force	Deflection	Stress	Strain
1	-1	-1	-1	0.0258300	36380.0	0.0006332
2	1	-1	-1	0.0121800	16400.0	0.0003210
3	-1	1	-1	0.0120600	18240.0	0.0003084
4	1	1	-1	0.0100000	7718.0	0.0001473
5	-1	-1	1	0.0602800	84890.0	0.0014780
6	1	-1	1	0.0284100	38260.0	0.0007490
7	-1	1	1	0.0281300	42570.0	0.0007196
8	1	1	1	0.0233400	18010.0	0.0003436
9	-2	0	0	0.0592900	72730.0	0.0011690
10	2	0	0	0.0164700	12770.0	0.0002589
11	**0**	**-2**	**0**	**0.0711800**	**107800.0**	**0.0020290**
12	0	2	0	0.0172800	15640.0	0.0002781
13	0	0	2	0.0337600	44630.0	0.0008154
14	0	0	-2	0.0037520	4959.0	0.0000906
15	0	0	0	0.0187600	24800.0	0.0004530

Table 3.4.5 - Pipe cross-section runs.

Experiment 11 was particularly high and running the regression without it increased the residual accuracy to 96.5%, 98.9% and 99.0% (for the deflection, stress and strain respectively). Graphs of the response surfaces are shown in Appendix B.

3.4.3 Build Compromise DSP

Word Formulation

Given

- Structural model of the frame.
- Response Surface Models of length (diameter, width), thickness and force.

Find

- Selection of tube (cross-section variables).
- Deviation variables of the Goals to bring the mean on target.

Satisfy

System Constraints:

- Stress must be less than the yield stress.
- Strain must be less than 2%

System Goals for bringing mean on target:

- Minimize the deflection.
- Minimize the stress.
- Minimize the strain.
- Minimize the weight.

Bounds

- The length (diameter, width) ranges from a minimum to a maximum value.
- The thickness ranges from a minimum to a maximum value.
- The product of each pair of deviation variables must equal zero.
- The deviation variables must be larger than zero.

Minimize

- The summation of the deviation products multiplied by the corresponding weights.

Mathematical formulation

Given

Structural model of the frame

Response Surface Models of length (diameter, width), thickness and force

Find

Selection of tube

- Design values - Diameter, Thickness
- Deviation values - d_i^- , d_i^+ (i=1,…,4)

Satisfy

System Constraints:

- stress <= 36000 (yield stress)
- strain <= 0.02 (2 % rule)

Goals

- (Deflection/Target) + d_1^- - d_1^+ = 1
- (Stress/Target) + d_2^- - d_2^+ = 1
- (Strain/Target) + d_3^- - d_3^+ = 1
- (Weight/Target) + d_4^- - d_4^+ = 1

Bounds

- min <= Diameter <= max
- min <= Thickness <= max
- $d_i^- * d_i^+ = 0$ (i=1,…,4)
- d_i^- , d_i^+ >= 0 (i=1,…,4)

Minimize

$$Z = W_1 d_1^+ + W_2\, d_2^+ + W_3\, d_3^+ + W_4\, d_4^+$$

Spreadsheet

I input the variables calculated from the RSM of the box analysis into a Microsoft Excel spreadsheet (see Table 3.4.6).

	Constant	D	Th	F
AOV Defl	0.017141	-0.000376	-0.000421	-0.006856
AOV Stress	14325	-1694	-2136	5730
AOV Strain	0.00025	-0.000015	-0.000046	0.00009

Table 3.4.6 - Box RSM constants.

C-DSP for the box analysis is shown in Table 3.4.7.

- The Targets are guesses based on our experience.
- The Width & Thickness Design Variables are varied by the spreadsheet's built in solver.
- The Force Design Variable is set by the designer.
- The Deflection Goal is equal to the AOV Deflection Constant + (deflection D * diameter coded) + (deflection Th * thickness coded) +(deflection F * force coded).
- The Stress & Strain Goals are calculated in a similar manner to the Deflection Goal.
- The Weight Goal is calculated based on the cross-section.
- The Deviation is the corresponding (Goal/Target) - 1.
- The weights have been arbitrarily assigned.
- The Deviation Function **Z** is the summation of the Deviations * the corresponding weight.

Category		Values	Units
Target value for	Deflection	0.01	inches
	Stress	36000	psi
	Strain	0.02	-
	Weight	51	pounds
Design Variables	Width	0.983	-
	Thickness	0.967	-
	Force	2	-
Goal	Deflection	0.01567	inches
	Stress	22054.29	psi
	Strain	0.000371	-
	Weight	53.12	pounds
		Over	Under
Deviation	Deflection	0.04917	0
	Stress	0	0.47013
	Strain	0	0.98
	Weight	0	0.041
Weights	Deflection	0.25	
	Stress	0.25	
	Strain	0.25	
	Weight	0.25	
Minimize	Z	0.012293	

Table 3.4.7 - C-DSP for the box cross-section.

Parameters were entered into the built-in solver and executed (see Figure 3.4.3). An initial guess for the Width & Thickness Design Variables (say 1, 1) is entered by the designer and the solver iterates within the bounds until the Deviation Function is minimized. This operation is repeated several times with the designer picking other initial guesses (within the variable bounds) to verify that convergence is reached.

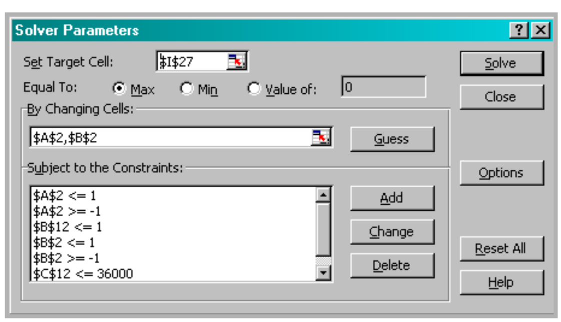


Figure 3.4.3 - C-DSP parameters in Excel solver.

3.4.4 Verify Model

The solver returned coded values of width = 0.983 and thickness = 0.967. These can be translated into the nearest box shape of 1.0 in X 0.049 in. The solver also estimates these values:

- Deflection = 0.0157 inches
- Stress = 16324 psi
- Strain = 2.81 E-4 estimated
- Weight = 53.12 lbf

Running the I-DEAS FEA model with the 1.0 in X 0.049 in cross-section yields:

- Deflection = 0.0295 in
- Stress = 19290 psi
- Strain = 3.370 E-4

Original model in I-DEAS yields:

- Deflection = 0.035 in
- Stress = 14920 psi
- Strain = 2.938 E-4
- Weight = 51 lbf

From the graph comparing the results shown in Figure 3.4.4, it is clear that the solution is a good one with the values in the same magnitude.

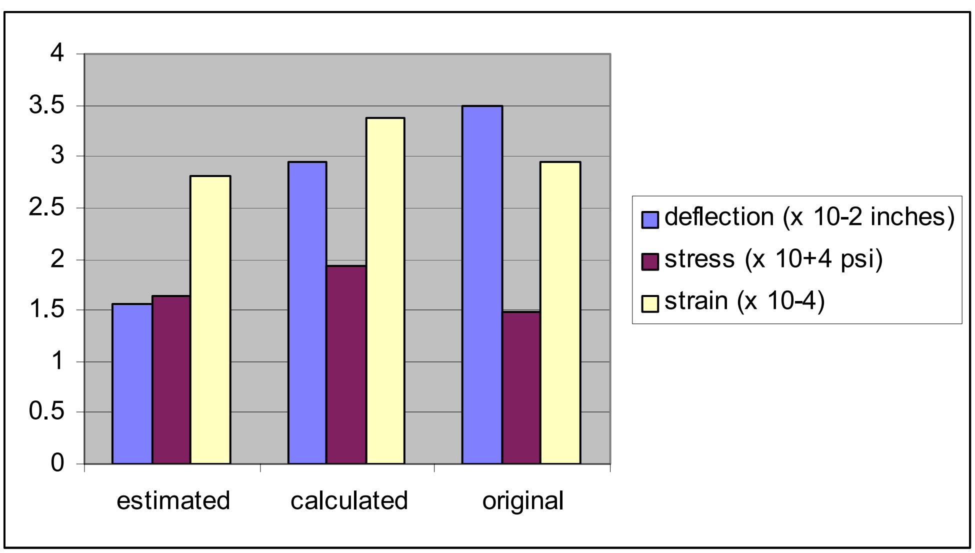


Figure 3.4.4 - Bar graph of deflection, stress and strain.

3.5 SUMMARY

In this chapter I applied the Pahl & Beitz method, augmented by the DSP Technique, to the design of the frame of the GTMS racecar. An RSM enabled me to quickly iterate through many cross-sections to approximate a satisficing solution to the problem of minimizing the number of cross-sections used in the frame. The FEA was used to generate input for the RSM and validate the results from the Compromise DSP. The pipe cross-section experiments violated my design constraints of keeping performance in the linear region of the stress-strain curve of the material. In order to explore the use of pipe cross-sections, I need to redefine the bounds of the diameter and thickness.

This was not the only formulation for the Compromise DSP that can be used to design the frame. Another possibility is to design a RSM for each tube and a C-DSP to control the interactions between RSMs. This approach allows me to examine the effects of changing one tube at a time but requires more set-up time than the previous method.

Overall I am quite pleased with the results:

- I demonstrated how the DSP Technique can augment the Pahl & Beitz method.
- I demonstrated how the Compromise DSP can be applied to find satisficing solutions.
- I demonstrated how FEA and RSM can be used in concurrence to achieve a goal.
- The FEA is useful to evaluate a point solution, the RSM is useful to evaluate a range of solutions.

CHAPTER 4

ME 6102 FINAL LEARNING ESSAY

In this chapter, I address the question for the semester by reflecting on the key concepts presented this semester in ME 6102 and articulating how I perceive them.

4.1 WHY STUDY DISTRIBUTED CONCURRENT ENGINEERING?

In the not so distant past, many companies had a "wall" mentality. Engineers in research were unfamiliar and uninterested in what happened in a project's design or manufacturing phases. Likewise, engineers in design were ignorant to the manufacturing concerns of the project. Once a design was done, it was handed over the wall to manufacturing with no regard to how well it could be manufactured (see Figure 4.1.1). Scrap and parts that failed the manufacturing phase were rejected and discarded as refuse. Designs that could not be manufactured efficiently were thrown back over the wall to be reengineered.

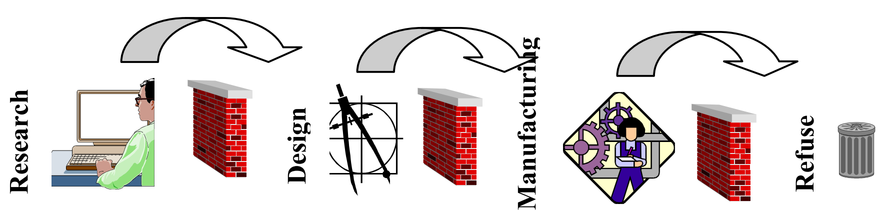


Figure 4.1.1 - The "wall" mentality.

In an effort to be competitive in the global economy and save costs, companies have come realized that engineers should work together towards a common goal. To avoid costly reengineering activities, each discipline must be aware of the other's capabilities and limitations (concurrent engineering). They must realize that there is inherent coupling between activities that cannot be broken and they may be able to initiate other coupling that could enhance their activities (see Figure 4.1.2). Companies also strive to reduce raw material waste by recycling as much material as many times as possible before discarding it as refuse.

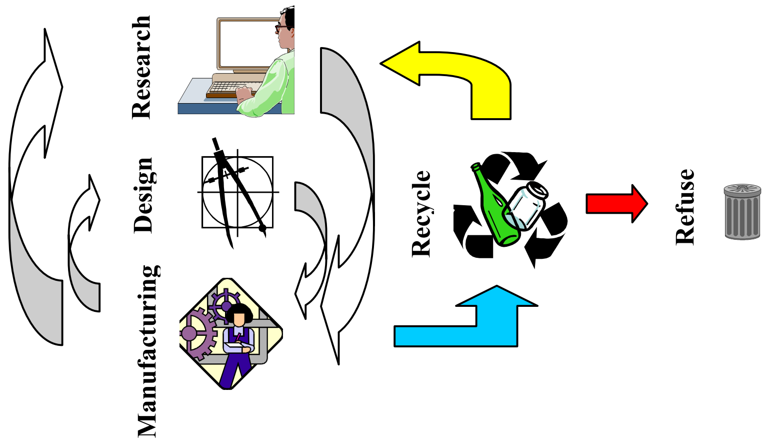


Figure 4.1.2 - Concurrent engineering model.

At the beginning of the 20th century, we began to recognized the significant contributions machines can make to our quality of life by performing the three Ds (dull, dangerous and dirty work). The rise of computers in the 1970's heralded the beginning of a another machine revolution enabling engineers to rapidly model physical entities mathematically. With **C**omputer **A**ided **D**esign (**CAD**) , engineers can quickly conceptualize an idea in a virtual 3 dimensional computer generated world without the large expenditure of building a prototype part. Using **C**omputer **A**ided **M**anufacturing (**CAM**) tools, the CAD engineer can control, monitor, and adjust tools and machinery to manufacture parts from computer generated images (see Figure 4.1.3). **C**omputer **A**ided **E**ngineering (**CAE**) allows the engineer to simulate the performance of systems with the need for experimental tests. CAD engineers can make small changes to components and immediately see the impact of these changes on the parts' performance using CAE tools. With CAE, engineers can virtually stress test prototypes literally hundreds of times. These 3D tools facilitate the concurrent engineering process and help reduce the amount of time (and costs) necessary to introduce new products by reducing the need for physical prototypes.

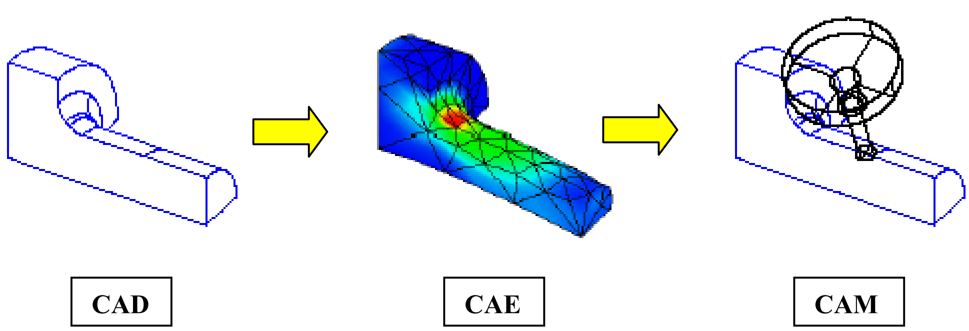


Figure 4.1.3 - Cooperative CAD/CAE/CAM activities.

The Big Three automakers; Ford, **G**eneral **M**otors (GM) and Chrysler, first attempted to enter the computer-aided arena by developing their own in-house CAD/CAD/CAE (C3) software packages. They soon found it was easier to concentrate on what they do best and purchase software from other vendors. Ford standardized on I-DEAS by **S**tructural **D**ynamics **R**esearch **C**orporation (**SDRC**), Chrysler standardized on CATIA by Dassault Systemes of France and UG standardized on Unigraphics by purchasing Unigraphics Solutions Inc. C3 works well when all of your engineers are based in a single location but today's business climate finds manufacturing and design operations scattered about different parts of the world. A fourth computer component; **P**roduct **I**nformation **M**anagement software (**PIM)**, automates the integration of CAD, CAE and CAM into a global system of common data. The information is accessible to all disciplines within a corporation to improve product quality, reduce cost and time to market.

Ford has succeeded in reducing the number of automobiles prototypes by 25 percent using C3P. Ford is working to reduce the amount of time it takes to introduce a new model by one year, and it estimates that the C3P project will help to eliminate half of costly late development changes. The C3P project at Ford integrates the company's CAD, CAE and CAM activities into a global system of common data functions resulting in a seamless, unified system encompassing all stages of vehicle and component development. Ford engineers can visualize and interact with entire vehicle assembly designs in real-time. The PIM database also features a wealth of data that represents best practices from Ford's engineers, past and present. Instead of reinventing solutions, engineers refer to the database to access historical data and avoid costly mistakes. Another benefit to Ford from C3P is the ability to take advantage of time zone differences to maximize the use of resources around the world for work collaboration. In a single day, an engineer laboring on a project for five hours in England will be able to hand off his design to another who works in Germany, who in turn works with someone in Australia. C3P allows Ford to distribute the workload more effectively and draw from expertise around the world literally turning the company into a 24 hour a day enterprise.

4.2 WHAT IS AN OPEN ENGINEERING SYSTEM (OES)?

To understand Open Engineering Systems, we must first define what an open system is. A system is defined as:

1. A group of interacting, interrelated, or interdependent elements forming a complex whole.
2. A group of independent but interrelated elements comprising a unified whole.

By this definition, a system is a finite set of entities with common attributes.

The definition of open is:

1. Affording unobstructed entrance and exit; not shut or closed.

Therefore an open system is a group of interacting, interrelated, or interdependent elements forming a complex whole in which elements (new or old) have the capability to enter or exit unobstructed. So an Open Engineering System would be comprised of elements engineered by humans.

Let's try another approach. Technology has placed every person physically 16 hours apart (via aeroplane) and literally seconds away by digital information (via cell phones and the internet). This reality has opened local markets to companies from distant regions, forcing local companies to change their attitudes: no more doing business as usual. To survive the dynamic environment of today's marketplace, companies must develop a system that can adapt quickly to the changing customer needs or become extinct. They must also compete against companies with diverse backgrounds and access to different resources in order to provide high quality goods and services in the shortest possible time at the lowest possible price. Companies must accept that change is inevitable, the only "business as usual" is the business of anticipating that there will be a change in the requirements for a product and flexible. . In order to be flexible and yet still profitable, a system must be:

- robust - able to weather changes that seem to be slightly out of its design parameters
- modular - able to fulfill other functions through rearrangement/replacement of physical components
- mutable - able to change in form to fit a new need while still retaining its function

These are the characteristics of an Open Engineering System (OES).

In a Closed System (see Figure 4.2.1), a product/process undergoes a birth process which is characterized by a steep increase in knowledge and costs. Then it moves into a production phase in which many copies of the prototype are made. Inevitably, some stimulus (i.e., change in customer requirements, tastes, goals) enters the system and ends the life of the product/process initiating a new cycle, a new product/process.

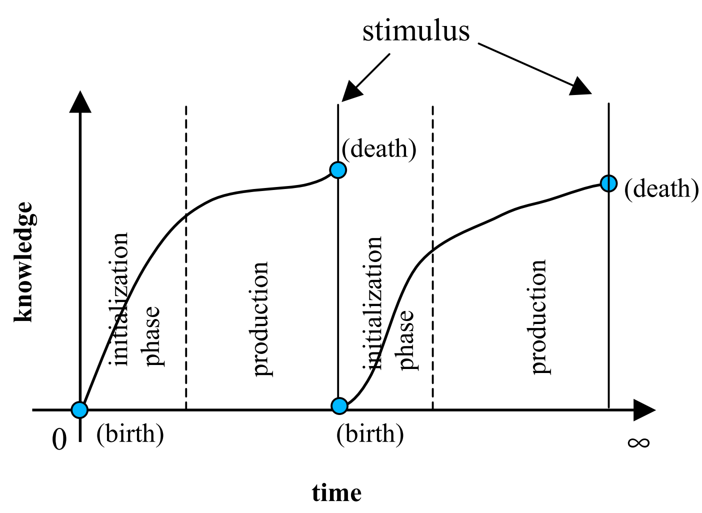


Figure 4.2.1 - Closed Engineering System.

The goal of an OES is to remain competitive by making modifications to an existing product/process without reinvention, eliminating the costly initialization phase. Note that the curve in Figure 4.2.2 undergoes a sharp increase only in the initialization phase. The bulk of its life exhibits a moderate change in slope.

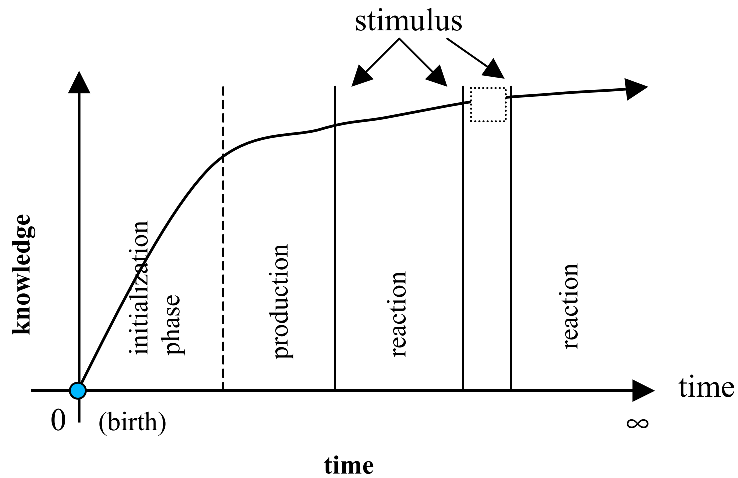


Figure 4.2.2 - Open Engineering System.

4.3 WHY IS PLANNING IMPORTANT?

The great Chinese general Sun Tzu [The Ancient Art of War] once said "the general who loses a battle makes but few calculations beforehand. Thus do many calculations lead to victory, and few calculations to defeat." Two basic facts of life are that resources are of finite supply (be it time, money, labor, etc.) and time equals money. Therefore the more mistakes one makes, the more time one spends working on a problem, the more costly the solution is (in time and resources). Some resources are irreplaceable and some mistakes can lead to irreversible situations (i.e., death)!

As an undergraduate I worked on the Formula SAE® racecar team. When I built the suspension carrier, my shop instructor told me "there is always enough time to do it again but never enough time to do it right the first time." This was his way of saying I need to plan my manufacturing process; what tools are needed, what order should the operations be performed, etc. I responded "this a simple part and I don't have time to make plans." Needless to say that once I had performed all of my operations on the lathe, I discovered that I had removed all of the "true" surfaces needed to drilled holes. Drilling holes off "untrue" surfaces resulted in a carrier that did not line up with the wheels and I had to rebuild it. One could argue, that the time I spent building two carriers may be equal to the time I would have spent planning and actually building one carrier. But the difference is that in one case I used twice the amount of aluminum that was needed.

The need to be competitive in a global economy has forced companies to adopt new strategies in order to be more responsive to customer needs and requirements. **J**ust-**in**-**t**ime (JIT) is a means of market pull inventory management imbedded within a humanistic environment of continuing improvement. The basic concept is to receive what is needed just in time for it to be used. This places the responsibility on the supplier to get what is needed to where it is needed, just before the time it is needed. Use of just-in-time methods results in considerably reduced inventory and enhanced customer response. However, to be successful, it requires a systemic and highly cooperative approach to inventory receipt, throughput, and delivery (i.e., planning).

Planning is of utmost concern when working in a complex concurrent engineering environment. Why?

- ✓ To keep the lines of communication open between teams that are interdependent.
- ✓ To keep teams working in parallel without duplication of efforts.
- ✓ To identify coupling between tasks (teams) and help facilitate information transfer between design teams.
- ✓ To display a process, revealing key information flows to discover previously unknown patterns: product architecture & organizational architecture.
- ✓ To maximize the use of available resources while minimizing waste.
- ✓ To avoid frequent changes in the direction of projects.

4.4 WHY USE THE DSP TECHNIQUE FOR CONCURRENT ENGINEERING?

It is accepted that the efficiency and effectiveness of a designer can be increased by:

- increasing the speed with which the design iteration is accomplished, and
- reducing of the number of iterations.

Therefore design productivity can be improved through the computerized application of a structured decision-making process. The Decision-Support Problem Technique aids in negotiating a superior, satisficing solution to a problem in engineering design by providing support for human judgement in the form of optimal solutions of **D**ecision **S**upport **P**roblems (**DSP**s). DSPs are codeable providing the means for modeling decisions encountered in design through domain specific mathematical models (templates). The DSP Technique is capable of conducting multiobjective mathematical programming across boundaries in a design process. Using DSPs, engineers can deal with coupling between dissimilar variables and determine the values of design variables which satisfy a set of constraints while achieving a set of conflicting goals as well as possible.

In this report I built a C-DSP to achieve a satisficing solution to reducing the number of cross-sections used while retaining the functions of the frame subject to fixed constraints from other substructures. To design the frame in a situation where the constraints from other substructures may vary, I can couple the C-DSP of the frame with other C-DSPs (i.e., . the front and rear suspensions as illustrated in Figure 4.4.1). This requires the redesign of the present frame C-DSP to take into account the change in geometry parameters from front and rear suspension C-DSPs.

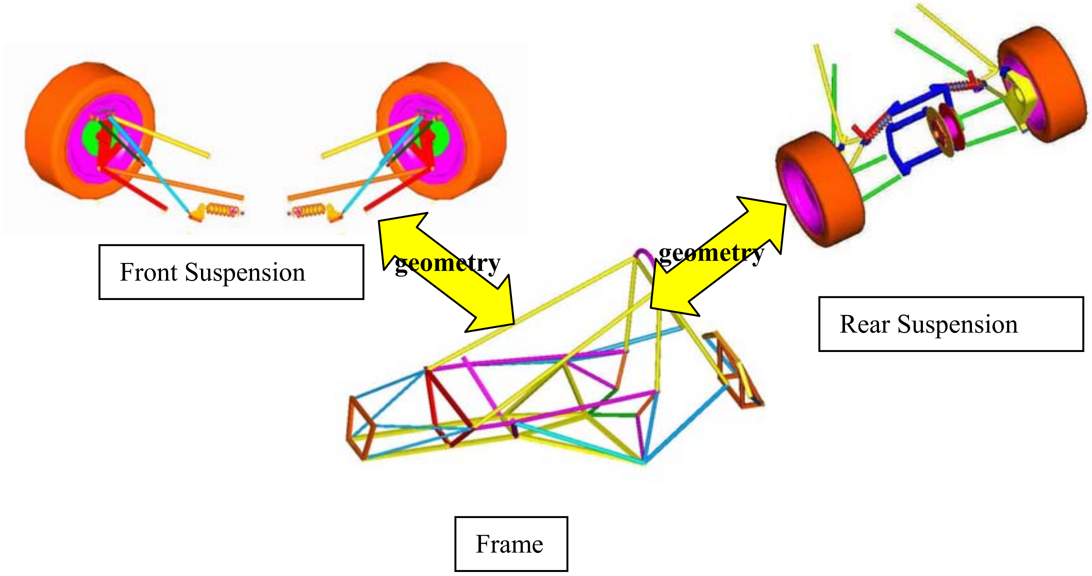


Figure 4.4.1 - Coupling Compromise DSPs.

4.5 WHY IS ME 6102 A GRADUATE COURSE?

One definition of **engineering** from http://www.dictionary.com is:

- The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems.

The answer the question "why is this a course in Engineering Design, nothing has been built" is that the design of processes is engineering and in this course we have designed the design process!

To answer the question "is there a need to teach a systematic approach to engineering design to university level students?" let's look at the definition of **science** from http://www.dictionary.com:

- Accumulated and established knowledge, which has been **systematized** and formulated with reference to the **discovery** of general truths or the operation of general laws; **knowledge** classified and made available in work, life, or the search for truth; comprehensive, profound, or philosophical knowledge.

We've established that engineering is a science (how else can you apply scientific principles without being a scientist?) therefore engineers must engage in the **systematic discovery** of **knowledge**.

Why is ME 6102 a graduate course? I believe that undergraduate school is when the foundations of a career are laid, the base elements are taught and undecided students get a taste of what path life may take if they stay the course. It is when the engineer's toolbox is packed with a variety of broad use tools because we are unsure of which ones will be needed. I think that the format of ME 6102 is more of "how to use these tools together" than "how to use the tools". To put it another way, in kindergarten we learned the alphabet before we learned the words, before we learned the sentences. Freshmen and Sophomores are learning the alphabet, Juniors are learning the words and Seniors and Graduate students are learning the sentences. I think that the information in ME 6102 is well suited for a senior level course but best suited for a graduate level course. I also believe that engineers should undergo at least another 2 years of formal instruction beyond undergraduate school to be considered professionals, but that's a whole 'nother argument.

4.6 SUMMARY

I have thoroughly enjoyed ME 6102 and I'm not being fictitious. I took ME 6101 when it was ME 6170 and was well aware of the level of dedication required for ME 6102. This didn't make it any easier on me, the work was still demanding, the hours grueling and my diet poor mostly because of my lifestyle and decisions I have made. This semester I taught labs for 2 classes (babysat 50 students), taught 3 classes as a consultant, mentored the GTMS team and bought a house while attempting to balance a personal life. I have become an expert at determining satisficing solutions to everyday problems.

My regrets:

- I didn't have the time or energy to pursue all of the topics and hints that Dr. Mistree and Gabriel tossed out in class.
- I didn't have the comradery of working in a team like I did in ME 6170.
- At times, I felt like an outcast, a lot of the students in the class were from SRL, they seems to be familiar with a lot of the elements that were discussed.

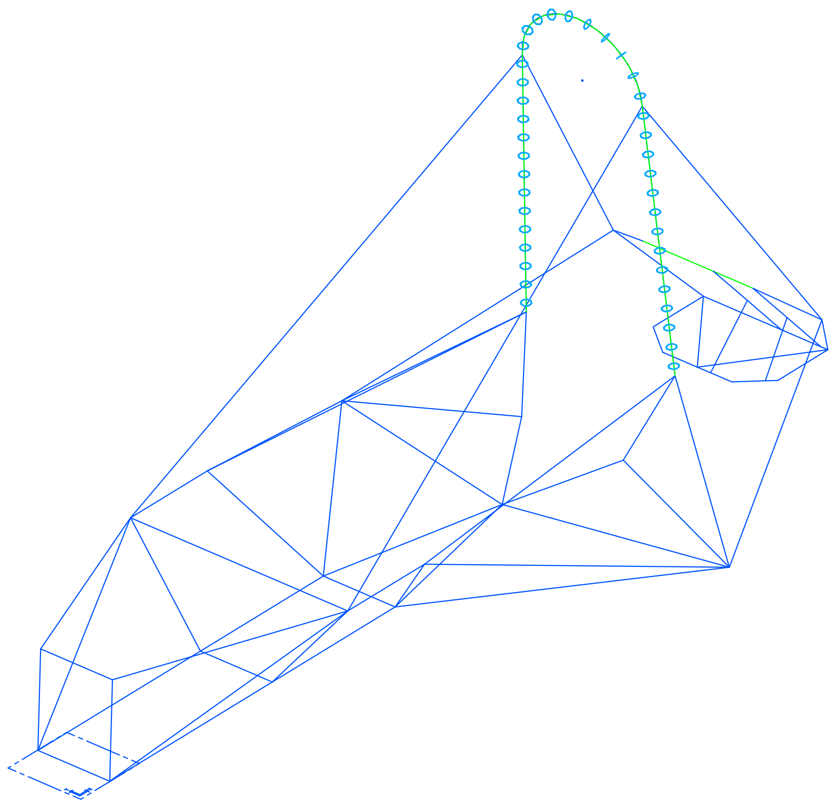
My successes:

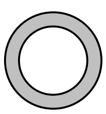
- Accomplished my goals of learning DBD in the form of the Pahl & Beitz method and the DSPT.
- Learned about OES and product families.
- Organized my Master's thesis! Much more to go.
- Learned to work as an individual and how to seek and find resources (hope I wasn't too much of a bother to Gabriel). The video tapes of the class were an excellent resource.
- Learned a lot about time management, planning and satisficing solutions. This report was done at 10 am.

Thanks Dr. Mistree and Gabriel for orchestrating my learning, I will be seeing you again soon.

APPENDIX A

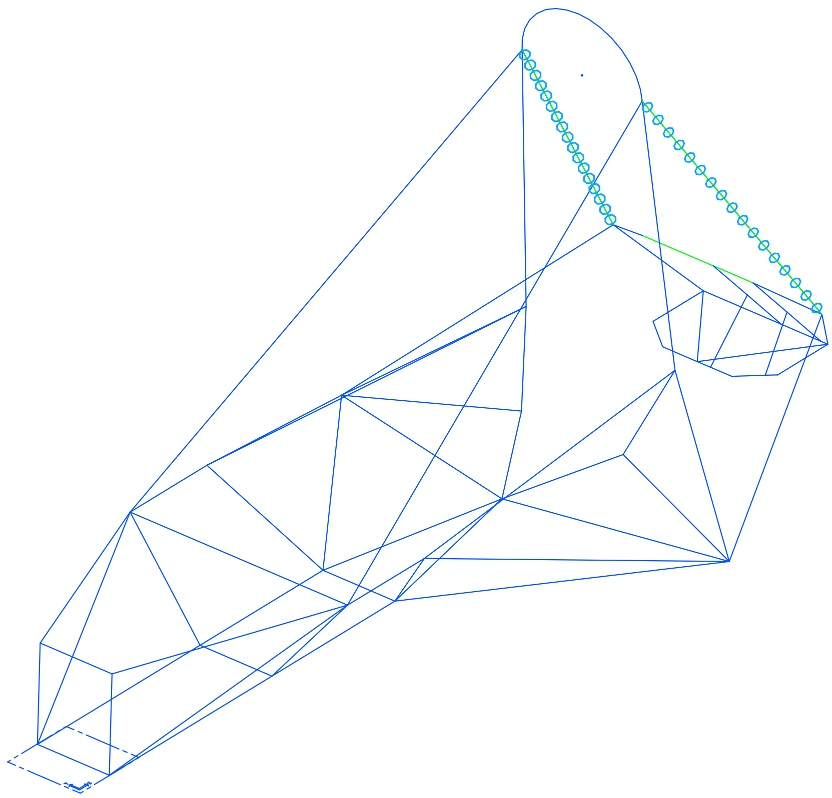
TUBING CROSS-SECTIONS

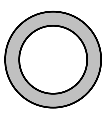




Shape	Diameter (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Pipe	1	0.065	0.395134	75.952	30.0112	8.485

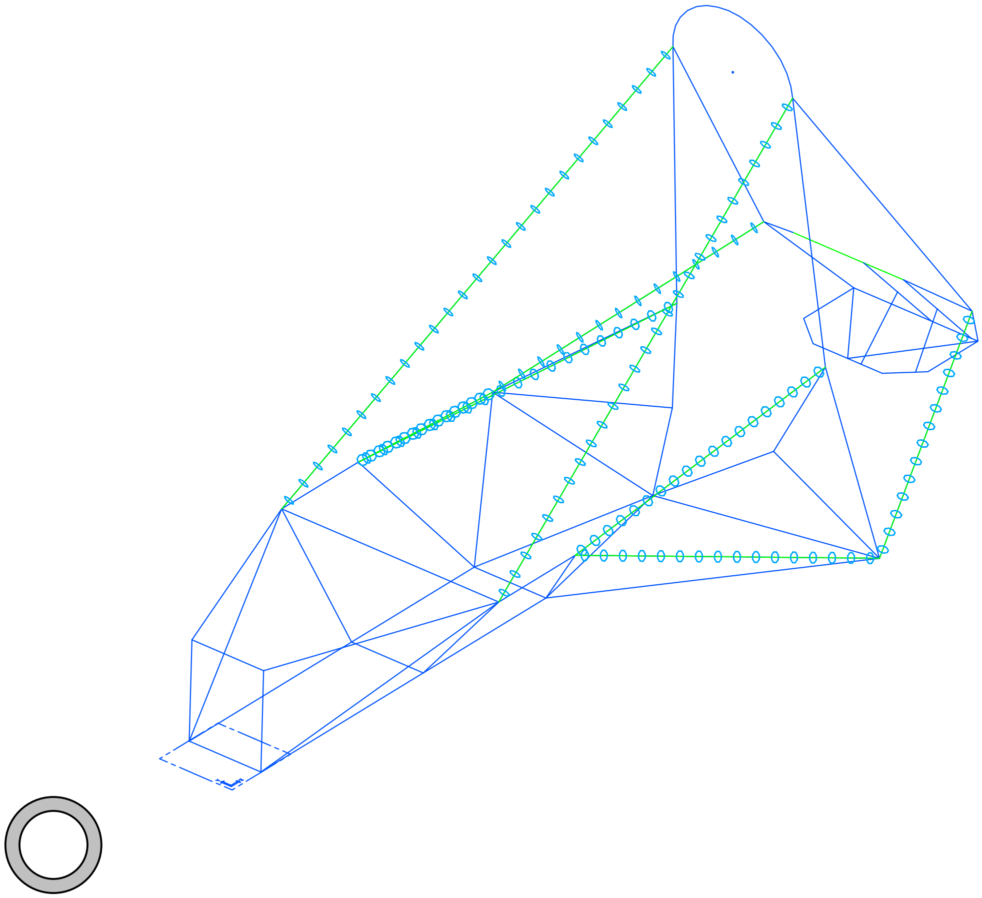
A 1 - Frame cross-section #1.





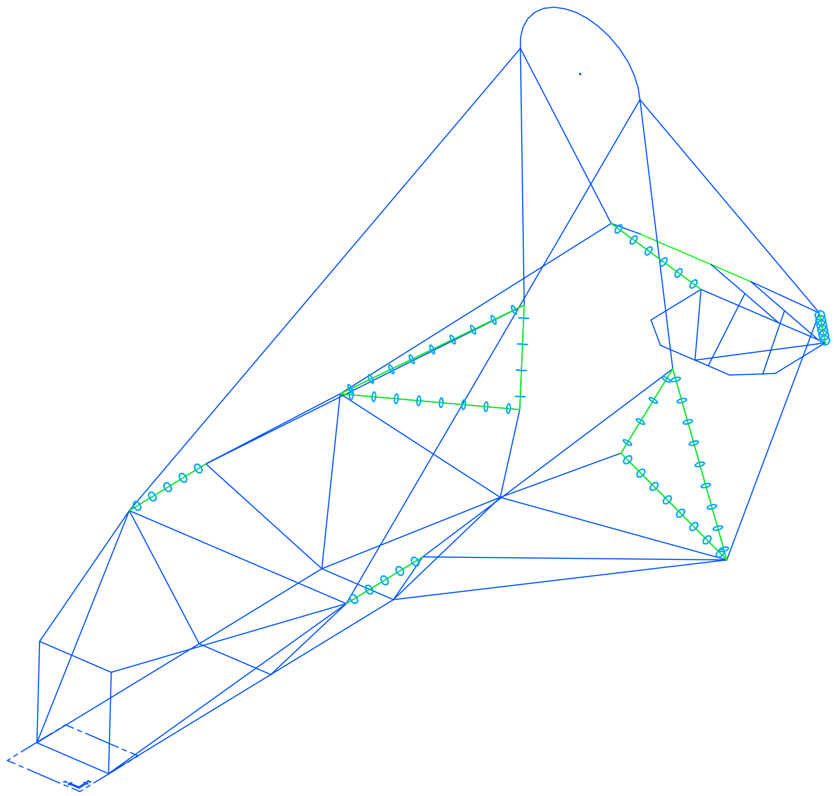
Shape	Diameter (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Pipe	1	0.049	0.300333	68.229	20.49143	5.794

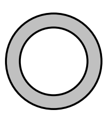
A 2 - Frame cross-section #2.



Shape	Diameter (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Pipe	1	0.028	0.173466	304.533	52.82618	14.935

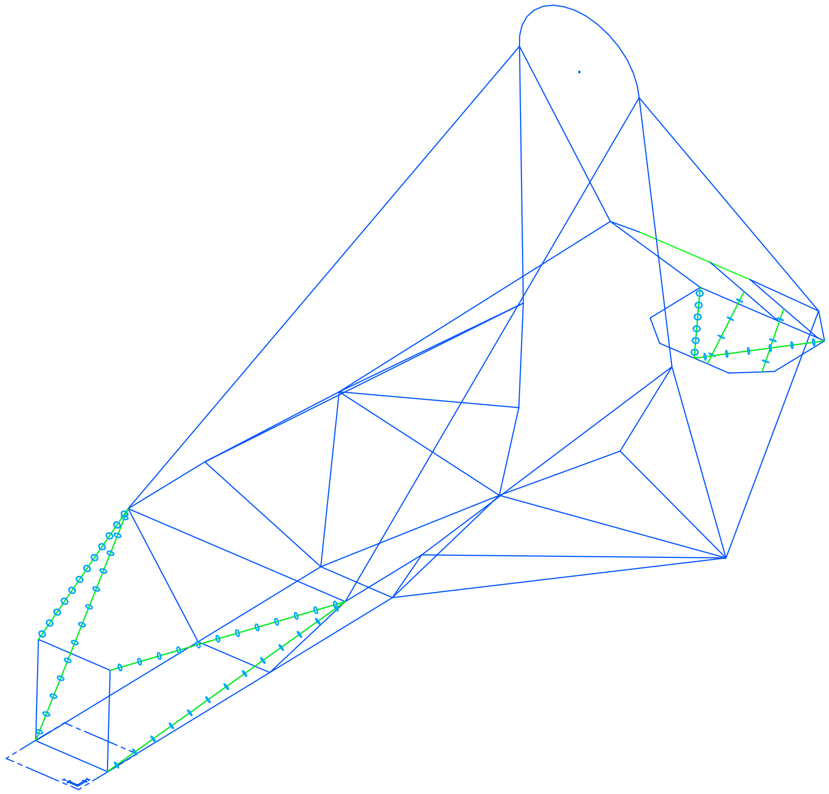
A 3 - Frame cross-section #3.

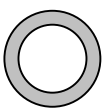




Shape	Diameter (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Pipe	0.875	0.035	0.188574	130.536	24.61571	6.960

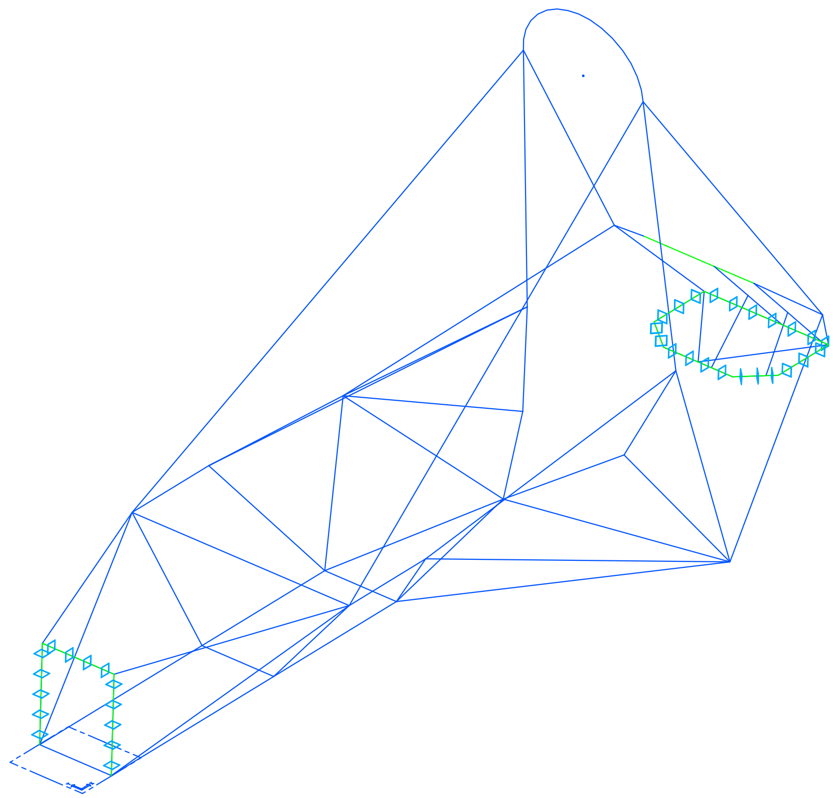
A 4 - Frame cross-section #4.

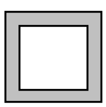




Shape	Diameter (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Pipe	0.625	0.035	0.133596	113.085	15.10773	4.271

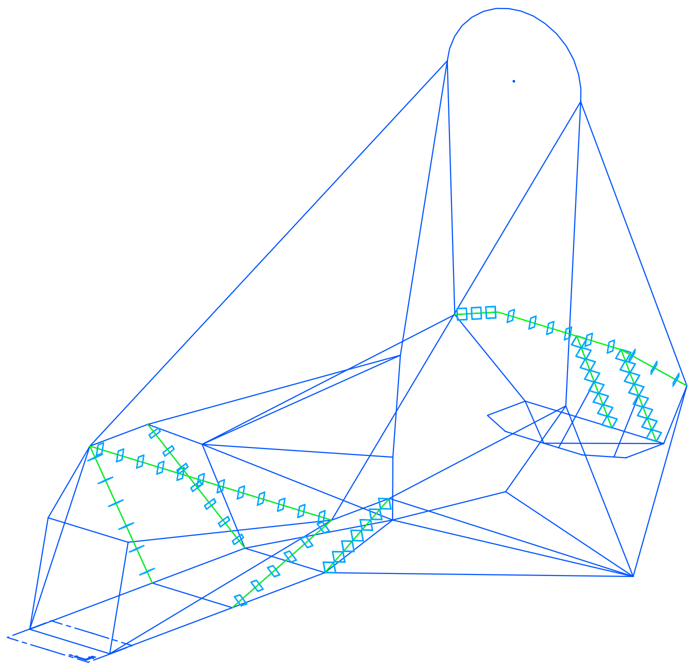
A 5 - Frame cross-section #5.

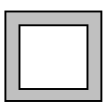




Shape	Width & Height (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Box	1	0.049	0.095599	70.438	6.733802	1.904

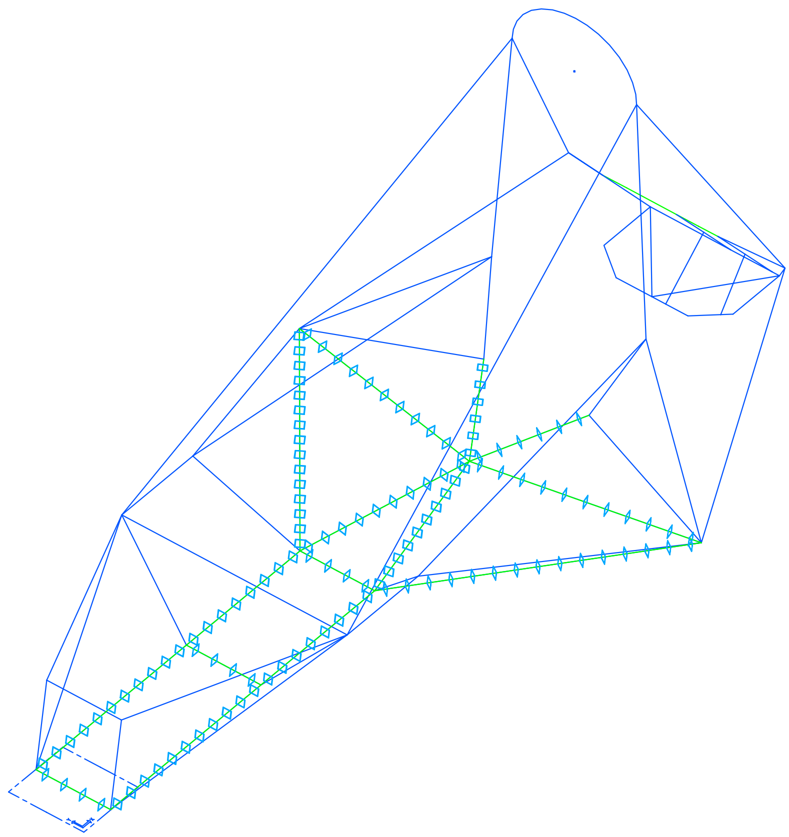
A 6 - Frame cross-section #6.

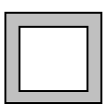




Shape	Width & Height (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Box	1	0.035	0.068775	129.894	8.93346	2.526

A 7 - Frame cross-section #7.

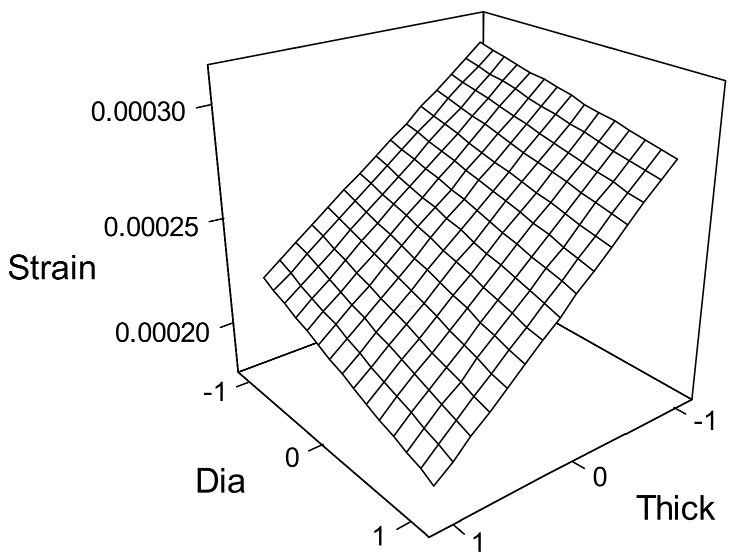




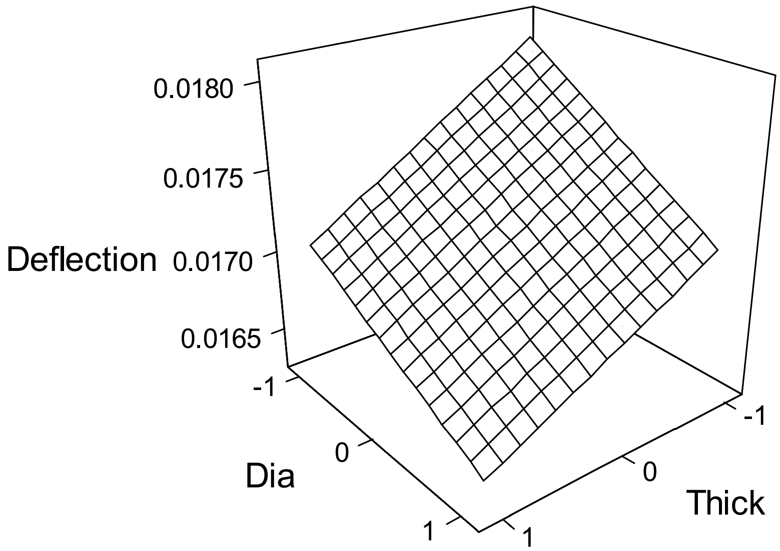
Shape	Width & Height (in)	Wall t (in)	Area (in)	Total length (in)	Total vol (sq in)	Total wt (lbf)
Box	0.875	0.049	0.083349	263.067	21.92637	6.199

A 8 - Frame cross-section #8.

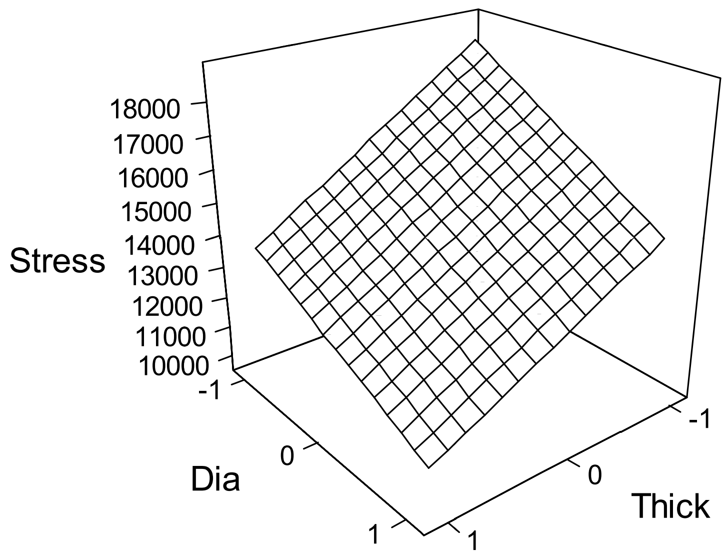
APPENDIX B
RESPONSE SURFACE GRAPHS



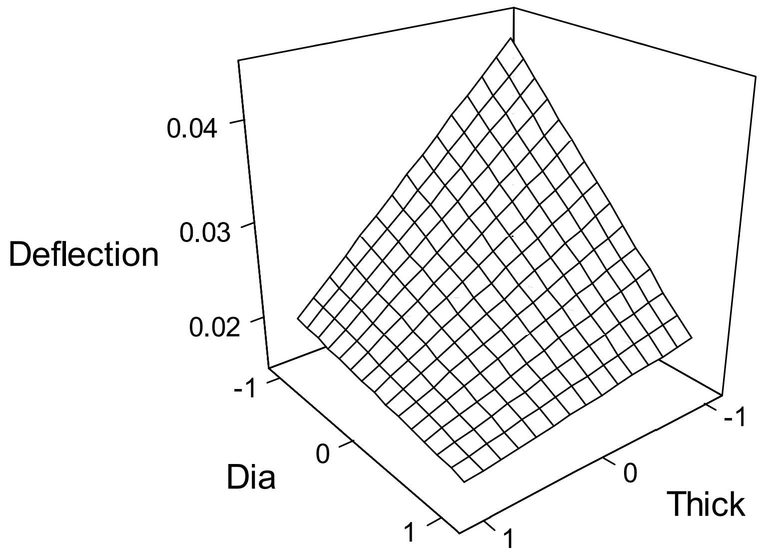
B 1 - Response surface graph for box cross-section, 8 runs (strain).



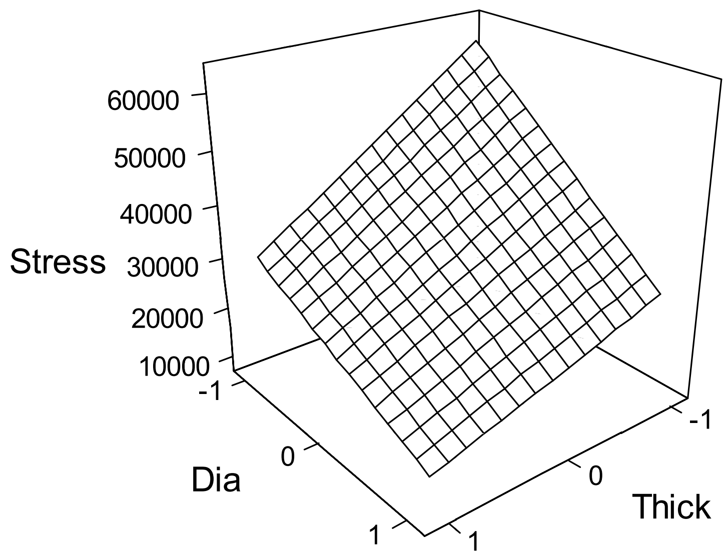
B 2 - Response surface graph for box cross-section, 8 runs (deflection).



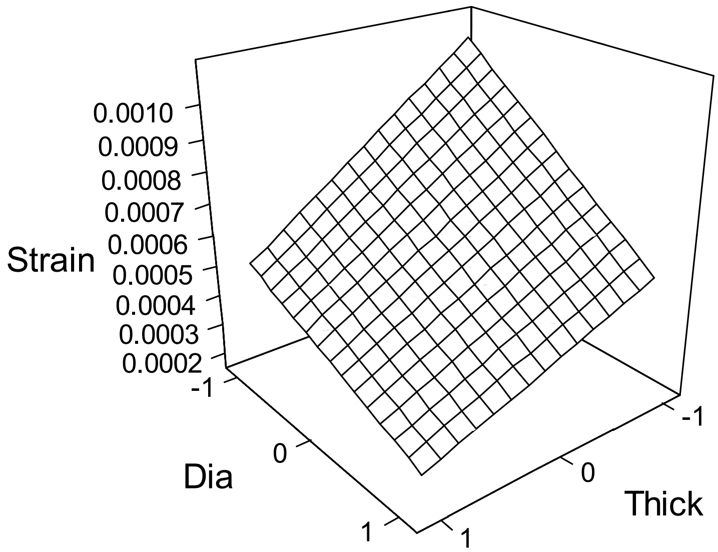
B 3 - Response surface graph for box cross-section, 8 runs (stress).



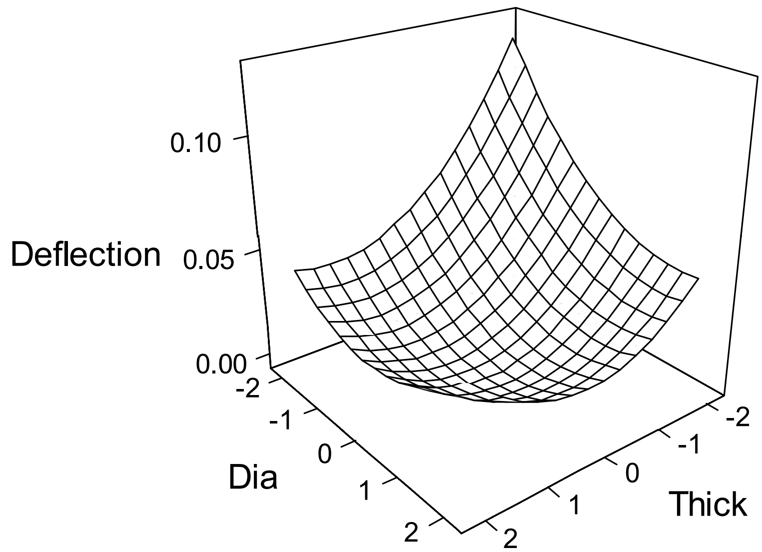
B 4 - Response surface graph for pipe cross-section, 8 runs (deflection).



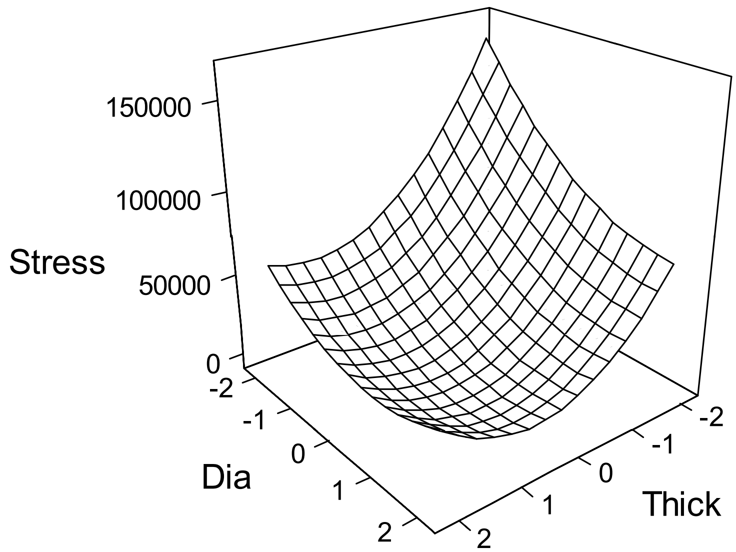
B 5 - Response surface graph for pipe cross-section, 8 runs (stress).



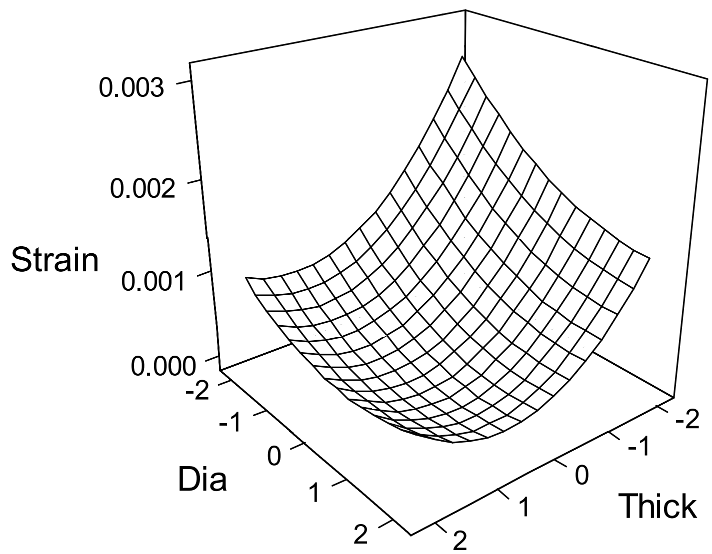
B 6 - Response surface graph for pipe cross-section, 8 runs (strain).



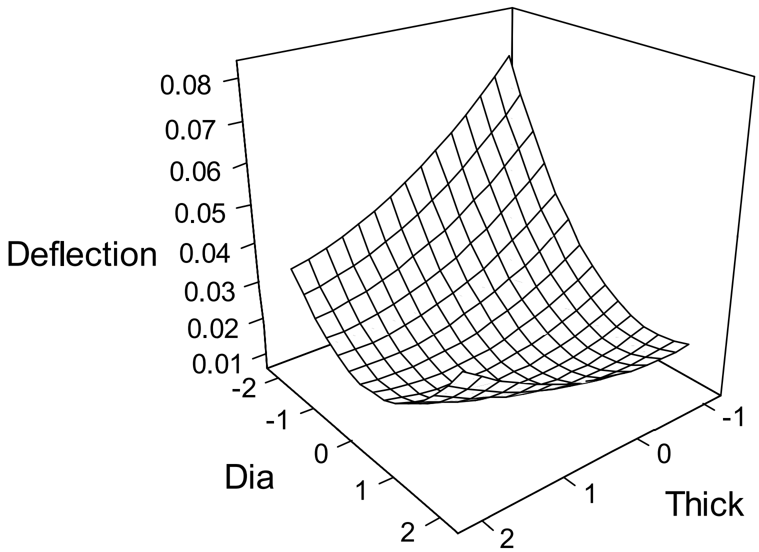
B 7 - Response surface graph for pipe cross-section, 15 runs (deflection).



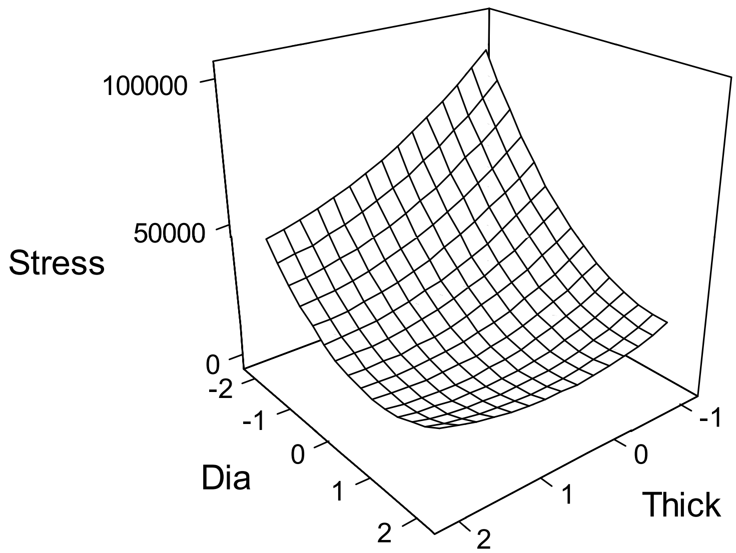
B 8 - Response surface graph for pipe cross-section, 15 runs (stress).



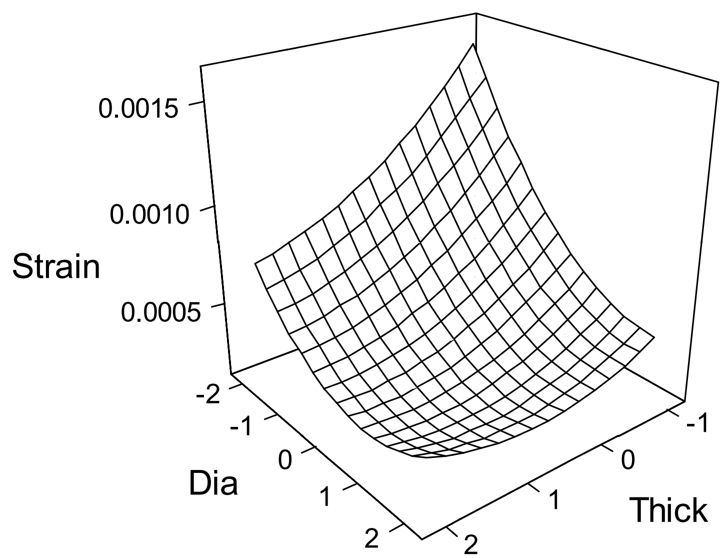
B 9 - Response surface graph for pipe cross-section, 15 runs (strain).



B 10 - Response surface graph for pipe cross-section, 15 runs, run 11 eliminated (deflection).



B 11 - Response surface graph for pipe cross-section, 15 runs, run 11 eliminated (stress).



B 12 - Response surface graph for pipe cross-section, 15 runs, run 11 eliminated (strain).

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