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MAPPING PROBLEM AND REQUIREMENTS TO SOLUTION: DOCUMENT ANALYSIS OF SENIOR DESIGN PROJECTS

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MAPPING PROBLEM AND REQUIREMENTS TO SOLUTION: DOCUMENT ANALYSIS OF SENIOR DESIGN PROJECTS

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ABSTRACT

Formulating and solving engineering problems and designing solutions that meet the established requirements are important skills that graduating engineering students need to possess. However, there are noticeable gaps in the literature with respect to understanding how the formulation of design problems and establishment of requirements affect the final design solution. This thesis is an initial attempt to understand the influence of level of detail of problem statement and requirements on the level of detail of final solution. In doing so, a document analysis of final reports from senior design class collected over a period of ten years from 1999 to 2008 is conducted. A coding scheme is developed to systematically organize and compare the information in the final design reports. Further, a data compression approach is developed to allow for the mapping of level of detail of problem statement and requirements to the level of detail of final solution. The findings of this research indicate that a low level of detail problem statement and requirements leads to no greater than a medium level of detail in the final solution. A high level of detail of final solution is more likely to result from either a high or medium level of detail of problem statement and requirements. Additionally, a high level of detail final solution is more likely to result in a high level of percentage requirements met by it. These findings are used to make several recommendations to faculty and students to improve the level of detail of final solution and consequently increase the probability of fulfilling more requirements. This assists in ensuring students possess the skills needed in the professional workforce.

DEDICATION

This thesis is dedicated to

Lord Shri Krishna,

My parents Premji and Jyotsna, to whom I owe my existence,

My Soul mate Parikshit who gives me a reason to cherish life.

ACKNOWLEDGMENTS

With utmost respect I would like to thank my advisor Dr. Joshua D. Summers for being a constant source of guidance and encouragement throughout my Master's Degree program at Clemson. He taught me how to perform research and provided ample opportunities to grow, not just as researcher but as an individual. He gave me freedom to pursue the topic of my interest and his confidence in me has encouraged me to perform beyond my capabilities. He is one of the best teachers and advisors that I know and I consider myself truly blessed to be able to have an opportunity to work with him.

I would like to thank my committee members Dr. Gregory Mocko and Dr. John Ziegert for helping me through the review of this thesis. Their dynamism and passion for their profession have been very inspiring to me.

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CHAPTER ONE: MOTIVATION

Engineering design is largely a problem solving activity [1]. The foremost task of the engineer entails the application of scientific and engineering knowledge in order to solve the technical problems. Further, they should be able to develop and improve the solutions within the boundaries of requirements and constraints [2]. Design problems impose challenges such that the ability to be able to handle them is essential for engineers. Thus, engineering education attempts to enhance the development of these essential skills to help students successfully and confidently address the design problems [3].

The Accreditation Board for Engineering and Technology (ABET) is the agency in United States that is solely responsible for the accreditation of engineering educational programs[1]. Of the several criterions set by ABET, *Criterion 3* is specifically established for *Program Outcomes and Assessment.* It has eleven requirements of which following three are of interest for this research [4]:

"Engineering programs must demonstrate that their graduates have:

(e) an ability to identify, formulate, and solve engineering problems

(c) an ability to design a system, component, or a process to meet desired needs

(f) an ability to communicate effectively"

These criterions indicate that the problem solving skills and the ability to design a solution that meets the desired requirements are important skills that graduating

[1] www.abet.org (accessed November 2, 2010)

engineering students must possess. Additionally, the importance of problem solving skills for students has been emphasized by several researchers [5,6,7,8,9]. However, not much literature is available on understanding the influence that problem formulation and requirements definition has on the developed solution. This serves as the motivation for this research. This thesis is an initial attempt to answer three broad research questions:

RQ1. What is the influence of the level of detail of problem statement on the level of detail of final solution?

RQ2. What is the influence of the level of detail of established requirements on the level of detail of final solution?

RQ3. What is the influence of the level of detail of final solution on the level of detail of the requirement met by it?

Formulating a problem statement and establishing a set of requirements are the preliminary steps that capstone design students follow towards solving the given design problem. Thus, it is important to research the influence of the level of detail of problem statement and requirements on the level of detail of final solution. The findings may be used to then make recommendations to the students to formulate problem statements and requirements with a specific level of detail to achieve the desired level of detail of final solution.

Further, it is necessary to study the influence of the level of detail of final solution on the level of detail of requirements as the findings may be used to predict or at least guide the level of detail of requirements that students may fulfill based on the level of detail of solution. For instance, if a high level of detail of solution is more likely to result after a high level of detail of requirements have been defined, the students developing a solution with low level of detail can be warned early in their project that they are more likely to miss fulfilling all the desired requirements.

To answer these research questions, a document analysis of the final design reports submitted as part of deliverable for the capstone senior design project was conducted. A coding scheme was developed to codify the problem statement, requirements and final solution. This was followed by the development of data compression approach for problem statement, requirements and final solution which allowed the mapping of level of detail of problem statement and requirements to the level of detail of final solution. The details of coding scheme and data compression approach are discussed in detail in Section 4.3 and Section 4.4 respectively.

Section 1.1 discusses the summary of the findings of this research.

1.1 Research Findings and Summary of Recommendations

This research aims at understanding the influence of level of detail of problem statement and requirements on the level of detail of final solution. Further, it aims at understanding the influence of the level of detail of final solution on the level of percentage requirements met by the final solution. The findings of this research indicate that a low level of detail of problem statement and requirements leads to no greater than a medium level of detail in the final solution. A high level detail of final solution is more likely to result from either a high or medium level of detail of problem statement and requirements. Additionally, a high level of detail of final solution is more likely to result to a high level of percentage requirements met by it. Based on these findings, several recommendations can be made to the students to improve the level of detail of final solution and consequently increase the probability of fulfilling more requirements. Table 1.1 summarizes the recommendations and their benefits.

Table 1.1 Summary of Recommendations and benefits

	Recommendation	Benefit
1	Students should be encourage to incorporate components such as current state, final state and some critical constraints while developing their problem statement	This may result to a greater chances of a high level of detail in the problem statement
2	Students should be encouraged to develop a high or at least a medium level of detail of problem statement and requirements	This may result to a greater chances of a high level of detail in the final solution
3	Teams with low level of detail in the problem statement and requirements may be warned early on.	This may prevent them from developing final solution with low level of detail
4	Student should be encouraged to develop a detailed description of the final solution, completely label all the figures and conduct more engineering.	This may result to a greater chances of a high level of detail in the final solution
5	Students should be encouraged to develop a high or at least a medium level of detail of final solution	This may result to greater chances of a high level of detail of % requirements met.

1.2 Thesis Organization

The remainder of this thesis is organized in five chapters:

- Chapter Two describes the related literature on the nature and structure of design problems, the importance of problem solving for capstone design students, and the importance of design requirements.

- Chapter Three describes the details of senior capstone design at Clemson. Specifically, it discusses the solicitation of industry projects, formation of student design teams, and the typical course timeline and deliverables.
- Chapter Four describes the research method, coding scheme, and data compression approach. It describes document analysis as a qualitative research method used in engineering design research. Further, it justifies and describes the details of using the final design reports for data collection. It also describes the scheme used for coding the problem statement, requirements and final solution. The approach for compressing the collected data to allow for the mapping of level of detail of problem statement and requirements to the level of detail of final solution is also discussed in this chapter.
- Chapter Five describes the analysis and results of mapping the level of detail of problem statement and requirements to the level of detail of final solution. It provides details of the key takeaways from this research.
- Chapter Six discusses the conclusions which summarize the findings of this research and provide recommendations. It also describes the direction for future research.

CHAPTER TWO: LITERATURE REVIEW

This chapter provides a review of the current literature on design problems and requirements with an emphasis on mechanical engineering. Section 2.1 discusses the current research in design problem solving with the details on the nature and structure of the problems. Section 2.2 discusses the importance of problem solving for senior capstone engineering design students. Section 2.3 discusses the importance and role of requirements in design process.

2.1 Nature and Structure of Design Problems

Primarily, design is a problem solving activity [1]. Some form of problem statement provided to or defined by the designer through the customer serves as the genesis of the design problem [10]. Much research has been done to understand the nature of design problems.

In early 1970s, Simon introduced the *rational problem solving* paradigm in which searching the design solutions would occur by surveying the design 'problem space' [11,12,13]. However, there are difficulties in applying the rational problem solving approach to design and this was addressed by Simon when he described the design problems as "*ill-structured problems*" [11]. As opposed to the well-structured problems that have a clear goal, often one correct answer, and rules or known ways of proceeding that will generate an answer [10], in the "*ill-structured problems*", the problem space is believed to be too large, not well structured, and poorly defined. This means that the possible solutions cannot be fully enumerated [11,12]. Some efforts to represent the possible solution space include the use of idea generation tools such as morphological charts, but these do not guarantee a complete representation of the space [14,15].

Schon introduced the reflective practice paradigm in which he describes design as process of reflection-in-action [16]. The comparative study of reflective practice paradigm and Simon's rational problem solving paradigm can be found in [17]. These comparisons indicate that the nature of the design problem in reflective practice paradigm is considered essentially unique as opposed to the ill-defined and ill- structured nature of design problems in Simon's rational problem solving paradigm. The design process, instead of being a rational search process, is a reflective conversation with the situation [16,17].

Dorst suggests that most design problems have three aspects. First, design problems are partly ***determined*** as they have 'hard' needs or requirements. Second, a major part of the design problem is ***underdetermined*** as it involves the possible interpretation of design problems and possible solutions to those problems by the designer. Finally, part of design problem is also ***undetermined*** as the designer is free to design according to his taste, style and abilities to a great extent [12].

Dreyfus argues that the nature of the problem considered in a problem solving situation depends on the level of expertise of the problem solver. He then distinguishes five levels of expertise: novice, beginner, competent, proficient, and expert. These levels are based on the ways that the designers perceive, interpret, structure, and solve problems [12,18]. Based on these distinctions, the graduating engineering students would fall under the category of novice designers who follow a set of rules set by experts to objectively solve a given design problem [12,18].

It is important to understand the nature and structure of design problems as this will lead to a better understanding of how designers work and the rationale behind the actions they take [12]. To that extent, it also becomes essential to understand the importance of problem solving for capstone senior design students.

Section 2.2 discusses about the importance of problem solving for students.

2.2 Importance of problem solving for Capstone design students

Solving open-ended problems is arguably the cornerstone of any engineering endeavor [5]. The ability to define problems as well as to solve them is among the many skills that today's engineers must have to succeed [6,7,8,9]. Verbal protocol studies indicate that scoping of design problem is essential for engineering graduate students [6]. These findings provide measures that can be used not only to determine the types of design problems to be used but also to determine the way to pose design problem so that it nurtures the development of broad thinking skills for engineering graduate students [6]. A comparative study of undergraduates' and practicing engineers' knowledge of the roles of problem definition and idea generation is presented in [19]. This research was conducted with subjects from freshman and senior level of engineering and practicing engineers. The subjects were asked to critically review a given design process and answer the questionnaire. Their responses were then analyzed yielding results that indicate, with respect to understanding the role of problem definition in design, that significant learning about the role of problem definition does not occur until the final senior capstone course [19]. This aligns with the structure of the engineering design curriculum at Clemson University in Mechanical Engineering where the primary instruction on engineering design occurs in the first semester of the senior year with application of this knowledge and understanding following in the capstone senior design course. It is this second semester senior design course that is the focus of the study of this thesis.

The findings of these studies indicate that greater emphasis on problem definition during the capstone design projects is paramount. This is also evident from the criteria listed by ABET in which the ability of engineering graduates to identify, formulate, and solve engineering problems is listed as one of the important requirements under program outcomes and assessment criterion [4]. To that end, it becomes essential to study the influence of the level of detail of problem statemetn on the level of detail of final solution in the Capstone design projects. This is one of the goals of this thesis.

2.3 Requirements in Engineering Design

In the systematic design process, the problem definition stage is followed by elicitation of design requirements [2]. Requirements play a critical role in the design process as they represent the specifications which are used to judge the success or failure of resulting product [2]. Ensuring that the needs of customer remains the main focus while developing the product and no critical need is either missed or forgotten are of the several important goals another prescribed design process [20]. Careful development of product requirements is listed as one of the ten key features of design best practice [21].

Several design activities, such as generating, testing, and validating of ideas are greatly influenced by engineering requirements [22,23]. Different ideas are generated when considering the myriad of requirements and the developed design solutions are tested to make sure that they meet the established requirements. The roles that requirements serve within the design process may include their use as a benchmarking tool to evaluate the ability of the existing solutions to meet customer needs or its use as a concept selection tool for selecting concepts based on how well the meet the customer needs [23]. Improvement in the understanding of design problem is indicated by the decreased abstraction of requirements and increased ability to write engineering specifications [21,23]. Ultimately, satisfaction of more requirements is an indication that the design is closer to completion [23].

The importance of generation and fulfilment of requirements is highly emphasized by researchers as evident from the literature. This suggests a necessity in emphasizing the importance of requirements while teaching design during the senior captsone design projects. This is also evident from the criterions listed by ABET in which the ability of engineering graduates to design solutions that meets customer needs is listed as one of the important requirements under program outcomes and assessment criterion [4]. To that end, it becomes essential to study the influence of the level of detail of requirements on the level of detail of final solution in the senior capstone design projects. This is a primary goal of this thesis.

CHAPTER THREE: CAPSTONE DESIGN AT CLEMSON

This chapter provides the overview of the Capstone design course at Clemson University. It discusses the details of soliciting the industry projects, forming the design teams and typical timeline and deliverables expected from the students for this class.

ME-402 is a senior mechanical engineering capstone design class taught in the Mechanical Engineering Department at Clemson University. This course is a three credit one semester long (~15 weeks) course and is offered in both Fall and Spring Semesters. An alternative version of the course is now offered during a summer semester in which students work on projects in industrial settings in Mexico on international student teams. For purposes of this thesis, only the traditional on-campus version of this course offering is considered here. The projects are solicited by the faculty coordinator for the class by contacting the industries. Sometimes the projects are also obtained from other departments of Clemson University with specific engineering design needs. The details of soliciting industry projects are described in Section 3.1. The students traditionally work in teams of typically four to five on industry sponsored projects. Section 3.2 describes the details of formation of student teams. A typical deliverable of the projects consists of final presentation, final design report, drawing package, and may include a physical prototype depending on the type of project. The details of a typical course timeline and deliverables for this class are described in Section 3.3. The grading rubric for senior design class is discussed in Section 3.4.

Section 3.1 discusses the details of how the industry projects are solicited.

3.1 Soliciting Industry sponsored projects

Nearly all the projects for the senior design class are sponsored by industry and are solicited by the faculty coordinator for the class. Sometimes the projects initially proposed by the industry sponsor are out of scope for the class and the faculty coordinator works with the industry sponsor to narrow or grow the scope of the design problem to suit the class. The types of design projects offered to the students include a wide variety [24] such as

- *Original design* which consists of designing a new product. Example: developing a screw feeding mechanism for BMW
- *Adaptive design* which consists of redesigning an existing design to satisfy a set of new constraints and making improvements. Example: redesign of bar pinion interface to reduce deformation.
- *Variant design* which involves varying parameters such as size, geometry, material to develop more robust design. Example: Ryobi impact driver noise reduction

The projects also cover a wide range of interests such as consumer product design, fluid, thermal, manufacturing, mechanics, and automotive while give ample opportunity to students to explore and learn as they progress in the projects. Each industry sponsor is contributes to the course by donating a sum of between $5,000 and $10,000 out of which each team on the project is given between $400 and $500 as a project budget. Typically three to four teams work independently on each project. For this research, one project was studied for each year starting from 1999 to 2008. The details of different types of projects studied for this research, the industry sponsor and the sponsorship cost are illustrated in Table 3.1.

Table 3.1 Details of project

Year	Name of Project	Faculty coordinator	Type of Project	Sponsor	Sponsorship cost
1999	Failure analysis of charge air cooler	Dr. Georges Fadel	Adaptive design	Griffin Thermal System	$5,000 + $400 per team
2000	Torrington bearing assembly	Dr. Georges Fadel	Adaptive design	Torrington/ Ingersoll Rand	$5,000 + $400 per team
2001	Design of heat treat belt furnace	Dr. Georges Fadel	Original design	Torrington/ Ingersoll Rand	$5,000 + $400 per team
2002	Speed reduction device for residential areas	Dr. Georges Fadel	Original Design	Hughes Investments Inc.	$5,000 + $400 per team
2003	Personal handicap all-terrain vehicle	Dr. Georges Fadel	Original Design	Clemson Club car	$5,000 + $400 per team
2004	Redesign of bar-pinion interface to reduce bar deformation	Dr. Frank Paul	Adaptive Design	Capsugel	$5,000 + $400 per team
2005	Paint shop door brake fixture design	Dr. Joshua Summers	Adaptive Design	BMW	$5,000+ $400*4= $6,600
2006	Ryobi drill clutch project	Dr. Joshua Summers	Variant Design	TTI	$5,000+ $400*3= $6,200
2007	Raytheon cobra nose landing gear	Dr. Joshua Summers	Adaptive design	Raytheon	$7,500+ $500*4= $9,500
2008	BMW screw feeding system	Dr. Joshua Summers	Original design	BMW	$7,500+ $500*3= $9,000

The typical number of projects for each semester varies from five to seven and three to four teams work independently on each project. Section 3.2 describes the details of team formation for a typical capstone design class.

3.2 Formation of student teams and advisory committees

At the beginning of the semester, the students are provided with a one page description of each different industry sponsored projects that are available for that semester. An example of one such project description is illustrated in Figure 3.1

CLEMSON UNIVERSITY

Project Number:
2010-08-Parker-Seal

Geothermal Sealing Backup System

Project Abstract:
Geothermal Energy has not gained worldwide popularity as a form of clean, alternative energy due to current geographic limitations. However, Enhanced Geothermal Systems (EGS) could potentially expand the use of geothermal energy around the world by overcoming the existing geographic challenges.

Water is typically pumped into drilled well holes at depths of up to 10,000 feet. At these depths the water is transformed to steam and is released to the surface through secondary wells to power gas turbines. Drilling at these depths and temperatures (600F) has proven to be extremely difficult and results in noncircular, oblong well holes due to "corkscrewing" of the drill. Sealing and redirecting steam/water to the turbines is performed by packer element systems which can be set (sealed) and then relocated throughout the well. Failure of these systems to properly seal can result in costly repairs, turbine inefficiency, and safety concerns.

The goal of the project is to design a packer element backup system that can effectively back-up packer elements in both a circular and oblong well hole configurations. The oblong well hole dimensions are approximately 9" to 10.5" in diameter. To ensure clearance while being lowered into the well, the entire system must be less than 8.3" in diameter and 32" in length before activation. Once the system is activated, it must expand radially and be able to seal 10,000psi of steam/water pressure at 600F. When the setting force is removed, the system must contract to its original shape for movement to other well locations.

Deliverables for this backup design include:

- Complete written engineering report of selected design concept including:
  - Material selection, mechanical design, finite element analysis, etc.
- PowerPoint style presentation of selected design concept
- Complete engineering drawings of developed concept
- Working prototype of packer backup system. This does not need to be manufactured from the final selected materials, but the prototype must show designed motion

Students will apply mechanism design, materials, and manufacturing systems knowledge in the execution of this project.

Project Leaders:
Mason Morehead
Design Engineer (Parker Hannifin Corporation, TechSeal Division)

Advisory Committee:
TBD
Weekly Meeting Details:
TBD

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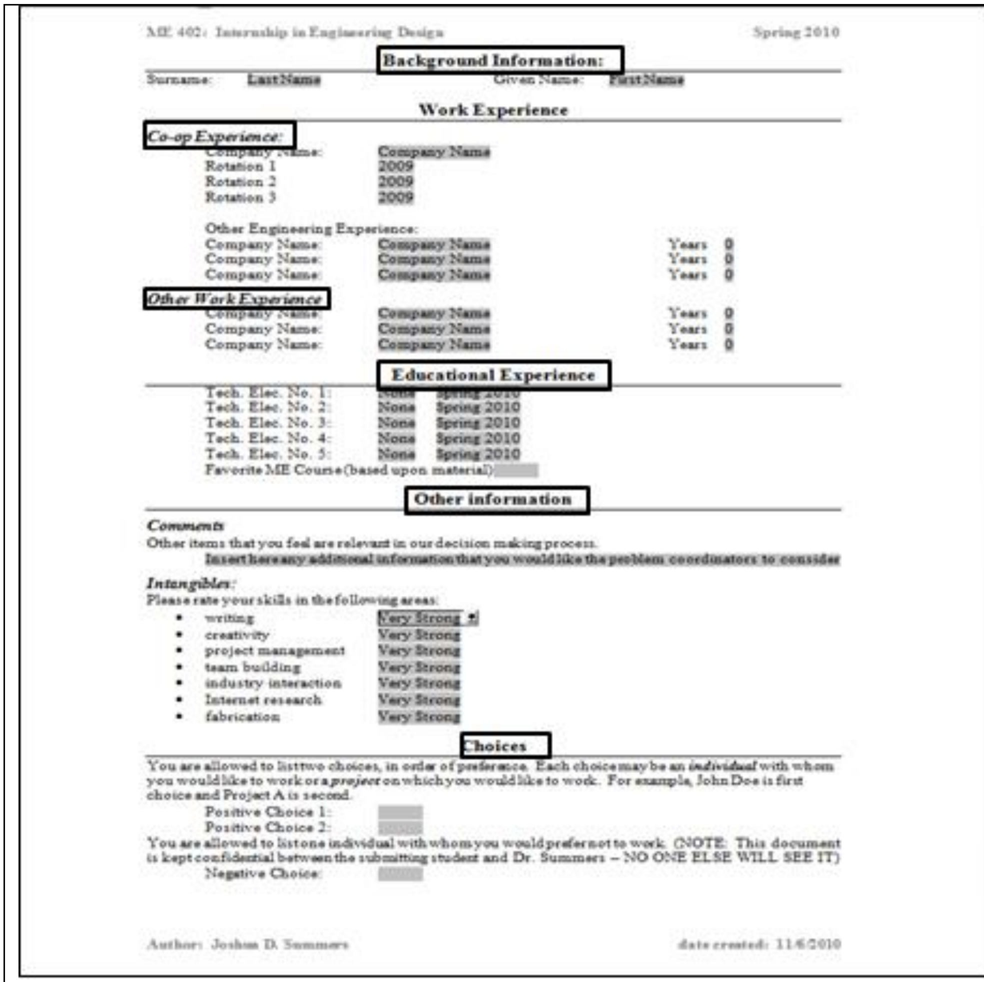
Figure 3.1 Example of one page project description

The students are then asked to submit their resumes to the faculty coordinator for the class. In their resumes, the students are asked to include information such as industry or co-op experience, fabrication experience, engineering skill expertise, interest in any particular field, and experience with any computer aided design or simulation software. Figure 3.2 illustrates an example of student resume in which the boxes indicate the different information fields that students are asked to fill.



ME 402: Internship in Engineering Design Spring 2010

Background Information:

Surname: LastName Given Name: FirstName

Work Experience

Co-op Experience:

Company Name:	Company Name	
Rotation 1	2009	
Rotation 2	2009	
Rotation 3	2009	
Other Engineering Experience:		
Company Name:	Company Name	Years 0
Company Name:	Company Name	Years 0
Company Name:	Company Name	Years 0

Other Work Experience

Company Name:	Company Name	Years 0
Company Name:	Company Name	Years 0
Company Name:	Company Name	Years 0

Educational Experience

Tech. Elec. No. 1:	None	Spring 2010
Tech. Elec. No. 2:	None	Spring 2010
Tech. Elec. No. 3:	None	Spring 2010
Tech. Elec. No. 4:	None	Spring 2010
Tech. Elec. No. 5:	None	Spring 2010

Favorite ME Course (based upon material)

Other information

Comments

Other items that you feel are relevant in our decision making process.

Insert here any additional information that you would like the problem coordinators to consider

Intangibles:

Please rate your skills in the following areas:

- writing Very Strong
- creativity Very Strong
- project management Very Strong
- team building Very Strong
- industry interaction Very Strong
- Internet research Very Strong
- fabrication Very Strong

Choices

You are allowed to list two choices, in order of preference. Each choice may be an *individual* with whom you would like to work or a *project* on which you would like to work. For example, John Doe is first choice and Project A is second.

Positive Choice 1:

Positive Choice 2:

You are allowed to list one individual with whom you would prefer not to work. (NOTE: This document is kept confidential between the submitting student and Dr. Summers – NO ONE ELSE WILL SEE IT)

Negative Choice:

Author: Joshua D. Summers date created: 11/6/2010

Figure 3.2 Example of student resume

The students are also asked to define two positive and one negative choice of either project or person. Based on the information collected from students' resume, teams are formed ensuring that students get at least one of their two top choices of either project or person. Moreover, the teams are balanced as closely as possible in terms of expertise and experience. Each team is assigned, when possible, at least one student that had co-op or internship experience.

It may be noted that this approach to forming teams was implemented in the Fall 2004 semester. Before that, teams were formed on the first day of class by self-selection when the projects were given to the students. The change was done to provide more rigor and control to team formation, to provide quicker entry into the project, and to elevate the perception of the students with respect to the formality of the course.

Each team typically consists of three to five students and each project typically will have three to four teams of students working independently to solve the given design problem. There are projects that have included larger teams and other projects on which only one team was assigned. These, however, are the exceptions to the rule. Having multiple teams working on same project improves the probability of success of the final design and provides variety of solutions for same project to the sponsor [25]. Each project has an advisory committee that typically consists of two faculty members and another non-faculty member. The advisory committee monitors the progress of the projects and does not serve as a detailed management or consulting agency.

In addition to the advisory committee, some teams also have a graduate coach [26,27,28,29]. A graduate coach is a student who is participating in the coaching as part of a graduate course on engineering design research methods and assists the team to accomplish their goals. In doing so, the coach does not directly participate in the design process but intervenes only when necessary such as to help obtain resources from the department, help resolve issues within the team, help to deal with a dysfunctional team, motivate the teams, and encourage healthy group dynamics. These graduate coaches are enrolled in a graduate class on collaborative design research. This class is taught by Dr.

Joshua D. Summers in the Mechanical Engineering Department at Clemson University typically during spring semesters. As a prerequisite for this graduate class, the students are required to take a class on advanced design methodologies. In the collaborative design research class, the students are taught the skills of project management, dealing with dysfunctional teams, group dynamics, and mentoring in addition to how to conduct structured case study research in engineering design. As this class was taught typically only in spring semesters, only the teams in spring semester may have had coaches. Figure 3.3 illustrates the hierarchical relationship between the people involved in senior design class.

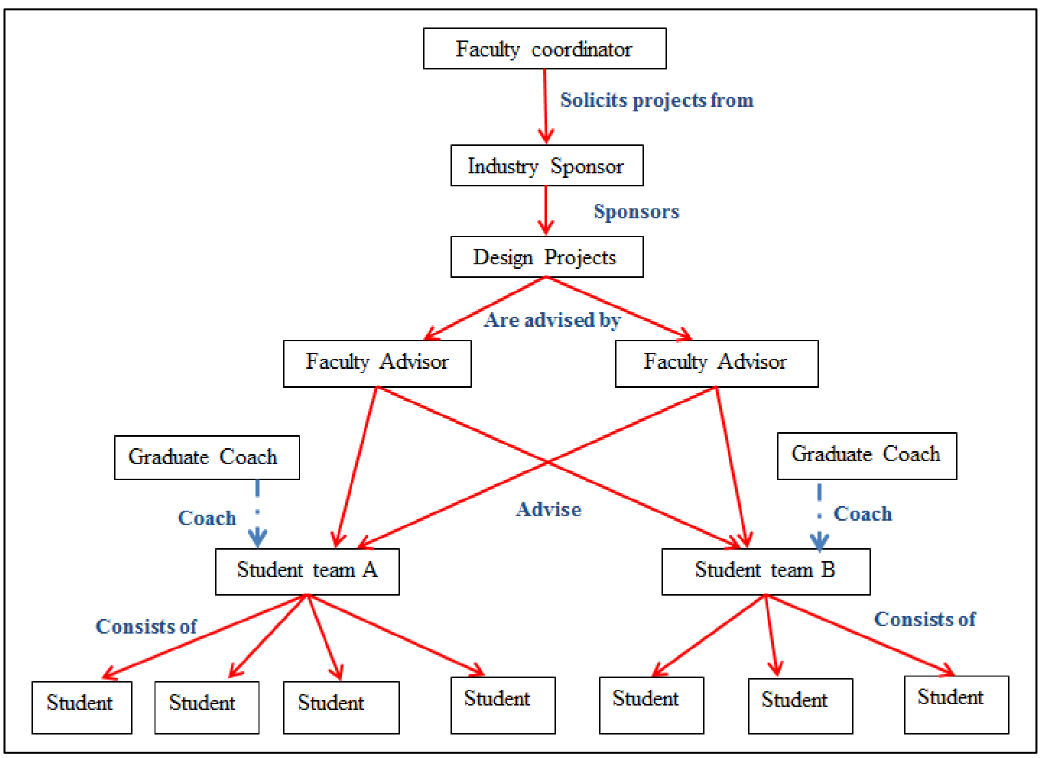


Figure 3.3 Hierarchical relations in senior design class

Since the Spring 2010 semester, all projects are also assigned gradvisors in addition to the advisory committee consisting of faculty members and industry sponsor. These gradvisors are graduate students serving on the advisory committee. The gradvisor is different from the graduate coach in a way that the graduate coach was responsible for coaching only one team, while the gradvisor not only coaches all the teams for a particular project but also serves on the advisory committee and provides feedback during the weekly meetings. To qualify as gradvisor, the graduate students are required to take class on advanced design methods, collaborative design research and product development. However, none of the project studied for this research had a gradvisor.

A typical course timeline and deliverables for senior design class are discussed in Section 3.3.

3.3 Course Timeline and Deliverables

The senior design course at Clemson University is approximately fifteen weeks long, spanning the fall and spring semesters. In the Summer of 2010, a six week international senior design project course offering was introduced, but is not considered in this research. The schedule of the course is flexible to accommodate the advisory committee's schedules and the industry sponsor's availability. A typical schedule is presented here. Figure 3.4 illustrates a typical timeline for senior design class.

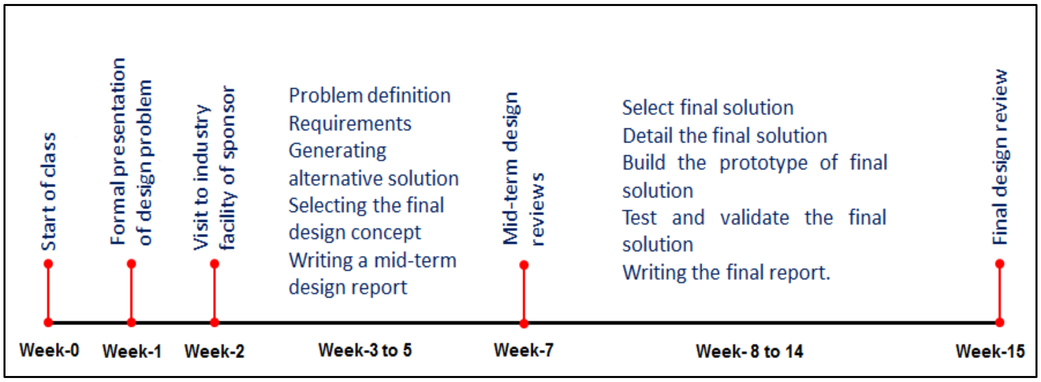


Figure 3.4 Typical timeline for senior design class

In the first week of the semester, the student teams are a given formal presentation of the design problem by the industry sponsor. In the second week, the students visit the industry facility to aid in better understanding of the problem. The students then develop their own version of the design problem that is then submitted for formal approval by the industry sponsor. Typically, the first seven weeks are spent in problem definition, defining the requirements, generating alternative solution, selecting the final design concept, and writing a mid-term design report for a preliminary design review. The remaining seven weeks are spent in detailing the final solution, building the prototype of final solution, testing and validating the final solution, and writing the final report. During the entire design process, the students are encouraged to interact with the sponsor to get their feedback. These interactions also help to clarify students' doubts.

The advisory committee oversees the progress of each student team during weekly thirty minute design reviews. The industry sponsors are often only present for the mid-term (preliminary design review) and final presentations (final design review). The teams from the same projects present individually and often do not discuss or see the progress of other teams on the same project except at the large design reviews mid semester and at the end of the semester. However, this varies with the advisory committee. Some advisory committees allow the presence of other teams during the weekly design reviews. In the seventh week, which is half way through the semester, the students deliver mid-term presentations. Typically, this is the first time that all the teams for the same project are present in the presentation and can see the progress of their peers. By the time of mid-term presentations, most teams have completed the conceptual design phase and to some extent embodiment design phase. Most teams have developed a preliminary solution at this time and after the midterm presentations, they work on the embodiment design and detail the solutions. The final deliverable of the project includes the written report of the proposed solution with complete drawing package and may also include prototypes of the proposed solution. The students are also required to give a final presentation to the advisory committee and industry sponsor.

3.4 Grading Rubric for ME-402

As mentioned earlier, ME-402 is a three credit class. The final grades of the students are assessed based on individual and team's performance. The students are graded with respect to four important aspects: 1) Product, 2) Process, 3) Presentation, and 4) People [30]. This research is focused mainly on the product aspect and to some extent on the process aspect of design.

Table 3.2 illustrates the grading rubric used for senior design class at Clemson University.

Table 3.2Grading Rubric for ME-402 [30]

Grade	Product	Process	Presentation	People
A	The design artifact is (one of) the best of all teams, likely used by the sponsor, and potentially worthy of a patent.	The design process is applied using appropriate tools that may require external research.	Presentations and reports are optimally clear, complete, and concise.	The team functions as a single unit
B	The design artifact is useable and has clear attributes beyond just meeting minimum requirements.	The design process is applied using appropriate tools, demonstrating a good understanding of the design process.	Presentations and reports are complete, and reasonably clear and concise.	The team is efficient and well-organized.
C	The design artifact works.	The design process is applied nominally using some design tools.	Presentations and reports are complete and without error.	The team is functional.
D	There is some doubt as to whether the design artifact works, or it works marginally.	The design process is applied without use of any design tools.	Presentations and reports lack some clarity or key information, or have minor errors.	The team is not a team, but individuals working on the same project. Absences are frequent.
F	The design artifact does not work.	There is no demonstrated use of the design process.	Presentations and reports are inadequate.	The team is dysfunctional.

Thus this chapter gives a brief overview of the senior design program in the Mechanical Engineering department at Clemson University. It discusses the details of soliciting industry projects, formation of design teams and advisory committee, typical course time-line and deliverables and the rubrics used for grading the students.

Chapter Four discusses the details of the research method used for this thesis, the coding schemas and the data compression approach.

CHAPTER FOUR: RESEARCH METHOD, CODING SCHEMES, AND DATA COMPRESSION APPROACH

Research methods used in design research are broadly classified as qualitative, quantitative, and mixed methods [31,32,25]. Quantitative research is a type of research where the researcher seeks to confirm a hypothesis about phenomena with closed-ended research question [33]. Qualitative research is a type of scientific research that seeks to explore phenomena with open-ended research questions [33]. Further, the data collected for quantitative research is numerical as opposed to the textual form of data collected for qualitative research [33]. Mixed methods are a combination of both quantitative and qualitative type of research [31]. The research presented in the thesis seeks to explore whether or not there is influence of the level of detail of problem statement and requirements on the level of detail of final solution. This is an open-ended question with no specified hypothesis. Further, the form of data collected for this research was mostly textual and graphical. Thus, this research falls under the category of qualitative research.

Of the numerous characteristics of qualitative research listed by different researchers, the following are some of the more critical:

- Qualitative research is *naturalistic*, which means that the researcher actually goes to the research sites such as schools, offices, families or neighborhoods to conduct research [31,34]. In the case of this research, completed senior design projects are studied within their regular curricular context.
- Several aspects of qualitative research emerge during the study. This may involve refinement of the research questions or refinement in the data collection [31]. The

coding schemas developed through this research, and reapplied continuously to all reports, were defined based on information that existed within the set of reports. This information was not known fully *a priori*, thus necessitating refinement.

- In qualitative research, the researchers are concerned with the process and not just the product or outcomes [31,34]. In this research, the end product as represented in the reports is still the primary focus, not the development process. Understanding the design processes followed is reserved for future research.
- Qualitative research is *inductive* in nature. This means that the qualitative researchers do not analyze the collected data to prove or disprove a hypothesis. The generalizations are built based on the collecting and grouping the data [34]. While research questions are formulated in this work, the research strategy employed is primarily exploratory to discover whether there are or are not relationships between the level of detail as presented in the problem statements against the level of detail of the final solutions.

Different types of qualitative research methods include individual or group interviews, document analysis, participatory research, ethnographic study, focus groups, experiential analysis, observatory study, cultural inventory, and protocol study [32,33]. The different types of data collected may include field notes, interview transcripts, audio or video recordings, scrapbooks, photographs, and e-mails. Further, the data collected is descriptive in nature as it mainly includes text and graphics as opposed to numbers [31,34]. Data analysis mainly involves deriving useful meaning of the text and graphic data collected which may include following steps:

- Systematically organize the collected data for analysis [31].
- Obtain a broad sense of the data by reading thoroughly through the collected data [31].
- In order to analyze the data with greater detail develop a coding scheme which involves systematically organizing the data such as text and images into categories and naming those categories [31,35].
- Use narrative passages to describe the findings of the analysis which may be descriptions of sequence of events or discussion of different themes or patterns. Additionally graphics, figures or tables can also be used for description [31].
- The concluding step would be to derive useful meaning from the data [31].

As mentioned earlier, the type of research method used for this research falls under the category of qualitative research as the research questions are open-ended and the form of data collected is largely textual and graphical. More specifically, document analysis, a type of qualitative research method, is used for the purpose of this study as final design reports submitted by the students at the end of Capstone design projects are used as data source for this study. As the research involves the study and comparison of the final design reports from senior capstone design projects for the past ten years, other forms of data collection methods such as surveys, interviews, or audio and video recordings could not be used [25].

Section 4.1 describes the details of document analysis as qualitative research method.

4.1 Document Analysis as Qualitative Research Method

A systematic procedure for studying or assessing documents is called document analysis [36]. The documents used in document analysis may include printed material such as newspapers, advertisements, reports, minutes of meetings, diaries, journals, or books; or electronic material such as computer-based or internet-transmitted electronic reports or electronic books [36].

Document analysis is often used as combination with other qualitative research methods such as case studies and ethnographic studies for triangulation. For instance, document analysis was used as a part of case study to develop design methods [25]. In addition, researchers have also used document analysis as a stand-alone research method. For instance, Sobek at Montana State University studied the student design journals to evaluate student design processes [37]. The findings indicate that students must be encouraged to maintain a high quality of journals. Additionally, he suggests that the measures such as rubric for evaluation, providing regular feedback on students' journals, and interactive exercises will help students to improve the quality of journals [37]. Wild et al. conducted a diary study to examine the information needs and document usage by engineers [38]. The findings of their study indicate that the data from the diaries of engineers can prove to be useful for designing engineering support tools. Stephen et al. conducted a study using the design notebooks to map creativity during team activities in Capstone design projects [39]. They present a coding rubric to describe and quantify the instances of creativity and the findings indicate that using design notebooks can be a useful tool to map the creativity in student design process. Further they also suggest that compared to expert designers, creativity occurs at multiple points in the design process for the senior design students [39].

Document analysis as a research method has several advantages and disadvantages. Some of the advantages of document analysis are as listed below:

- Documents are often easily available. They may be obtained as print copies from archives or as electronic copies via internet [36]. For the purpose of this research, the final design reports submitted by the students were easily available data source. The final reports were obtained as print copies from department archives.
- Document analysis is a cost effective and less time consuming method as it does not require involvement of participants or their time and so more efficient than other research methods [36]. This research did not require involvement of the senior design students and thus proved effective in terms of using time of participants.
- In some of the qualitative research methods, such as observation, where the presence of researcher may alter the behavior of subjects, documents are not affected by the presence of researcher or the research process [36]. The research presented in this thesis did not require the presence of the researcher during the execution of senior design projects under study and thus the documents collected were not influenced.
- Document analysis can be very useful when doing historical studies as the participants are no longer available for interview or observation

[25,40]. This research is a historical study to understand the influence of the level of detail of problem statement and requirements on the level of detail of final solution for the senior design projects. It would be difficult to have the availability of the participants for interview or observation as the students have already graduated. Thus, document analysis as a research method proved very useful.

- It may be advantageous to use documents in research process as they may provide exact details such as exact names, references and details of events [41]. For the purpose of this research, the details such as fully defined problem statements, requirements and the details of final solution were easily available from the final reports that were studied to answer the research questions.
- Another advantage of using documents in research is that they provide comprehensive reportage. The reporting may be done over a long period of time and cover numerous events and settings [41]. As mentioned earlier, the reports collected for the purpose of this research provided comprehensive reportage of the problem statements, requirements and the final solution.

However, there are several disadvantages of using document analysis as research method. These are:

- Though documents are often easily available, sometimes it is difficult to retrieve certain documents as they are either blocked or not available due to confidentiality issues and this is one of the disadvantages of document analysis [36,40,41]. Yet, for this research, the final design reports were easily available from department archives.

- It takes considerable amount of time and effort to sort through and derive useful information from documents [40]. This disadvantage did not limit the use of documents for the purpose of this research as the required information such as problem statement, requirements and details of final solution were clearly document and thus it did not involve much effort to sort through the reports to derive it.
- Documents may either have a large amount of unnecessary information or they may lack sufficient details required to answer research questions [36] [40]. Again, this disadvantage did not limit the use of documents for this research as the final design had sufficient information to answer the research questions.

Section 4.2 explains the details and justification of using the final design reports as data collected. The coding scheme used to code the data collected is explained in detail in Section 4.3.

4.2 Data Collection

A final design report is submitted by the students as a part of the deliverable for senior design class. This is the final document that the students submit at the end of the semester as a part of completion of the project. For the purpose of this research, final reports from ME 402 projects for past ten years (1999-2008) were collected and studied.

The ten year period involved three different faculty coordinators for the class and a wide variety of students. Thus, any biases caused due to a single faculty coordinator or similar pool of students could be easily avoided. Further, one project was selected for each year and since there were different types of projects for each year, this selection was done randomly to avoid any bias.

The goal of this research is to study the influence of the level of detail of problem statement and requirements on the level of detail of final solution. The final report submitted by the students will have fully defined problem statement, requirements, and final solution. Other documents generated during the senior design class, which may include the executive summaries, power-point presentations, mid-term reports, may not have the complete information needed for this research. For instance, the complete description of final design solution is not reported in the mid-term report or power-point presentation or executive summary. Therefore final reports were used for this research. Further, the report set under study contains the reports from past years and students have already graduated; no other form of data collection method such as surveys, interviews, audio or video recordings could be used [25]. The final reports were the only form of data available for all the projects for past ten years. Thus, the choice to study ten years of reporting to mitigate against the possibility of anomalous results from high or low student cohorts and the possibly influencing factors of specific course coordinators necessitates that only static, historical data, such as that encapsulated in the final reports, could be used in the study.

An assumption made for the purpose of this research is that all the projects under study are essentially at the same level of complexity. This assumption is based on the rationale that for every semester, all the projects were selected and reviewed by single course coordinator.

4.3 Coding Schemes

As mentioned earlier, final project reports submitted by the senior design students are used for this analysis. These reports contain a large amount of information about the completed projects, specifically an explanation of the problem and of the proposed solution. Most of this information is represented as textual information such as description of problem statement, requirements, and description of solutions. However, there is also graphical information such as sketches of solution, free-body diagrams, and manufacturing drawing packages. The typical, but not prescribed or required, structure of the report consists of an abstract, table of contents, executive summary, problem statement, constraints and criteria (requirements), and description of final solution. The details, such as description of alternative solutions, analysis and test results, bill of materials, and drawing package, often times are attached to the report as appendices, though there is no required organization format for the reports.

In order to be able to answer the research questions developed for this study, it was necessary to systematically analyze and compare the information in the final reports. For this purpose, two coding schemes are developed; one for coding the problem statements and one for coding the solution. A scheme was also developed to systematically study the requirements.

4.3.1 Coding of problem statement

Formulating the 'right problem' is the first step towards the successful completion of any design task [21]. One of the goals of this research is to understand the influence of the level of detail of problem statement on the level of detail of the final design solution. In order to understand this, it is necessary to develop a scheme to measure the level of detail of the problem statement. One of the ways to do this would be to break down the problem statement into components. The components of problem statement that can be derived from design texts include:

1) Initial undesirable state – This refers to the existence of a state which is not desirable or is substandard and therefore needs to be addressed by the designers [2,42].
2) Desirable goal state – This refers to the realization of the acceptable state which needs to be achieved by the designers. This could also be a description of goal state which includes the key benefits that customer can derive from the final product [2,20,42,43].
3) Obstacles – The obstacles refer to the conditions which prevent the transformation from initial undesirable state to desirable goal state. These obstacles could be the time delay caused during information sharing process between different departments involved in the design project or delay in obtaining the resources necessary for completion of the project [2].
4) Key Business goals – These include goals such as timing for introducing a new product in the market, market share targets and desired financial performance [20]

5) Target market for the product- This part of problem statement may refer to the primary and secondary markets that are considered while developing the design solution [20].

6) Constraints and criteria – These are essentially the constraints that are considered while designing the solution [20]. Essentially, these are the customer requirements that final design solution should be able to meet [21,42,43].

7) Stakeholders – This includes the list of all people who are affected by the attributes of the product. Examples of these may be end user, retailer, and service center [20].

The different components of a problem statement proposed by different design texts are summarized in Table 4.1 with the 'x' indicating that the component of problem statement in that row is mentioned in the design text in the corresponding column.

Table 4.1 Components of problem statement described by design texts

		Design Texts				
	Component of problem statement	Pahl and Beitz	Ulrich and Eppinger	Ullman	Hyman	Dym and Little
1	Initial undesirable state	x			x	
2	Desirable goal state	x	x		x	x
3	Obstacles	x				
4	Key business goals		x			
5	Target market for product		x			
6	Constraints and criteria		x	x	x	x

Before developing the coding scheme for the problem statement, much iteration was done which required reading the problem statements in the reports under investigation. This was done to understand what possible components of problem statements could be derived from the problem statements developed by the student designers. Table 4.2 illustrates the frequency of mention of different components of problem statement in various design texts and problem statement developed by the students.

Table 4.2 Frequency of mention of problem statement components in design texts and students' problem statement

	Component of problem statement	Frequency of mention in design texts (5 design texts used for reference)	Frequency of mention in students' design problem (31 reports used for investigation)
1	Initial undesirable state	2/5	11/31
2	Desirable goal state	4/5	29/31
3	Obstacles	1/5	0/31
4	Key business goals	1/5	0/31
5	Target market for product	1/5	0/31
6	Constraints and criteria	4/5	25/31

From Table 4.2, it can be observed that the components of problem statement shaded in gray- initial desirable state, desirable goal state and constraints and criteria are not only mentioned more frequently in different design texts but also in the problem statements developed by the students. The components – obstacles, key business goals and target market for product are mentioned by one design text only and are not mentioned at all in the problem statements developed by the students. Based on the initial investigation a coding scheme was developed incorporating the components- initial undesirable state, desirable goal state and constraints and criteria to study the level of detail of problem statements. This was done by creating a matrix, which has problem statements as rows, components of problem statement as columns and the cells representing the component of each problem statement. Figure 4.1 shows the matrix representing the coding of problem statements. The type of entry in each cell of the matrix is also shown in Figure 4.1

	Column – 1	Column - 2	Column - 3
	Mentions Current undesirable state	Mentions desirable goal state	Mentions constraints and criteria
Problem statement	**Yes/No**	**Yes/No**	**Yes/No**

Figure 4.1 Matrix representing coding scheme for problem statement

The components of the problem statement used in the coding scheme are as explained below:

1. Mentions current undesirable state – Column 1 of the matrix represents whether the problem statement mentions the current undesirable state. The current undesirable state could either be current bad design of the product or problem in current process followed by the client. The typical entry in this column would be 'Yes', indicating that the problem statement mentions a current undesirable state or 'No' indicating that the problem statement does not mention the current undesirable state. No assessment is made as to the quality of the description of the current undesirable state.

2. Mentions desirable goal state – Column 2 of the matrix represents whether the problem statement mentions the desirable goal state. The desirable goal state could be a new product or process that performs desired functions or improvements in existing product or process as desired by the customer. The typical entry for this column would be 'Yes', indicating that the problem statement mention the desirable goal state, or 'No', indicating that the problem statement does not mention the desirable goal state. Again, no assignment of quality metrics is used in this research.

3. Mentions constraints and criteria - Column 3 of the matrix represents if the problem statement mentions the constraints or criteria for the design. It may be noted that all the constraints and criteria for the project may not be mentioned in the problem statement but it may only have some constraints or criteria. The typical entry in this column would be 'Yes', indicating that problem statement mentions constraints and criteria, or 'No', indicating that problem statement does not mention the constraints and criteria.

For the purpose of this research, the problem statement that has all the components as mentioned above is considered to be in greater detail than incomplete statements. The problem statement with greater detail can be considered as an indication that the students have a better understanding of the problem at hand. If this is the case, then greater detail problem statements should be indicators for greater detailed solutions as the teams would have greater understanding to solve the problem.

To further illustrate how each problem statement was coded into its components, an example of problem statement is explained below. The problem statements have been taken from student design reports.

Consider Problem statement A and Problem statement B as written below:

Problem statement – A

The current process of riveting mold pins into a bar is causing deformation of the assembled mold-sets. This deformation hinders the production process and creates *unnecessary cost. Possible designs are constrained by bar geometry, including straightness of the bar, and the material of the pin* [44].

Problem statement – B

Capsugel's current process of joining mold pins and holding bars utilizes a riveting machine which, during riveting, bends the holding bars. The manual process of straightening the bar is the limiting factor in the mold making process. A design solution is to include any process which eliminates this problem by eliminating the original bending, automating the straightening process, etc. [45].

The coding of both the problem statements is as shown in Figure 4.2. The underlined part of the problem statement indicates the corresponding component.

	Mentions current undesirable state	Mentions Desirable goal state	Mentions constraints and criteria
Problem statement – A- The current process of riveting mold pins into a bar is causing deformation of the assembled mold-sets. This deformation hinders the production process and creates unnecessary cost. Possible designs are constrained by bar geometry, including straightness of the bar, and the material of the pin.	**Yes**	**No**	**Yes**
Problem statement – B - Capsugel's current process of joining mold pins and holding bars utilizes a riveting machine which, during riveting, bends the holding bars. The manual process of straightening the bar is the limiting factor in the mold making process. A design solution is to include any process which eliminates this problem by eliminating the original bending, automating the straightening process, etc.	**Yes**	**Yes**	**Yes**

Figure 4.2 Coding of Problem statement A and B

It can be observed from Figure 4.2 that Problem statement A has only two out of three components of problem statement while problem statement B has all three components of problem statement.

By following the same process, the problem statements from all the reports under investigation were read and coded. The coding of all the problem statements can be found in Appendix A:.

4.3.2 Coding of final solution

After developing the coding scheme for the problem statements, the next step was to develop a coding scheme for solutions. The requirement for developing a coding scheme was to be able to systematically analyze the level of detail of solutions reported in the final report. Similar to developing the coding scheme for the problem statement, the goal was to identify different components of description of a design solution.

The typical components of description of a design solution would be description of working principles or functions of different components of proposed design, figures showing the design concept, and description of analysis, simulation, or experimentation done to validate the concept. Before developing the coding scheme, the researcher read through the solutions described in the reports under investigation to derive the possible components of description of design solution. This took several iterations and, based on this, a coding scheme was developed. The developed coding scheme is as shown in Figure 4.3.

	Column 1	Column 2			Column 3		
	Description	**Figures**			**Engineering**		
	Brief/ Medium/ Detailed	Labeled	Poorly Labeled	Not Labeled	Analysis	Simulation	Experiment
Typical Entry	Brief/ Medium/ Detailed	Number	Number	Number	Number	Number	Number

Figure 4.3 Coding Scheme for final solution

It may be noted that while coding the different aspects of design solution reported, only the aspects pertaining to final solution were considered. As a preliminary study, it is important to first determine whether there is a predictable relationship between the initial inputs (problem statements) and final outputs (final solution). If these relationships are found, then additional investigation may be necessary to determine what the specific design activities are that help drive the relationships. For example, if the report had analysis that was done to understand the problem, it was not codified as it did not pertain to the final solution.

The protocol for coding the different components of final solutions such as description, figures and engineering is explained below:

1. **Description** –Column-1 in Figure 4.3 indicates 'how much' description of the final solution is reported in the report. The level of detail of description is measured by counting the number of pages dedicated to describing the final solution in the main body of the report. Figure 4.4 shows snap shot of typical example of description of final solution. Following considerations were taken into account while counting the number of pages for the level of description:

- For this research, both textual and graphical descriptions are considered as description of solution. This was based on the rationale that along with the textual description, the graphic description such as sketches, free body diagrams, or CAD models also aid in describing the design. Figure 4.4 shows snap shot of a typical description of final solution [46]. In Figure 4.4, **A** indicates description of final solution. In this case it is 1.75 pages.
- The textual description generally consists of the explanation of different components of the design or the functionality of the design or both. In some cases, it may also include brief mention of the analysis or testing done for the final solution. However, the detailed description of different types of analysis such as economic or cost analysis, stress analysis, thermal analysis, failure analysis, material selection, or description of tests conducted are not taken into consideration while counting the number of pages for description of solution. The details of analysis, simulation, and experiments are considered while coding engineering aspect of final solution.
- The graphical description typically consists of sketches, free body diagrams, or CAD models of the final solution. For counting the number of pages for the level of description, only the graphical descriptions within the description of final solution are considered. The pages are counted irrespective of the size of the figure. A typical example of graphical description is indicated by **B** in Figure 4.4
- The blank spaces which are greater than or equal to 0.25 of a page are not counted while counting the number of pages. The blank space indicated by **C** in Figure 4.4

is 0.25 pages and therefore is not considered while counting the number of pages for description.

- Double line spacing is considered as standard line spacing. So if a report does not have the description in double line spacing, the numbers of pages are counted after adjusting for double line spacing. The double line spacing is indicated by **D** in Figure 4.4.

Figure 4.4 Example Coding of description [46]

In a typical design report, the level of description of a solution varies from a less than a half page to few pages for description of final design. To make this distinction clear, the level of description is further categorized as brief description, medium description and detailed description and these are explained as below:

1.1 Brief Description – The quantity of information in brief description of a solution is less than or up to 0.5 pages.

1.2 Medium Description – The quantity of information in medium description of a solution is from greater than 0.5 pages up to 2 pages.

1.3 Detailed Description – The quantity of information that is greater than 2 pages is considered as detailed description.

In order to populate the column for level of detail of description, the number of pages of description of the solutions were counted after taking all the above mentioned considerations into account and the entry ‘brief’, ‘medium’, or ‘detailed’ was made.

2. Figures – Column-2 in Figure 4.3 indicates ‘how many’ figures are included in the report for the final solution. This information is obtained by counting the number of figures for final solution. Different types of figures that are considered for this purpose include concept diagrams, free body diagrams, photographs, simulation figures and drawing package.

It may be noted that various figures used here for illustrations are obtained from student’s design reports. Several considerations applicable to all the different types of figures were made while counting the number of figures. These considerations are explained in detail as follows:

- While counting the number of figures, the figures in the main body as well as the appendix of the report are taken into consideration. However, only the figures pertaining to final solution are taken into consideration.

- For the figures that have multiple views, each figure is counted as separate figures because different views of the figure convey different information. Here, *multiple views* refer either to different views such as top view, front view, side view or figures showing different position of concept. Figure 4.5 shows an example of figure with multiple views [47]. In this case, the figure shows the views of the device before and after activation. Each view was considered as a separate figure. Essentially, each view in this image provides different information. As the figure count is intended to be a surrogate measure of level of detail, or amount of information, when the figure is clearly divisible in terms of information contained, it will be treated as multiple figures.

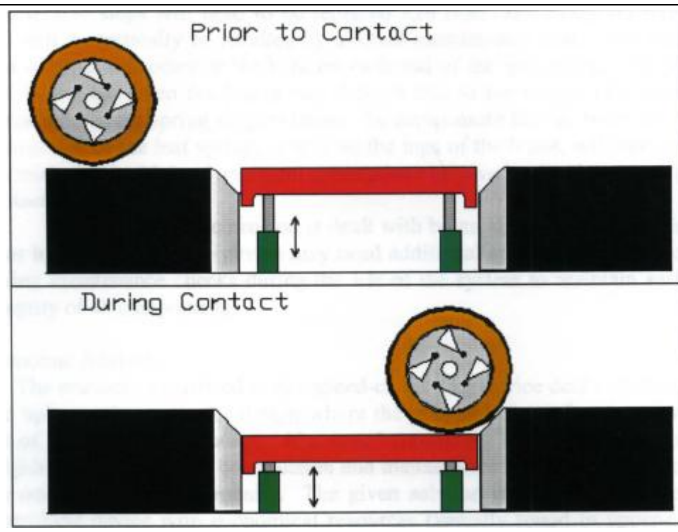


Figure 4.5 Example of figure with multiple views [47]

- If the same figure is repeated multiple times in the report, it is counted as a separate figure each time. In this case, even though the same information is contained multiple times with identical figures, the information that is being addressed or extracted by the reader will vary for each of the figures. Therefore, the information extracted from each figure is considered to be distinct each time the figure appears in the report.

- Exploded views showing different components of the design concept are considered as one figure. Essentially, the exploded view shows the components of same design concept and therefore it is counted as one figure. Figure 4.6 shows example of a figure with exploded view [48].

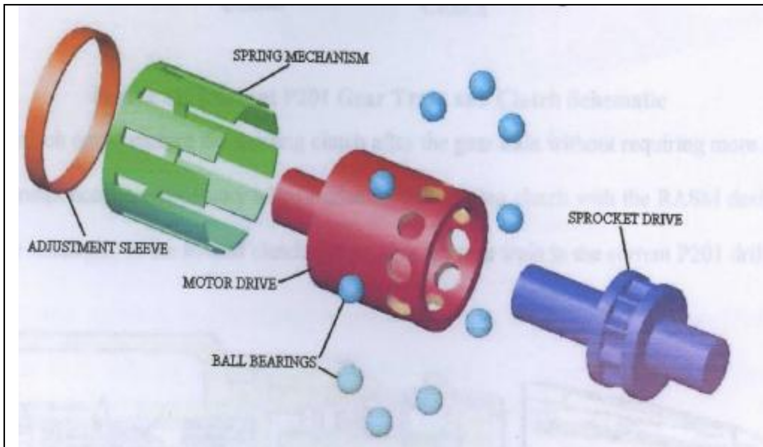


Figure 4.6 Example of Figure with exploded view [48]

In order to codify the level of detail of figures, they are further classified as, *labeled* (L), *poorly-labeled* (PL) and *not-labeled* (NL). As mentioned earlier there are different types of figures such as concept diagrams, free body diagrams, photographs, simulation figures, and drawing package. The protocol followed to codify each type of figure as *labeled*, *poorly-labeled*, and *not-labeled* is explained below:

Concept diagram – Concept diagrams are the diagrams showing the design concept. These could be hand drawn or generated using drawing software. Concept diagrams could either be 2-dimensional or 3-dimensional.

A concept diagram would be classified as *labeled* when all the components are completely labeled. Figure 4.7 shows an example of a *labeled* 3-dimensional concept diagram where all the components of the concept are labeled [48].

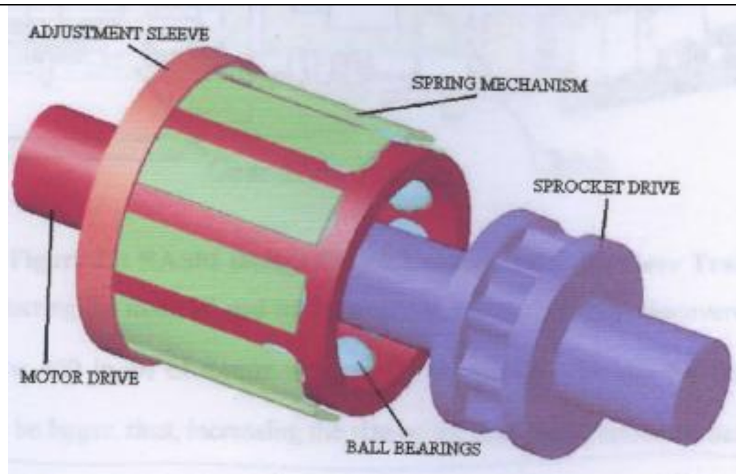


Figure 4.7 Example of *Labeled* concept diagram [48]

A concept diagram would be classified as *poorly-labeled* when the components are partially labeled. Figure 4.8 adapted from [46] shows an example of *poorly-labeled* 3-dimensioal concept diagram where the components of the design concept are only partially labeled.

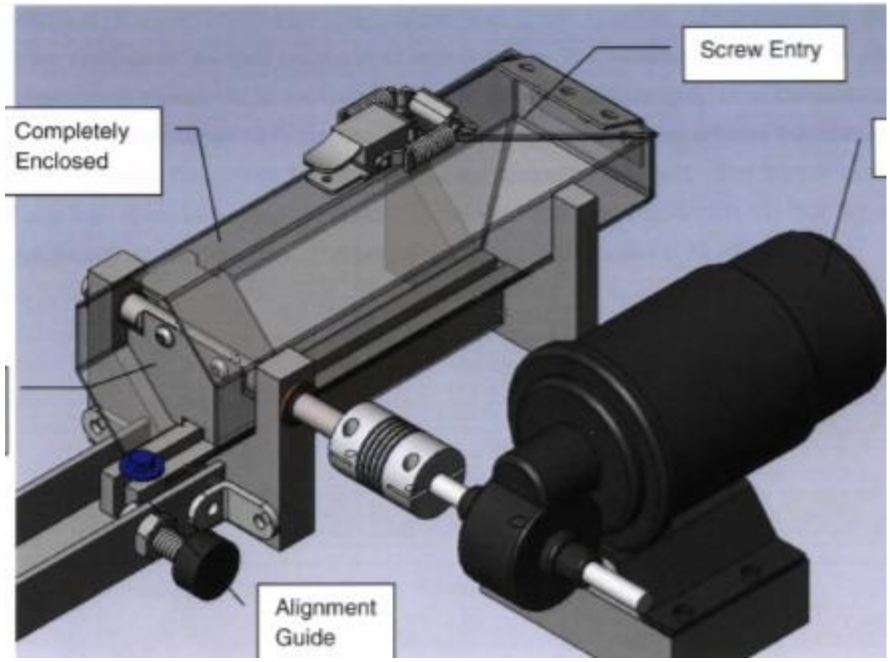


Figure 4.8 Example of *Poorly-labeled* concept diagram [46]

A concept diagram would be classified as *not-labeled* when all its components are not completely labeled. Figure 4.9 shows an example of *not-labeled* 2-dimensional concept diagram where none of the components of the design concept are labeled [49].

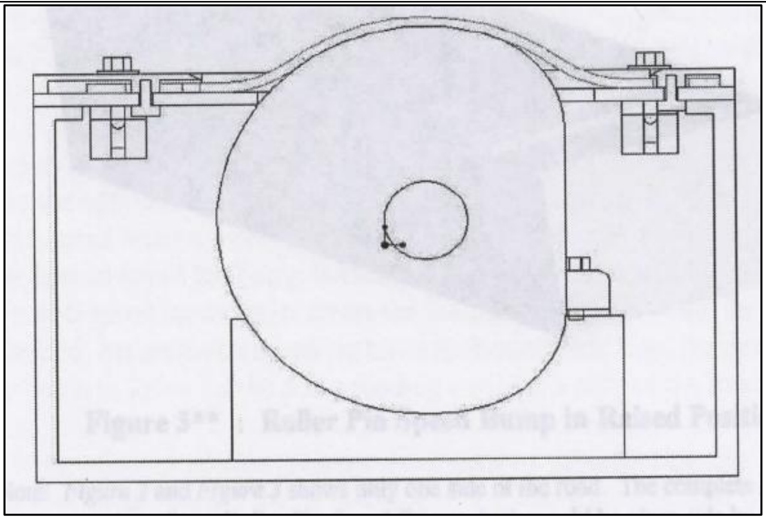


Figure 4.9 Example of *Not-labeled* concept diagram [49]

Free-body diagrams – Free-body diagrams could be hand drawn or generated using drawing soft wares such as Microsoft word, PowerPoint or CAD. Further, for this research, three different types of free-body diagrams were considered; mechanical, electrical and thermal.

A mechanical free-body diagram would be classified as *labeled* when the all parameters are completely specified in the figure. These parameters may include forces and direction of forces, distance, stiffness, mass, moments, reaction forces and constants. Figure 4.10 shows illustration of a *labeled* mechanical free-body diagram [50]. It can be observed that all the forces, reactions and distances are specified in the figure.

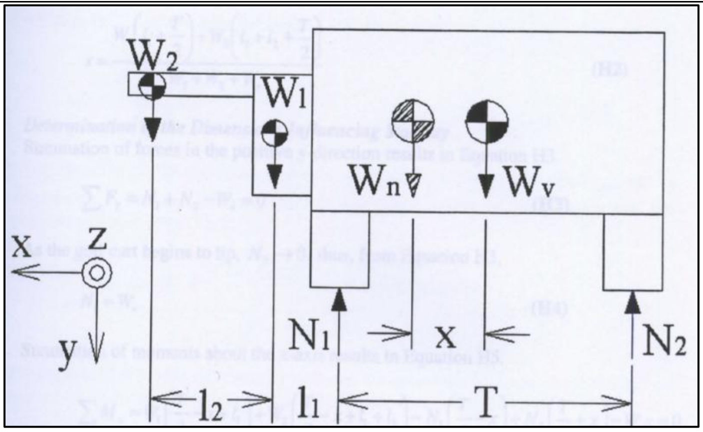


Figure 4.10 Example of *Labeled* mechanical free-body diagram [50]

A mechanical free-body diagram would be classified as *poorly-labeled* when only some parameters are specified in the figure. These parameters may include force, distance, reaction, moments, stiffness and constants. Figure 4.11 adapted from [51] illustrates an example of a poorly-labeled mechanical free-body diagram. It can be observed that the parameters such as mass, spring stiffness, damping constant and degree of freedom are not completely specified in the figure and therefore it would be classified as *poorly-labeled*.

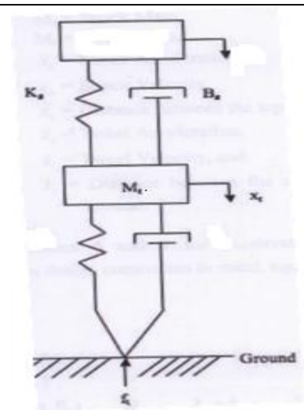


Figure 4.11 Example of *poorly-labeled* mechanical free-body diagram (Adapted from [51])

A mechanical free-body diagram would be classified as *not-labeled* when none of the parameters are specified in the figure. These parameters may include force, distance, reaction, moments, stiffness, and constants. Figure 4.12 illustrates an example of a *not-labeled* mechanical free-body diagram. It may be noted that none of the reports had *not-labeled* mechanical free-body diagram. Figure 4.12 is only for illustration purposes.

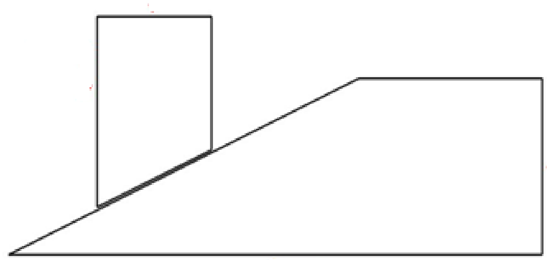


Figure 4.12 Example of *not labeled* mechanical free-body diagram

An electrical free-body diagram would be classified as *labeled* when all the features are completely specified. Examples of such parameters may include voltage, current, resistance, inductance, switches, and transformers. The diagram is also considered *labeled* in the cases where the diagram follows a standard nomenclature or symbols. Figure 4.13 illustrates a *labeled* electrical free body diagram [52].

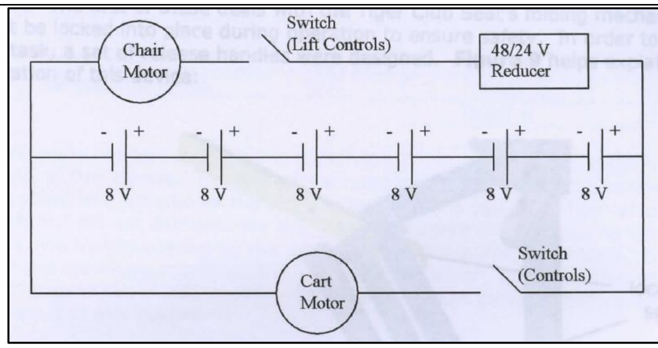


Figure 4.13 Example of *labeled* electrical free- body diagram [52]

An electrical free-body diagram would be classified as *poorly-labeled* when the different features are not completely specified. Examples of such parameters may include voltage, current, resistance, inductance, switches, and transformers. Figure 4.14 illustrates a *poorly-labeled* electrical free body diagram. It may be noted here that none of the reports had *poorly labeled* electrical free body diagram. Figure 4.14 is adapted from [50] only for illustration purpose.

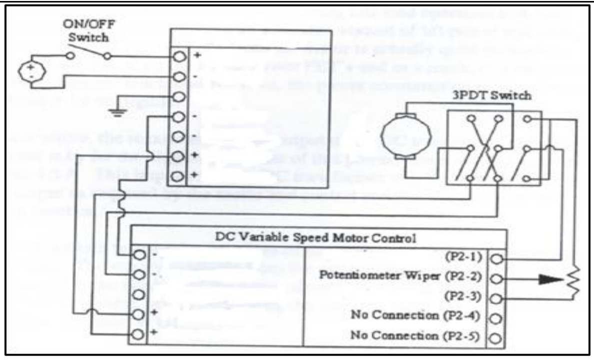


Figure 4.14 Example of poorly-labeled electrical free-body diagram (Adapted from [50])

An electrical free-body diagram would be classified as *not-labeled* when all its features are not specified. Examples of such parameters may include voltage, current, inductance, switches, and transformers. Figure 4.15 illustrates *not-labeled* electrical free body diagram. It may be noted that none of the reports had a *not-labeled* electrical free body diagram. Figure 4.15 is adapted from [52] only for illustration.

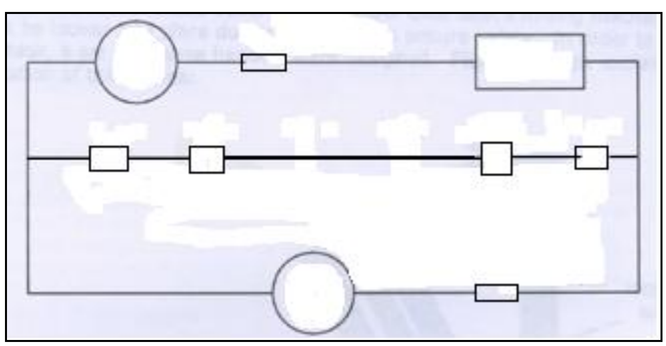


Figure 4.15 Example of not-labeled electrical free-body diagram (Adapted from [52])

A thermal free-body diagram would be classified as *labeled* when all its parameters are completely specified. Examples of such parameters may include temperature, flow directions, heat, energy and constants. Figure 4.16 illustrates a *labeled* thermal free-body diagram [53].

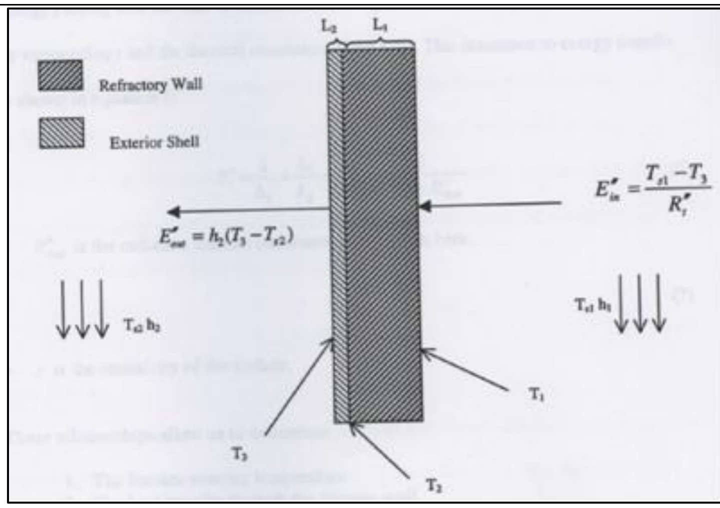


Figure 4.16 Example of labeled thermal free-body diagram [53]

A thermal free-body diagram would be classified as *poorly-labeled* when only some of its parameters are completely specified. Examples of such parameters may include temperature, flow directions, heat, energy and constants. Figure 4.17 is adapted from [54] for illustrating a *poorly-labeled* thermal free-body diagram.

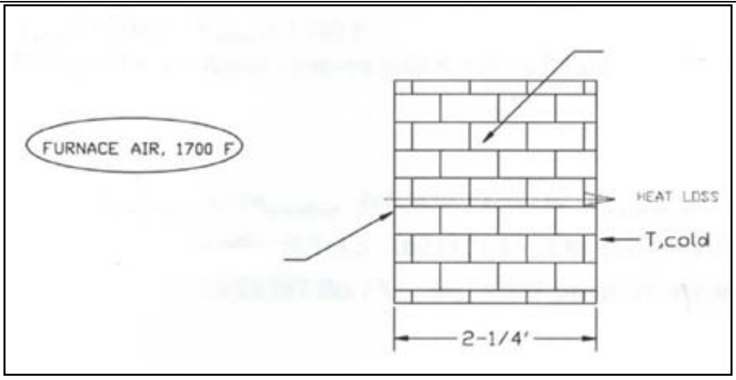


Figure 4.17 Example of poorly-labeled thermal free-body (Adapted from [54])

A thermal free-body diagram would be classified as *not-labeled* when none of its parameters are completely specified. Examples of such parameters may include temperature, flow directions, heat, energy and constants. Figure 4.18 illustrates *not-labeled* thermal free-body diagram. It may be noted that none of the reports under investigation had *not-labeled* thermal free-body diagram. Figure 4.18 is adapted from [53] only for illustration purpose.

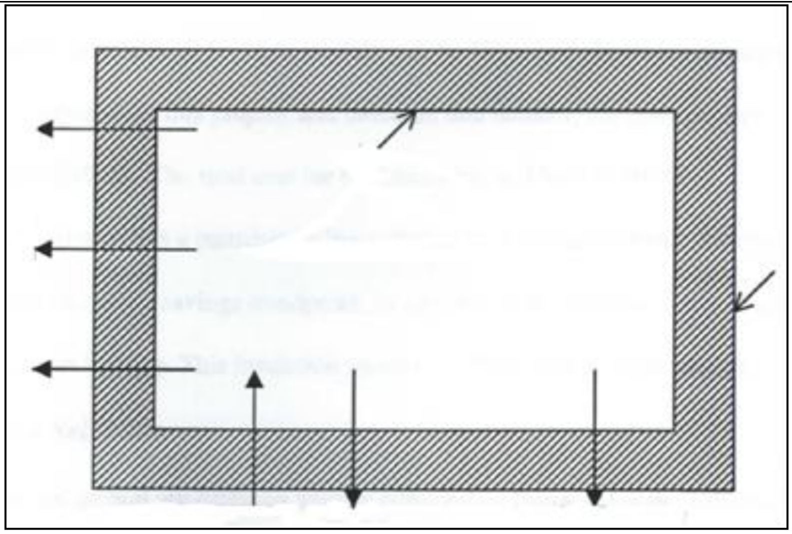


Figure 4.18 Example of not-labeled thermal free-body diagram (Adapted from [53])

Photographs- The graphical information in final description could also include photographs of the prototype of final design concept or prototypes of different components or test set-ups.

A photograph is classified as *labeled* when all it is completely labeled. An illustration of a *labeled* photograph is shown in Figure 4.19 [55]. It can be observed that all the components of the concept shown in the photograph are labeled.

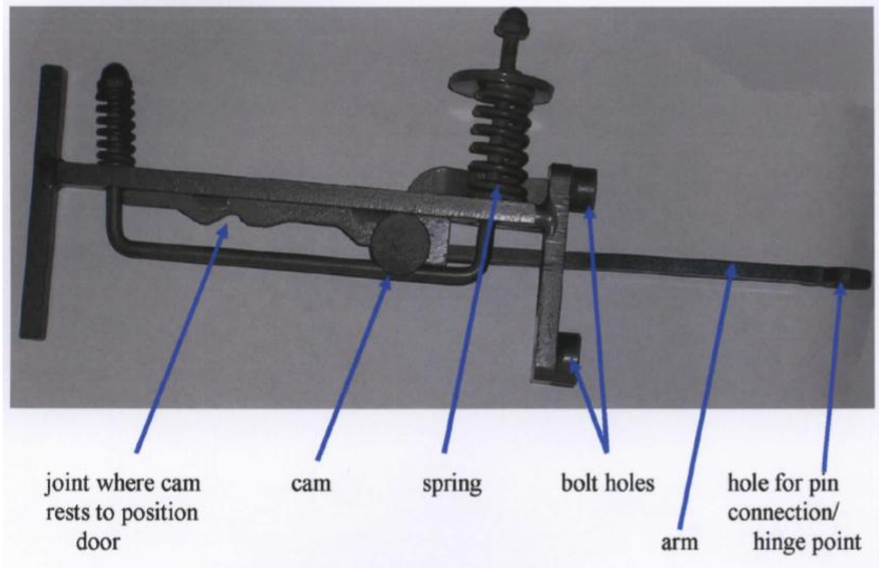


Figure 4.19 Example of *labeled* photograph [55]

When only some components of the photograph are labeled, it is classified as *poorly-labeled*. An example of poorly-labeled photograph is shown in Figure 4.20 [56].

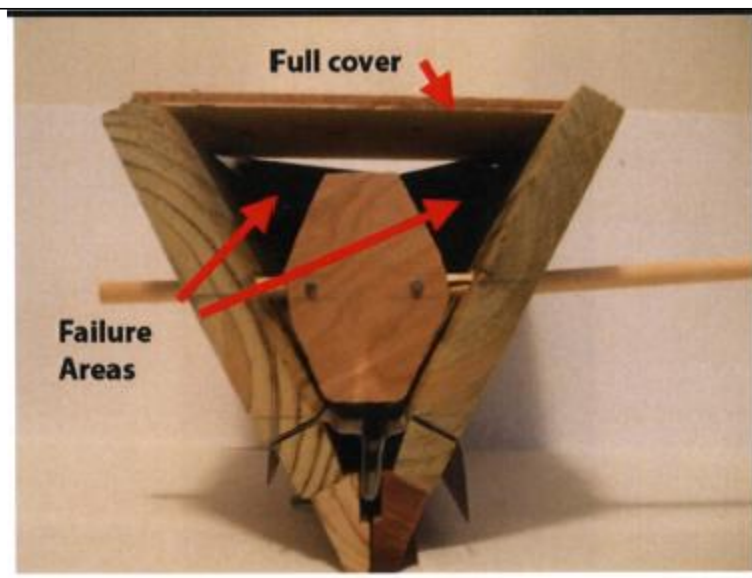


Figure 4.20 Example of *poorly-labeled* photograph [56]

A photograph is classified as not-labeled when none of the components of the photograph are labeled. Figure 4.20 is adapted from [46] and illustrates a not-labeled photograph.

Figure 4.21 Example of not-labeled photograph (Adapted from [46])

Simulation pictures – Simulation pictures may include the pictures showing the results of simulation, for instance thermal or mechanical simulation.

A simulation picture would be classified as *labeled* when the distributions of stress, pressure or temperature are clearly shown along with readable legends for the values and units of the same. Figure 4.22 illustrates a labeled simulation picture [51]. It can be observed that the stress distribution is clearly shown along with the legends for stress values and unit. This would therefore be classified as labeled.

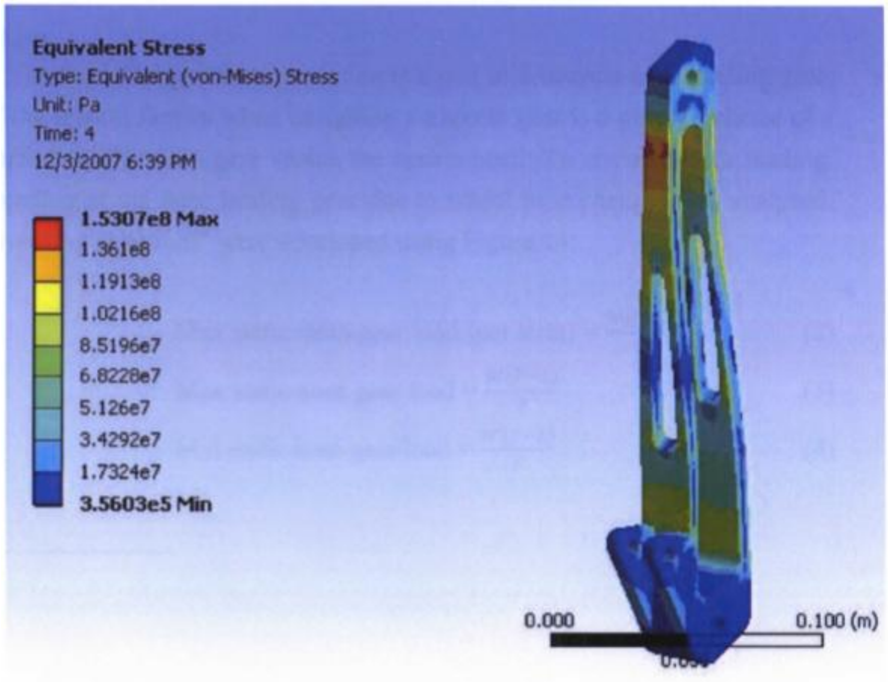


Figure 4.22 Example of *Labeled* simulation picture [51]

A simulation picture would be classified as *poorly-labeled* when the distributions of stress, pressure or temperature are not clearly shown, the legends for the same are not readable or the units are not mentioned. Figure 4.23 is adapted from [52] to illustrate a *poorly-labeled* simulation picture. It can be observed that the values and units of the stress distribution are not mentioned and therefore this figure would be classified as *poorly-labeled*.

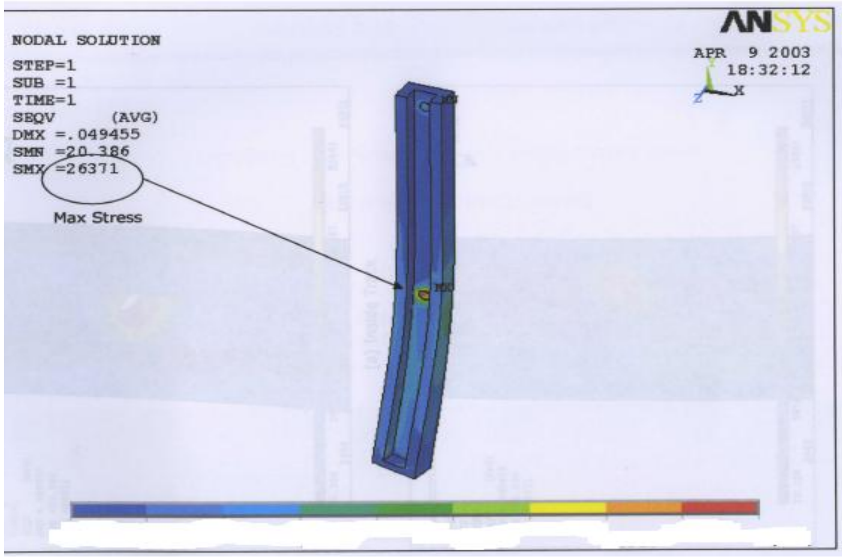


Figure 4.23 Example of *poorly-labeled* simulation picture (Adapted from [52])

A simulation picture would be classified as *not-labeled* when the distributions of stress, pressure or temperature are not clearly shown, the legends for the same are not shown or the units are not mentioned. Figure 4.24 is adapted from [57] and illustrates a *not-labeled* simulation picture. For this figure, the legend and the units for stress distribution are not shown, so it would be classified as *not-labeled*.

Figure 4.24 Example of *not-labeled* simulation picture (Adapted from [57])

Drawing package - Drawing package includes the detailed drawings of the final design concept with all dimensions. It may be noted that each figure in the sheet of drawing package is considered as a separate figure.

The figures in the drawing package would be considered *labeled* when either all components or dimensions are labeled or can be interpreted from other views in the same sheet. Figure 4.25 shows an illustration of labeled drawing package [50]. In this case, the drawing sheet shows two views A and B. These views would be considered as two different figures and both would be considered labeled as all the dimensions are labeled.

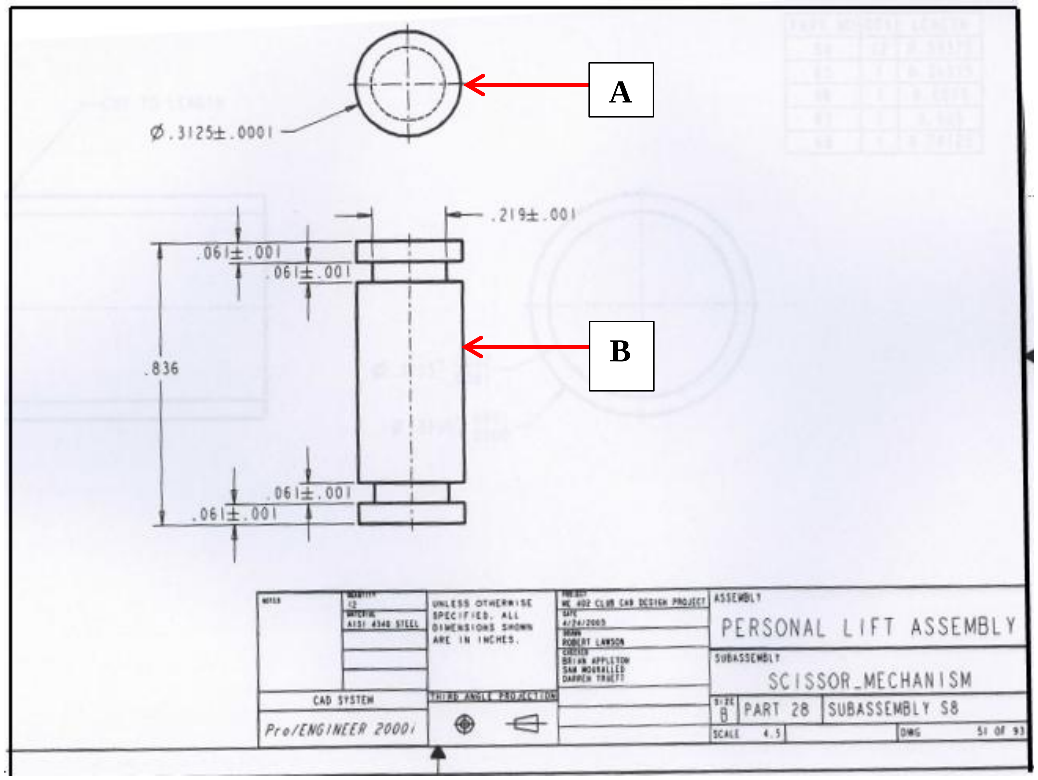


Figure 4.25 Example of Labeled drawing package [50]

The figures in the drawing package would be considered *poorly-labeled* when either some components or dimensions are not labeled or cannot be interpreted from other views in the same sheet. Figure 4.26 is adapted from [57] and illustrates poorly labeled drawing package figures. A, B and C in Figure 4.26 are three different views of the figure and would be counted as three figures. Only some dimensions of view A can be interpreted from B and C, additionally all dimensions of B and C are not completely labeled. Therefore all three views, A, B and C would be considered as poorly labeled.

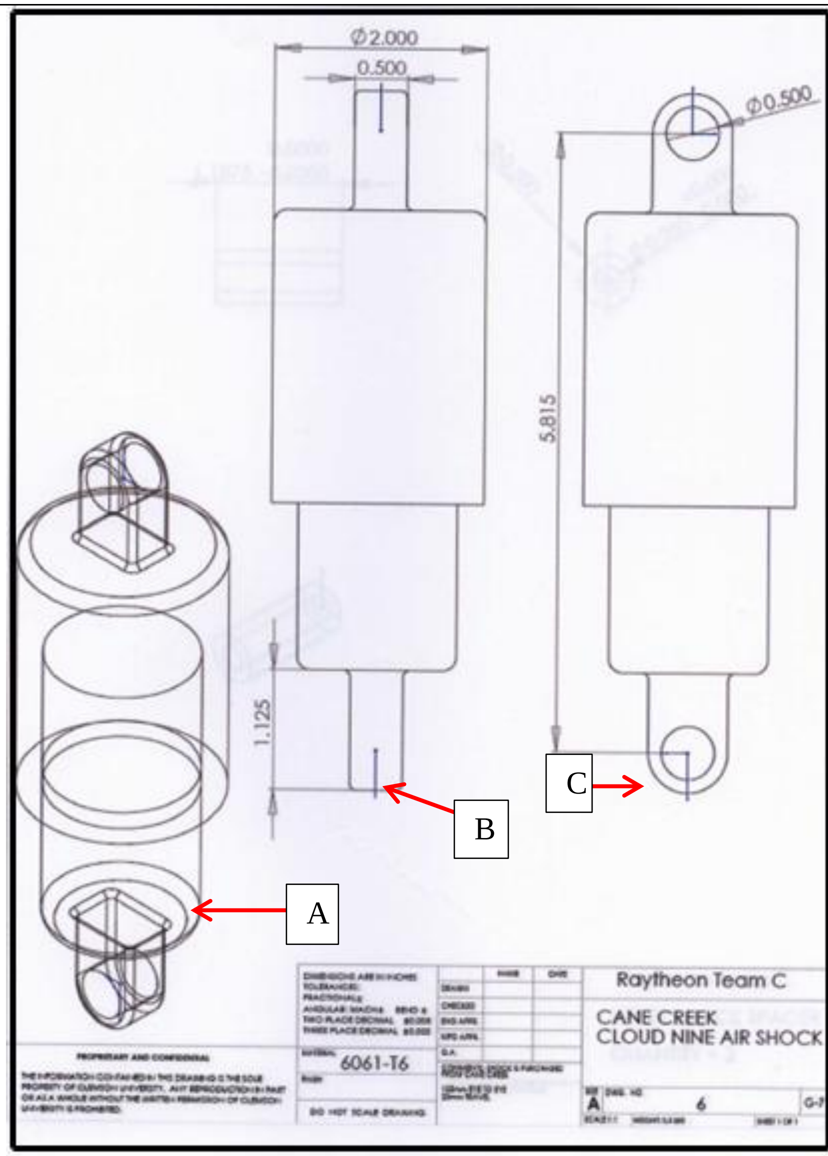


Figure 4.26 Example of *Poorly-labeled* drawing package figures (Adapted from [57])

The figures in the drawing package would be considered *not-labeled* when either all components or dimensions are not labeled or cannot be interpreted from other views in the same sheet. Figure 4.27 illustrates *not-labeled* drawing package. It can be observed that none of the dimensions of the three views are labeled and therefore all three figures would be classified as not labeled. It may be noted that none of the drawing packages in the final design reports under investigation were *not-labeled*. Figure 4.27 adapted from [58] is only for illustration purpose.

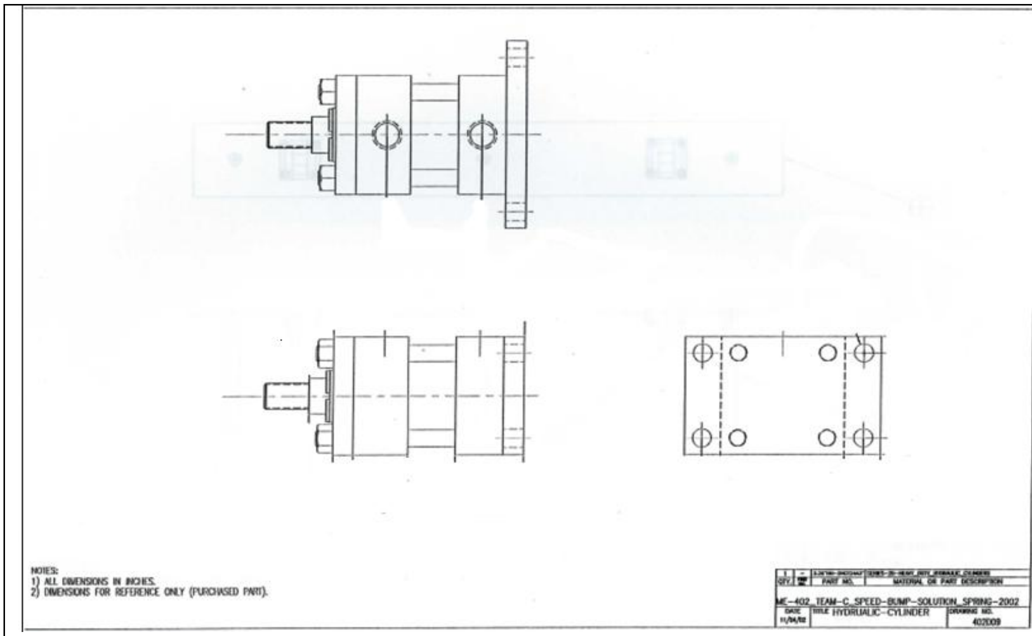


Figure 4.27 Example of Not-labeled drawing package (Adapted from [58])

In order to populate the column for each category of figures, the figures for final solution were counted and the number for labeled, poorly labeled or not labeled was entered in the column to which they corresponded.

3. Engineering – Column-3 gives information about the number and different types of engineering reported by the students. Here engineering refers to analysis, simulation and experimentation. The level of detail of engineering is measured by counting the number analysis, simulation and experimentation. Each of these is explained as below:

3.1 Analysis – This column reports how many different types of engineering analysis are reported by the students. The different types of engineering analysis could be design of different components, force and stress calculations, heat transfer analysis, failure analysis of components, cost or economic analysis or material selection. Following considerations were taken while counting the number of analysis:

- Multiple loading scenarios on same component were considered as one analysis but when different type of analysis was done on same component, it was counted as a separate analysis.

For example, if stress analysis was done on a component considered loads at multiple points, it was counted as one analysis. However, if stress and fatigue analysis was done on the same component, then it was counted as different analysis.

- Same analysis done on different components was counted as separate analysis.

For instance, if stress analysis was done on two different components of design solution such as pin and shaft, it was counted as a separate analysis. The typical entry for this column would be the number indicating how many analysis were done or 'No' indicating that no analysis is reported.

3.2 Simulation –This column reports how many different types of simulation are reported by the students. Reporting of simulation refers to the report on simulations done to test the functionality or failures on various components. In most cases this would be Finite Element Analysis simulated using different software such as ABAQUS™[2] or

[2] http://www.simulia.com/

COSMOS™[3]. The typical entry for this column would be the number indicating how many simulations were done or ‘No’ indicating that no simulation is reported.

3.3 Experimentation – This column reports what type of and how many different types of experiments were reported by the students. Reporting of experimentation refers to the report on the various experiments done to verify the analysis and simulation results. Sometimes, experiments may be done to make sure that the design is functioning as desired. The typical entry for this column would be the number indicating how many different experiments were done or ‘No’ indicating that no experimentation was recorded.

It may be noted that no formal ontologies or taxonomies were used to populate the types of analysis, simulation or experiments. The types of analysis, simulations and experiments reported in the final reports were used for classification for types of analysis, simulations and experiments.

The complete coding of all the final solutions can be found in Appendix B:.

4.3.3 Coding for requirements

One of the goals of this research is to analyze the influence of the level of requirements on the level of detail of final solution. Also, it is the goal of this research to analyze the influence of the level of detail of final solution on the level of detail of requirements met. In order to fulfill these research goals, a requirements matrix was developed as illustrated in Figure 4.28.

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[3] www.**cosmos**m.com

	Column-1	Column-2
	Number of requirements	% Requirements met
Typical entry	Number	Number

Figure 4.28 Requirements matrix

Column 1 of requirements matrix indicates number or requirements. In order to populate this column, each report under investigation was read through and the number of requirements reported were counted and entered in column-1. It may be noted that both constraints and criteria were taken into account while counting the number of requirements. However, the values associated with the constraints or criteria were not considered as the focus was on the type of requirement and not on the value. Further, if the constraints and criteria were same *type* of requirement with different values, they were only counted once. For instance, the report has a cost constraint of $5,000 and cost criteria of $3,000, it was only counted once as a cost requirement. The typical entry for column-1 would be a number that indicates the number of requirements reported in the report.

Column-2 of requirements matrix indicates the percentage of requirements met by the final design solution. Here percentage value of requirements met is used rather than absolute value as the percentage requirements met value gives an idea of number of requirements met in relation to the number of requirements established. In order to populate this column, the reports were read thoroughly and the requirements that were explicitly stated as fulfilled by the final solution were counted and the percentage value was then calculated and entered in the column. For example, if the report had ten requirements out of which five requirements were explicitly stated as fulfilled by the final solution then the percentage of requirements fulfilled value for the report would be 50%. The typical entry for column-2 would be a number indicating the percentage value of the requirements met by the final solution. In order to populate the requirements matrix, all the reports were read thoroughly and the entry of number of requirements and percentage requirements met was made. The requirements matrix for all reports under investigation can be found in Appendix C:.

After coding the problem statement, requirements, and final solution, the next step was to develop a data compression scheme which would then help in mapping the level of detail of problem statement and requirements to the level of detail of final solution. Section 4.4 explains the details of data compression scheme developed for problem statement, requirements and final solution.

4.4 Data Compression Approach

In order to derive meaningful conclusions from the data collected and coded, a data compression approach was developed. This data compression approach allowed for mapping the level of detail of problem statement and requirements to the level of detail of solution. The goal was to compress the data obtained from coding the problem statements, requirements, and final solution into the detail levels – high, medium, and low. This compressed scaling can then be used for mapping. The details of the compression approaches used for problem statement, requirements, components of final solution and final solution are explained in the sections that follow.

4.4.1 Data compression approach for problem statement

Section 4.3.1 discusses the coding scheme for problem statement. The problem statement is coded into three components 1) current state, 2) desirable goal state, and 3) constraints and criteria. The problem statements from all 31 reports were thoroughly read and coded using this scheme. The following protocol was used to compress the coded data into high, medium and low level of detail:

- **High** – The problem statement having all three of the above mentioned components was considered as having high level of detail and was ranked 'High'.
- **Medium** – The problem statement having two of the above mentioned three components was considered as having medium level of detail and was ranked 'Medium'.
- **Low** - The problem statement having one or none of the above mentioned components was considered as having low level of detail and was ranked 'Low'.

Figure 4.29 illustrates the data compression scheme for two problem statement. It can be observed that problem statement **A** which has two out of three components has a medium level of detail while problem statement **B** which has all three components of problem statement has a high level of detail.

	Number of components	Level of detail
Problem statement – A- The current process of riveting mold pins into a bar is causing deformation of the assembled mold-sets. This deformation hinders the production process and creates unnecessary cost. Possible designs are constrained by bar geometry, including straightness of the bar, and the material of the pin.	2 out of 3	Medium
Problem statement – B - Capsugel's current process of joining mold pins and holding bars utilizes a riveting machine which, during riveting, bends the holding bars. The manual process of straightening the bar is the limiting factor in the mold making process. A design solution is to include any process which eliminates this problem by eliminating the original bending, automating the straightening process, etc.	3 out of 3	High

Figure 4.29 Data compression for problem statement

The data compression for all problem statements can be found in Appendix D:.

4.4.2 Data compression approach for requirements

Section 4.3.3 describes the scheme for requirements analysis. Two important areas of interest here were requirements reported by the students and percentage of requirements actually met by the final solution. For each report, the number of requirements reported and percentage of requirements met were recorded in two separate columns as described in section 4.3.3. In order to compress this data and rank each report as high, medium and low level of detail in terms of reporting requirements following protocol was used:

- For the column 'Number of requirements' that indicates the total number of requirements reported, find the mean and standard deviation values.

- The ranking for high, medium and low level of detail was then given as follows –
  - High ≥ Mean + standard deviation
  - Medium - > Low and < High
  - Low ≤ Mean – standard deviation
- The decimal values were rounded to the nearest whole number.
- Similar procedure was also followed for percentage of requirements met by the final design.

Section 4.4.2.1 discusses the justification for using the standard deviation values for ranking as High, Medium and Low.

Figure 4.30 illustrates the data compression scheme used for requirements.

Column-1	**Column-2**	**Column-3**	**Column-4**	**Column-5**
Report Number	Number of requirements	Level of detail High/Medium/ Low	% Requirements met by final design	Level of % requirements met– High/Medium/ Low
1	7	Low	0.00	Low
2	4	Low	50.00	Medium
3	11	Medium	9.09	Low
4	8	Low	50.00	Medium
5	8	Low	50.00	Medium
6	19	Medium	42.11	Medium
7	20	High	50.00	Medium
8	17	Medium	70.59	High
9...	24	High	50.00	Medium
31	18	Medium	100	High
	Average - 14.5		Average – 41.6	
	Standard deviation - 6.2		Standard deviation - 28.5	

Figure 4.30 Data compression scheme for Requirements

Column-2 and Column-4 in Figure 4.30 respectively indicate the number of requirements and percentage of requirements met by the final design for each report. The mean and standard deviation values for the *Number of requirements* are respectively 14.5 and 6.2. Therefore the scales for High, Medium and Low are determined as below:

- High ≥ 20 (High = 14.5 + 6.2 = 20.7)
- Medium = 9 to 19
- Low ≤ 8 (Low = 14.5 – 6.2 = 8.3)

Based on the above values for high, medium and low levels of detail, each report is then given a rank of ‘high’, ‘medium’ or ‘low’ for number of requirements as can be observed in column-3 of Figure 4.30. Similar procedure is followed for percentage of requirements met. The complete data compression of requirements for all 31 reports can be found in Appendix E:.

4.4.2.1 Justification for ranking scheme for data compression

This section discusses the justification for using the mean and standard deviation values for ranking as High, Medium and Low. Table 4.3 illustrates the data compression scheme for requirements using different approaches.

Table 4.3 Data compression using different approaches

	Column-2	Column-3	Column-4	Column-5	Column-6	Column-7	Column-8
Year	Report number	Number of requirement	Standard deviation	Half standard deviation	Twice standard deviation	Equal intervals	Within project
1999	1	7	Low	Low	Medium	Low	High
	2	4	Low	Low	Medium	Low	Low
2000	3	11	Medium	Low	Medium	Medium	Medium
	4	8	Low	Low	Medium	Low	Medium
	5	8	Low	Low	Medium	Low	Medium
2001	6	19	Medium	High	Medium	Medium	Medium
	7	20	High	High	Medium	Medium	Medium
	8	17	Medium	Medium	Medium	Medium	Low
	9	24	High	High	Medium	High	High
2002	10	10	Medium	Medium	Medium	Low	Low
	11	16	Medium	Medium	Medium	Medium	Medium
	12	21	High	High	Medium	High	High
	13	18	Medium	High	Medium	Medium	Medium
2003	14	24	High	High	Medium	High	High
	15	13	Medium	Medium	Medium	Medium	Low
	16	18	Medium	High	Medium	Medium	Medium
2004	17	9	Medium	Low	Medium	Low	High
	18	4	Low	Low	Medium	Low	Low
	19	7	Low	Low	Medium	Low	Medium
2005	20	11	Medium	Low	Medium	Medium	Medium
	21	28	High	High	High	High	High
	22	10	Medium	Low	Medium	Low	Low
2006	23	20	High	High	Medium	Medium	Medium
	24	17	Medium	Medium	Medium	Medium	Medium
	25	21	High	High	Medium	High	Medium
2007	26	8	Low	Low	Medium	Low	Low
	27	16	Medium	Medium	Medium	Medium	High
	28	13	Medium	Medium	Medium	Medium	Medium
	29	13	Medium	Medium	Medium	Medium	Medium
2008	30	18	Medium	High	Medium	Medium	Medium
	31	18	Medium	High	Medium	Medium	Medium

Column 4 in Table 4.3 shows the data compression using mean and standard deviation, and columns 5 and 6 show the data compression using half and twice standard deviations respectively. It may be noted that adding standard deviation to mean was used for ranking as high, medium and low as it gave a more uniform distribution of Highs, Mediums and Lows. Adding or subtracting half the standard deviation to the mean resulted to more Highs and Lows as compared to Mediums. Also adding or subtracting twice the standard deviation to mean resulted to more Mediums as compared to Highs or Lows. This is illustrated in Table 4.3, where using half standard deviation results to more highs and lows and using twice standard deviation results to more mediums.

Column 7 in Table 4.3 shows the data compression using equal intervals. This means that the reports with number of requirements between 0 and 10 were ranked as 'Low', the reports with number of requirements between 11 and 20 were ranked as 'Medium' and the reports with number of requirements between 21 and 30 were ranked as 'High'. The rankings of high, medium and lows obtained by using the equal intervals are very similar when compared to the ranking using the mean and standard deviation values. Only 5 out of 31 reports, which is 16.12 percent, showed different results. However, for the purpose of this research, the ranking using the mean and standard deviation values was used.

Column 8 in Table 4.3 illustrates the data compression within the projects. Table 4.4 illustrates the protocol for data compression within the project.

Table 4.4 Data compression within Projects

	Column-2	Column-3	Column-4	Column-5	Column-6
Year	Average	Maximum value of number of requirements	Minimum value of number of requirements	Difference of max and min	Ratio of Max-Min and Average
1999	5.5	7	4	3	0.55
2000	9	11	8	3	0.33
2001	20	24	17	7	0.35
2002	16.25	21	10	11	0.68
2003	18.33	24	13	11	0.60
2004	6.66	9	4	5	0.75
2005	16.33	28	10	18	1.10
2006	19.33	21	17	4	0.21
2007	12.5	16	8	8	0.64
2008	18	18	18	0	0.00

In order to rank the level of detail of reporting requirements within same project, following protocol was followed:

- Compute the average value of number of requirements reported for the same project as illustrated in column 2 of Table 4.4
- For the reports for same project, compute the difference of maximum and minimum number of requirements as illustrated in column 5 of Table 4.4.
- The next step is to compute the ratio of the difference of maximum and minimum and average value of number of requirements as illustrated in column 6 of Table 4.4.
- If the ratio is greater than 0.3, then rank the reports as high, medium and low based on decreasing number of requirements and if this ratio is less than 0.3, then all the reports are ranked as medium.

The ranking of high, medium, and low within the projects is illustrated in Column 8 of Table 4.3. The data compression within the projects gives similar results to the approach using mean and standard deviation values in terms of the number of highs, mediums, and lows. However, the distribution of highs, mediums, and lows are different in both approaches. This is illustrated in Table 4.5. It can be observed that both approaches have 7 highs, 17 mediums and 7 lows. The distribution of rankings is different for 13 reports.

Table 4.5 Comparison of data compression approach

Year	Report number	Number of requirement	Level of detail of requirements	Within project
1999	1	7	Low	High
	2	4	Low	Low
2000	3	11	Medium	Medium
	4	8	Low	Medium
	5	8	Low	Medium
2001	6	19	Medium	Medium
	7	20	High	Medium
	8	17	Medium	Low
	9	24	High	High
2002	10	10	Medium	Low
	11	16	Medium	Medium
	12	21	High	High
	13	18	Medium	Medium
2003	14	24	High	High
	15	13	Medium	Low
	16	18	Medium	Medium
2004	17	9	Medium	High
	18	4	Low	Low
	19	7	Low	Medium
2005	20	11	Medium	Medium
	21	28	High	High
	22	10	Medium	Low
2006	23	20	High	Medium
	24	17	Medium	Medium
	25	21	High	Medium
2007	26	8	Low	Low
	27	16	Medium	High
	28	13	Medium	Medium
	29	13	Medium	Medium
2008	30	18	Medium	Medium
	31	18	Medium	Medium

Thus, this section discusses different approaches that can be followed for compressing the data in terms of high, medium and low. For the purpose of this research, the data compression approach using mean and standard deviation is used as it gives a uniform distribution of highs, mediums, and lows. The data compression within the projects is reserved for future work.

4.4.3 Data compression approach for components of final solution

As mentioned in Section 4.3.2, the final solution is coded into three main components namely description, figures and engineering. The ranking for high, medium and low level of detail for the solution was calculated by taking each of these components into consideration. For this purpose, each of these components was first ranked as high, medium and low level of details. Sections 4.4.3.1, 4.4.3.2 and 4.4.3.3 explain the protocol for ranking each component as ‘high’, ‘medium’ and ‘low’.

4.4.3.1 Description

The level of detail of description was ranked as ‘high’, ‘medium’ or ‘low’ based on if the description was detailed, medium or brief respectively. ‘Low’ ranking was also given for the case which did not have a description for final design. Figure 4.31 illustrates the ranking for description. It may be noted that only 10 reports are considered here for ease of explanation. The complete data compression for ‘description’ of final solution of all reports can be found in Appendix F:.

Report Number	Description	Level of detail High/Medium/Low
Report 1	No description	Low
Report 2	Detailed	High
Report 3	Detailed	High
Report 4	Medium	Medium
Report 5	Detailed	High
Report 6	Detailed	High
Report 7	Detailed	High
Report 8	Detailed	High
Report 9	Detailed	High
Report 10	Detailed	High

Figure 4.31 Data compression for description

4.4.3.2 Figures

Section 4.3.2 explains the coding of final solution where the figures were further categorized as 'labeled', 'poorly labeled' and 'not labeled'. The entry in each of these columns would be a number indicating the number of figures in the final solution that are labeled, poorly labeled or not labeled. Following protocol was followed to rank each category of figure as 'high', 'medium' and 'low':

- For the columns indicating the number of figures that are labeled, poorly labeled or not labeled, find the average and standard deviation values.
- The ranking for high, medium and low level of detail were then given as follows –
    - High ≥ Mean + standard deviation
    - Medium - > Low and < High
    - Low ≤ Mean – standard deviation
- The decimal values were rounded to the nearest whole number.

Figure 4.32 illustrates the data compression for each category of figure. Column 1, 3 and 5 indicate the number of figures that are labeled, poorly labeled and not labeled respectively.

Report Number	Column-1 Labeled	Column-2 Level of detail for labeled	Column-3 Poorly labeled	Column-4 Level of detail for poorly labeled	Column-5 Not Labeled	Column-6 Level of detail for not labeled
1	0	Low	0	Low	0	Low
2	1	Low	0	Low	3	Medium
3	19	Medium	25	High	21	Medium
4	4	Medium	7	Medium	5	Medium
5	5	Medium	1	Low	2	Medium
6	1	Low	6	Medium	1	Low
7	3	Medium	16	Medium	19	Medium
8	10	Medium	6	Medium	0	Low
9…	14	Medium	26	High	5	Medium
31	17	Medium	13	Medium	48	High
	Average -14.46		Average-13.66		Average -16.25	
	Std-dev-13.69		Std-dev -11.60		Std-dev -16.23	

Figure 4.32 Data compression for each category of figures

For Column 1 which indicates the number of labeled figures, the average and standard deviation values are respectively 14.46 and 13.69. Therefore the scales for High, Medium and Low are determined as below:

- High ≥ 28 (High = 14.46 + 13.69 =28.15)
- Medium = 2 to 27
- Low ≤ 1 (Low = 14.46 – 13.69 = 0.77)

Based on the above values for high, medium and low levels of detail, each report is then given a rank of 'high', 'medium' or 'low' for labeled figures as can be observed in column-2 of Figure 4.32. Similar procedure was followed for poorly labeled and not labeled figures.

For considering the figures for final solution, it was necessary to find the total ranking of figures. Figure 4.33 illustrates the data compression for all categories of figure combined. Following protocol was followed to find the total score for figures:

- The labeled, poorly labeled and not labeled figures were respectively given weight of 9, 3 and 1 as indicated in Figure 4.33.
- The high, medium and low ranks were given a weight of 9, 3 and 1 respectively and this is indicated by the numbers in bracket for high, medium and low in Figure 4.33 .
- The total score for figures was then obtained as:

  Total score for figures = (weight for labeled x weight for level of detail) + (weight for poorly labeled x weight for level of detail) + (weight for not labeled x weight for level of detail)

  So, for instance, for report 1, the total score for figures would be:

  Total score for figures = (9 x 1) + (3 x 1) + (1 x 1) = 13

Similarly, the total score for figures for all reports is calculated as indicated in column 4 of Figure 4.33.

	Column-1	**Column-2**	**Column-3**	**Column-4**	**Column-5**
	Level of detail for labeled	Level of detail for poorly labeled	Level of detail for not labeled	Total score for figures	Level of detail for all figures
Report	**9**	**3**	**1**		
1	Low (1)	Low (1)	Low (1)	13	Low
2	Low (1)	Low (1)	Medium (3)	15	Low
3	Medium (3)	High (9)	Medium (3)	57	Medium
4	Medium (3)	Medium (3)	Medium (3)	39	Medium
5	Medium (3)	Low (1)	Medium (3)	33	Medium
6	Low (1)	Medium (3)	Low(1)	19	Low
7	Medium (3)	Medium (3)	Medium (3)	39	Medium
8	Medium (3)	Medium (3)	Low (1)	37	Medium
9….	Medium (3)	High (9)	Medium (3)	57	Medium
31	Medium (3)	Medium (3)	High (9)	45	Medium
				Average – 50.22	
				Std-dev- 32.04	

Figure 4.33 Data compression for all categories of figure combined

After finding the total score for figures, the average and standard deviations values are calculated and the ranking for level of detail of all figures combined is then given as:

- High ≥ Mean + standard deviation
- Medium - > Low and < High
- Low ≤ Mean – standard deviation

The decimal values were rounded to the nearest whole number.

Column 5 in Figure 4.33 indicates the ‘high’, ‘medium’ and ‘low’ ranking for all figures combined. The complete data compression for figures for all reports can be found in Appendix G:.

4.4.3.3 Engineering

As explained in Section 4.3.2, engineering is further categorized as analysis, simulation and experiments. The entry in each of these columns would be a number which indicates the number of analysis, simulation and experiments. Following protocol was followed to rank each category of figure as ‘high’, ‘medium’ and ‘low’:

- For the columns indicating number of analysis, simulation and experiments find the average and standard deviation values.

- The ranking for high, medium and low level of detail were then given as follows –
  - High ≥ Mean + standard deviation
  - Medium - > Low and < High
  - Low ≤ Mean – standard deviation
- The decimal values were rounded to the nearest whole number.

Figure 4.34 illustrates the ranking for analysis, simulation and experiment.

Report	**Column-1**	**Column-2**	**Column-3**	**Column-4**	**Column-5**	**Column-6**
	Analysis	Level of detail for analysis	Simulation	Level of detail for simulation	Experiments	Level of detail for experiment
1	0	Low	0	Low	0	Low
2	0	Low	0	Low	0	Low
3	3	Medium	0	Low	1	Medium
4	3	Medium	0	Low	4	High
5	2	Medium	0	Low	1	Medium
6	8	Medium	0	Low	0	Low
7	8	Medium	0	Low	0	Low
8	8	Medium	0	Low	0	Low
9….	14	High	0	Low	0	Low
31	1	Low	0	Low	10	High
	Average -5.77		Average-0.58		Average - 1.03	
	Std dev-5.27		Std-dev – 0.98		Std-dev – 2.02	

Figure 4.34 Ranking for analysis, simulation and experiment

Column 1, 3 and 5 indicate the numbers of analysis, simulations and experiments reported. For Column 1 which indicates the number of analysis, the average and standard deviation values are respectively 5.77 and 5.27. Therefore the scales for High, Medium and Low are determined as below:

- High ≥ 11 (High = 5.77 + 5.27 = 11.04)
- Medium = 2 to 10
- Low ≤ 1 (Low = 5.77 – 5.27 = 0.5)

Based on the above values for high, medium and low levels of detail, each report is then given a rank of 'high', 'medium' or 'low' for analysis as can be observed in column-2. Similar procedure was followed for simulation and experiment.

For considering the engineering for final solution, it was necessary to find the total ranking of analysis, simulation and experiments. Figure 4.35 illustrates the data compression for engineering.

	Column-1	Column-2	Column-3	Column-4	Column-5
	Level of detail for analysis	Level of detail for simulation	Level of detail for experiment	Total score for engineering	Level of detail for engineering
Report	1	1	1		
1	Low (1)	Low (1)	Low (1)	3	Low
2	Low (1)	Low (1)	Low (1)	3	Low
3	Medium (3)	Low (1)	Medium (3)	7	Medium
4	Medium (3)	Low (1)	High (9)	13	Medium
5	Medium (3)	Low (1)	Medium (3)	7	Medium
6	Medium (3)	Low (1)	Low (1)	5	Medium
7	Medium (3)	Low (1)	Low (1)	5	Medium
8	Medium (3)	Low (1)	Low (1)	5	Medium
9….	High (9)	Low (1)	Low (1)	11	Medium
31	Low (1)	Low (1)	High	11	Medium
				Average – 10.09	
				Std Dev – 6.42	

Figure 4.35 Data compression for engineering

Following protocol was followed to find the total score for engineering:

- The analysis, simulation and experiment were weighted equally and the given value of weight was 1 as can be seen in Figure 4.35.
- The high, medium and low ranks were given a weight of 9, 3 and 1 respectively and this is indicated by the numbers in bracket for high, medium and low in Figure 4.35.
- The total score for engineering was then obtained as:

Total score for engineering = (weight for analysis x weight for level of detail) +

(Weight for simulation x weight for level of detail) +

(Weight for experiment x weight for level of detail)

So, for instance, for report 1, the total score for engineering would be:

Total score for engineering = (1 x 1) + (1 x 1) + (1 x 1) = 3

Similarly, the total score for engineering for all reports is calculated as indicated in column 4 in Figure 4.35.

After finding the total score for engineering, the average and standard deviations values are calculated and the ranking for level of detail for engineering is then given as:

- High ≥ Mean + standard deviation
- Medium - > Low and < High
- Low ≤ Mean– standard deviation

The decimal values were rounded to the nearest whole number.

Column 5 in Figure 4.35 indicates the ‘high’, ‘medium’ and ‘low’ ranking for engineering. The complete data compression for engineering can be found in Appendix I:.

4.4.4 Data compression approach for final solution

In order to rank the level of detail of final solution as ‘high’, ‘medium’ and ‘low’, the combined rankings of its components, description, figures and engineering was taken into consideration. In addition to these components, percentage requirements fulfilled were also considered as a component of final solution while calculating the level of detail based on the findings of [59]. A protocol was then developed to find the total score of final solution and then rank it as 'high', 'medium' or 'low' level of detail.

Figure 4.36 illustrates the ranking for the level of detail of final solution.

	Column-1	**Column-2**	**Column-3**	**Column-4**	**Column-5**	**Column-6**
	Description	% Requirement fulfilled	Figures	Engineering	Total score for final solution	Level of detail of final solution
1	Low (1)	Low (1)	Low (1)	Low (1)	4	Low
2	High (9)	Medium (3)	Low (1)	Low (1)	14	Low
3	High (9)	Low(1)	Medium (3)	Medium (3)	16	Medium
4	Medium (3)	Medium (3)	Medium (3)	Medium (3)	12	Medium
5	High (9)	Medium (3)	Medium (3)	Medium (3)	18	Medium
6	High (9)	Medium (3)	Low (1)	Medium (3)	16	Medium
7	High (9)	Medium (3)	Medium (3)	Medium (3)	18	Medium
8	High (9)	High (9)	Medium (3)	Medium (3)	24	Medium
9…	High (9)	Medium (3)	Medium (3)	Medium (3)	18	Medium
31	High (9)	High (9)	Medium (3)	Medium (3)	24	Medium
					Average-19.6	
					Std-dev-6.24	

Figure 4.36 Data compression for final solution

Following protocol was followed to find the total score for final solution:

- The different components of solution namely description, percentage requirements fulfilled, figures and engineering were weighted equally and were given weight of 1.
- High, medium and low levels of detail were given weight of 9, 3 and 1 respectively.
- The total score for final solution was then calculated as:

  Total score for solution = (weight for description x weight for level of detail) +

(weight for % requirement x weight for level of detail) +

(Weight for figures x weight for level of detail) +

(Weight for experiment x weight for level of detail)

So, for instance, for report 1, the total score for final solution would be:

Total score for final solution = (1 x 1) + (1 x 1) + (1 x 1) + (1 x 1) = 4

Similarly, the total score for final solution for all reports is calculated as indicated in column 5 in Figure 4.36.

After finding the total score for final solution, the average and standard deviations values are calculated and the ranking for level of detail for final solution is then given as:

- High ≥ Mean + standard deviation
- Medium - > Low and < High
- Low ≤ Mean – standard deviation

The decimal values were rounded to the nearest whole number.

Column 6 in Figure 4.36 indicates the ‘high’, ‘medium’ and ‘low’ ranking for final solution. The complete data compression for final solution for all reports can be found in Appendix J:.

CHAPTER FIVE: ANALYSIS AND RESULTS

After coding and compressing the data collected, the next step of the research is to map the level of detail of problem statement and requirements to the level of detail of final solution. The protocol of the mapping and the results obtained are discussed in this chapter. In each of the three sections of this chapter, multiple different mapping combinations are explored. The anticipated pattern for each mapping is defined, the results presented, and a key takeaway extracted. As is common in document analysis research, pattern matching is the fundamental research analysis tool. These patterns are not formally stated as hypotheses, but the takeaways may serve as the foundations for future research questions and formal hypotheses.

Further, it may be noted that Report 1 and Report 21 did not have a final solution and were therefore considered as outliers during the mapping. This was not known when the reports were identified for study. Therefore to maintain the integrity of research and remain unbiased, they were not excluded from study but were considered as outliers.

5.1 Mapping level of detail: problem statement to final solution

This section discusses the mapping of level of detail of problem statement to the level of detail of solution. Section 5.1.1 discusses the results of mapping low level of detail of problem statement to the level of detail of final solution. Section 5.1.2 discusses the results of mapping medium level of detail of problem statement to the level of detail of final solution. Finally, Section 5.1.3 discusses the results of mapping high level of detail of problem statement to the level of detail of final solution.

5.1.1 Mapping low level of detail

The goal of mapping the low level of detail of problem statement to level of detail of final solution was to learn to what level of detail of final solution a low level of detail of problem statement leads. In order to do this mapping, the reports with low level of detail of problem statement were grouped together. After grouping the reports, the level of detail of final solution for each report in the group was compared to the corresponding low level of detail of problem statement. The anticipated pattern would be that a low level of detail of problem statement would result in a low level of detail of final solution. Table 5.1 illustrates the mapping of low level of detail of problem statement to the level of detail of solution.

Table 5.1 Mapping low level of detail of problem statement to level of detail of final solution

Report Number	Level of detail of problem statement	Level of detail of final solution
Report 9	Low	Medium
Report 20	Low	Medium
Report 22	Low	Medium
Report 27	Low	Medium
Report 28	Low	Medium

From Table 5.1 it can be observed that in all cases, a low level of detail of problem statement leads to a medium level of detail of final solution. This is contradictory to what would be expected. It is interesting to note that not a single case was observed where a low level of detail of problem statement leads to a low level of detail of final solution as would be expected. Likewise, a low level of detail of problem statement never resulted in a high level of detail of final solution.

Takeaway 1: Low level of detail in the problem statement leads to no greater than a medium level of detail of final solution.

5.1.2 Mapping medium level of detail

The goal of mapping the medium level of detail of problem statement to the level of detail of final solution was to observe what level of detail of final solution a medium level of detail of problem statement leads to. For this purpose, the reports with low level of detail of problem statement were grouped together. After grouping the reports together, the level of detail of final solution for each report in the group was compared to the corresponding medium level of detail of problem statement. The anticipated pattern would be that a medium level of detail of problem statement would lead to a medium level of detail of final solution. Table 5.2 illustrates the mapping of medium level of detail of problem statement to the level of detail of final solution.

Table 5.2 Mapping medium level of detail of problem statement to the level of detail of final solution

Report Number	Level of detail of problem statement	Level of detail of final solution
Report 14	Medium	High
Report 15	Medium	High
Report 5	Medium	Medium
Report 6	Medium	Medium
Report 7	Medium	Medium
Report 8	Medium	Medium
Report 10	Medium	Medium
Report 11	Medium	Medium
Report 13	Medium	Medium
Report 18	Medium	Medium
Report 23	Medium	Medium
Report 24	Medium	Medium
Report 25	Medium	Medium
Report 30	Medium	Medium
Report 31	Medium	Medium
Report 2	Medium	Low
Report 1	Medium	Low
Report 21	Medium	Low

It may be noted here that Report 1 and Report 21 did not have a final solution reported and therefore these two reports were considered as outliers and are marked in red text and shaded cells. From Table 5.2, it can be observed that for most cases a medium level of detail of problem statement leads to a medium level of detail of final solution as expected. However, for two cases, Reports 14 and 15, a medium level of detail of problem statement leads to a high level of detail of final solution. Excluding the outliers, only for one case, Report 2, does a medium level of detail of problem statement leads to a low level of detail of final solution. Therefore, medium level of detail of problem statement seems to lead to medium level of detail of the final solution.

Takeaway 2: Generally, a Medium level of detail for the problem statement implies a Medium or High level of detail in the final solution. Only 1/18 yielded results different from this takeaway.

5.1.3 Mapping high level of detail

The goal of mapping the high level of detail of problem statement to the level of detail of final solution was to observe to what level of detail of final solution a high level of detail of problem statement leads. In order to do this mapping, the reports with high level of detail of problem statement were grouped together. After grouping the reports together, the level of detail of final solution for each report in the group was compared to the corresponding high level of detail of problem statement. The anticipated pattern would be that a high level of detail of problem statement leads to a high level of detail of final solution. Table 5.3 illustrates the mapping of high level of detail of problem statement to the level of detail of final solution.

Table 5.3 Mapping high level of detail of problem statement to the level of detail of final solution

Report number	Level of detail of Problem statement	Level of detail of final solution
Report 3	High	Medium
Report 4	High	Medium
Report 12	High	Medium
Report 16	High	Medium
Report 17	High	Medium
Report 19	High	Medium
Report 26	High	Medium
Report 29	High	High

From Table 5.3, it can be observed that for most cases a high level of detail of problem statement results to a medium level of detail of final solution. This is contrary to expectations. It is observed that only for one case, Report 29, does a high level of detail of problem statement results to a high level of detail of final solution. It is interesting to note that not a single case was observed where a high level of detail of problem statement resulted in low level of detail of final solution.

> ***Takeaway 3: High level of detail in the problem statement leads to no lower than a medium level of detail of final solution.***

5.2 Mapping the level of detail: requirements to final solution

This section describes the mapping of level of detail of requirements to the level of detail of final solution. Section 5.2.1 describes the mapping of low level of detail of requirements to the level of detail of final solution. Second, Section 5.2.2 describes the mapping of medium level of detail of requirements to the level of detail of final solution. Next, Section 5.2.3 describes the mapping of high level of detail of requirements to the level of detail of final solution

5.2.1 Mapping low level of detail

The mapping of low level of detail of requirements to the level of detail of final solution was done with a goal of understanding to what level of detail of final solution a low level of detail of requirements leads. For the purpose of doing this mapping, the reports with a low level of detail of requirements were grouped together. After grouping the reports, the level of detail of final solution for each report in the group was compared with the corresponding low level of detail of requirements. The anticipated pattern would be that a low level of detail of requirements would lead to a low level of detail of final solution. Table 5.4 illustrates the mapping of low level of detail of requirements to the level of detail of final solution.

Table 5.4 Mapping low level of detail of requirements to the level of detail of final solution

Report Number	Level of detail of requirements	Level of detail of final solution
Report 1	Low	Low
Report 2	Low	Low
Report 4	Low	Medium
Report 5	Low	Medium
Report 18	Low	Medium
Report 19	Low	Medium
Report 26	Low	Medium

Report 1 did not have a final solution reported and therefore it is considered as outlier and marked in red text with gray cell shading. Excluding the outlier, only one case, Report 2, is observed where a low level of detail of requirements leads to a low level of detail of final solution as expected. It is evident from Table 5.4 that for most cases a low level of detail of requirements results to a medium level of detail of final solution. It is interesting to note here that no case was observed where a low level of detail of requirement resulted to a high level of detail of the final solution.

Takeaway 4: Low level of detail of requirements leads to no greater than a medium level of detail of final solution.

5.2.2 Mapping medium level of detail

With the goal of understanding what level of detail of final solution results from a medium level of detail of requirements, the medium level of detail of requirements was mapped to the level of detail of final solution. In order to do this mapping, the reports with medium level of detail of requirements were grouped together. After grouping the reports, the level of detail of final solution for each report in the group was compared with the corresponding medium level of detail of requirements. The anticipated pattern would be that a medium level of detail of requirement results to medium level of detail in final solution. Table 5.5 displays the mapping of medium level of detail of requirements to the level of detail of final solution.

Table 5.5 Mapping of medium level of detail of requirements to the level of detail of final solution

Report Number	Level of detail of Requirements	Level of detail of final solution
Report 3	Medium	Medium
Report 6	Medium	Medium
Report 8	Medium	Medium
Report 10	Medium	Medium
Report 11	Medium	Medium
Report 13	Medium	Medium
Report 16	Medium	Medium
Report 17	Medium	Medium
Report 20	Medium	Medium
Report 22	Medium	Medium
Report 24	Medium	Medium
Report 27	Medium	Medium
Report 28	Medium	Medium
Report 30	Medium	Medium
Report 31	Medium	Medium
Report 15	Medium	High
Report 29	Medium	High

Most cases fall under the expected result where medium level of detail of requirement results to a medium level of detail of final solution as can be observed in Table 5.5. However for Reports 15 and 29, medium level of detail of requirements results to a high level of detail of solution.

Takeaway 5: Generally, a Medium level of detail for the requirements implies a Medium or High level of detail in the final solution.

5.2.3 Mapping high level of detail of requirements to the level of detail of final solution

The goal of mapping the high level of detail of requirements to the level of detail of final solution was to learn what level of detail of final solution is resulted from a medium level of detail of requirements. In order to do this mapping, the reports with high level of detail of requirements were grouped together. Then the level of detail of final solution for each report in the group was compared with the corresponding high level of detail of requirements. The expected result would be that a high level of detail of requirements would lead to a high level of detail of final solution. Table 5.6 illustrates the mapping of high level of detail of requirements to high level of detail of final solution.

Table 5.6 Mapping high level of detail of requirements to high level of detail of final solution

Report Number	Level of detail of Requirements	Level of detail of final solution
Report 7	High	Medium
Report 9	High	Medium
Report 12	High	Medium
Report 23	High	Medium
Report 25	High	Medium
Report 14	High	High
Report 21	High	Low

It may be noted that Report 21 did not have a final solution reported and was therefore considered as outlier (red text and gray cell shading). Excluding the outlier, no case was observed where a high level of detail of requirement resulted to a low level of detail of final solution. However, it is also interesting to note that only for Report 14 does a high level of detail of requirements resulted to a high level of detail of final solution, as would have been expected. For most of the cases, a high level of detail of requirements resulted to a medium level of detail of final solution.

Takeaway 6: High level of detail of requirements leads to no lower than a Medium level of detail of final solution.

5.3 Mapping level of detail: final solution to percentage requirements met

This section discusses the mapping of level of detail of final solution to the level of percentage requirements met. It may be noted that for mapping the level of detail of final solution to the level of percentage requirements met, the percentage requirements met was not considered while calculating the total score for final solution. Section 5.3.1 discusses the results of mapping low level of detail of final solution to the level of detail of percentage of requirements met. Section 5.3.2 discusses the results of mapping medium level of detail of final solution to the level of percentage of requirements met. Finally, Section 5.3.3 discusses the results of mapping high level of detail of final solution to the level of detail of % requirements met.

5.3.1 Mapping low level of detail

The goal of mapping the low level of detail of final solution to level of detail of % requirements met was to learn what level of percentage requirements met a low level of detail of final solution leads to. The anticipated pattern would be that a low level of detail of final solution results to a low level of detail of % requirements met. In order to do the mapping, the reports with low level of detail of final solution were grouped together and the level of detail of % requirements met for each report in the group was compared with the corresponding low level of detail of final solution. Table 5.7 illustrates the mapping of low level of detail of final solution to level of percentage requirements met.

Table 5.7 Mapping low level of detail of final solution to level of % requirements met

Report Number	Level of detail of final solution	Level of detail of % requirements met
Report 1	Low	Low
Report 21	Low	Low
Report 2	Low	Medium
Report 4	Low	Medium

It may be noted that Reports 1 and 21 did not have a final solution reported and are therefore considered as outliers. Excluding the outliers, none of the cases depicted the anticipated pattern of a low level of detail of final solution leading to a low level of percentage requirements met. Two cases were observed where a low level of detail of final solution leads to a medium level of percentage requirements met. However, it is important to note that a low level of detail of final solution never resulted into a high level of percentage requirements met.

Takeaway 7: A Low level of detail of final solution results to no greater than a Medium level of % requirements met.

5.3.2 Mapping medium level of detail

The goal of mapping the medium level of detail of final solution to level of percentage requirements met was to learn what level of percentage requirements met a medium level of detail of final solution leads. In order to do the mapping, the reports with medium level of detail of final solution were grouped together and the level of percentage requirements met for each report in the group was compared with the corresponding medium level of detail of final solution. The expected result would be that a medium level of detail of final solution results to a medium level of percentage requirements met. Table 5.8 illustrates the mapping of medium level of detail of final solution to level of detail of % requirements met.

Table 5.8 Mapping medium level of detail of final solution to the level of % requirements met

Report Number	Level of detail of final Solution	Level of detail of % requirements met
Report 3	Medium	Low
Report 11	Medium	Low
Report 12	Medium	Low
Report 5	Medium	Medium
Report 6	Medium	Medium
Report 7	Medium	Medium
Report 9	Medium	Medium
Report 13	Medium	Medium
Report 18	Medium	Medium
Report 19	Medium	Medium
Report 23	Medium	Medium
Report 24	Medium	Medium
Report 30	Medium	Medium
Report 8	Medium	High
Report 16	Medium	High
Report 17	Medium	High
Report 20	Medium	High
Report 31	Medium	High

From Table 5.8, it can be observed that for most cases, a medium level of detail of final solution results to either a medium or high level of percentage requirements met. However, for three cases, a medium level of detail of requirements leads to low level of percentage requirements met.

Takeaway 8: Generally a Medium level of detail of final solution results to Medium or High level of %requirements met. Only 3/18, which is 16.6%, yielded results different from this takeaway.

5.3.3 Mapping high level of detail

The goal of mapping the high level of detail of final solution to level of percentage requirements met was to learn to what level of percentage requirements met a high level of detail of final solution leads. In order to do the mapping, the reports with high level of detail of final solution were grouped together and the level of percentage requirements met for each report in the group was compared with the corresponding high level of detail of final solution. The expected result would be that a high level of detail of final solution results to a high level of percentage requirements met. Table 5.9 illustrates the mapping of high level of detail of final solution to level of percentage requirements met.

Table 5.9 Mapping high level of detail of final solution to the level of % requirements met

Report Number	Level of detail of final solution	Level of detail of % requirements met
Report 10	High	Low
Report 26	High	Low
Report 14	High	Medium
Report 15	High	Medium
Report 22	High	Medium
Report 25	High	Medium
Report 27	High	Medium
Report 28	High	Medium
Report 29	High	High

From Table 5.9, it can be observed that for most cases, a high level of detail of final solution leads to a medium level of percentage requirements met. The expected result where a high level of detail of final solution leads to a high level of percentage requirements met was found for one case only. However, two cases are also observed where a high level of detail of final solution leads to a low level of percentage requirements met.

Takeaway 9: For most cases, a High level of detail of final solution results to Medium level of % requirements met.

CHAPTER SIX: CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

The research presented in this thesis is an initial attempt to answer three broad research questions:

1. What is the influence of the level of detail of problem statement on the level of detail of final solution?
2. What is the influence of the level of detail of established requirements on the level of detail of final solution?
3. What is the influence of the level of detail of final solution on the level of detail of the requirement met by it?

In order to answer these research questions, a document analysis was conducted. A total of 31 final reports, which consisted of reports from multiple design teams for one project for each year from 1999 to 2008, were collected and studied. To be able to systematically analyze the information in final reports a coding scheme was developed for the problem statement and the final solution. Further, a data compression approach was developed to capture the collected data and allow for the mapping of levels of detail. Section 6.1 summarizes the findings and recommendations derived from this research.

6.1 Research Findings and Recommendations:

This section discusses the key takeaways from this research and suggests recommendation that can help to improve the level of detail of final solutions that students develop. The key takeaways derived from mapping the level of detail of problem statement to the level of detail of final solution are summarized in Table 6.1.

Table 6.1 Takeaways from mapping level of detail of problem statement to level of detail of final solution

Mapping level of detail: Problem statement to final solution	
Takeaway-1	Low level of detail in the problem statement leads to no greater than a medium level of detail of final solution.
Takeaway-2	Generally, a Medium level of detail of problem statement implies a medium or high level of detail of final solution
Takeaway-3	High level of detail in the problem statement leads to no lower than a medium level of detail of final solution

These takeaways indicate that a low level of detail of problem statement would most likely result to a low or medium level of detail of final solution. Additionally, there are greater chances for a high level of detail of solution to result from a high or medium level of detail of problem statement. Based on these takeaways, it can be recommended that students should be encouraged to develop a high, or at least a medium, level of detail of problem statement. This may lead to better chances of students' understanding of the problem at hand and have a greater probability of resulting to a high level of detail in the final solution. Conversely, a team with a lower level of detail of problem statement can be warned early in the semester that it has greater chances of poorly understanding the problem and resulting to a low level of detail in the final solution. This study provides concrete evidence to support these recommendations as opposed to the general anecdotal based recommendations that faculty advisors may be able to offer. The level of detail of problem statement can be measured by using the components of problem statement discussed in Section 4.3.1.

The key takeaways derived from mapping the level of detail of requirements to the level of detail of final solution are summarized in Table 6.2.

Table 6.2 Takeaways from mapping level of detail of requirements to level of detail of final solution

Mapping level of detail: Requirements to Final solution	
Takeaway-1	Low level of detail of requirements leads to no greater than a Medium level of detail of final solution.
Takeaway-2	Generally, a medium level of detail of requirements implies a Medium or high level of detail in final solution.
Takeaway-3	High level of detail of requirements leads to no lower than Medium level of detail of final solution.

These takeaways indicate that a low level of detail in requirements will at most result to a medium level of detail of requirements. High level of detail of solution results from either a high or medium level of detail of requirements. Based on these takeaways derived by mapping the level of detail of requirements to the level of detail of final solution, it can be recommended that students should be encouraged to develop the requirements with a high or at least a medium level of detail so that there is a greater probability of development of high level of detail of solution. On the other hand, the team with a low level of detail of requirements can be warned that it has greater chances of resulting to a low level of detail of solution.

Currently, absolute measurement for the level of detail of requirements is not available. However, the level of detail of requirements for a team can be determined relatively by comparing the number of requirements developed by different teams on the project. The key takeaways derived from mapping the level of detail of final solution to level of percentage requirements met are summarized in Table 6.3

Table 6.3 Takeaways from mapping level of detail of final solution to level of % requirements met

Mapping level of detail: Requirements to Final solution	
Takeaway-1	Low level of detail of final solution results to no greater than a Medium level % requirements met.
Takeaway-2	Generally a Medium level of detail of final solution results to Medium or High level of %requirements met. Only 3/18, which is 16.6%, yielded results different from this takeaway.
Takeaway-3	For most cases, a High level of detail of final solution results to Medium level of % requirements met.

These takeaways indicate that a low level of detail of solution results to no greater than a medium level of percentage requirements fulfilled. Further, there are greater chances for a high level of percentage requirements fulfilled to result from either a high or medium level of detail in the final solution. Based on these takeaways, it can be recommended that students should be encouraged to develop their final solutions with a high or at least a medium level of detail and this will increase their probability of meeting more number of established requirements. Currently, the absolute measures of level of detail of solution are not available. However, as mentioned in Section 4.3.2, a high level of detail in the solution can be determined based on the level of detail of various components such as description, figures and analysis. Thus, students should be encouraged to give a detailed description of final solution, completely label all the figures and conduct more analysis, simulations, and experiments to validate their final solution.

Also, as mentioned earlier, there are greater chances that a high level of detail of solution results from a high or medium level of detail of problem statement and requirements. Thus, it can be re-emphasized that encouraging students to develop high or at least a medium level of detail of problem statement and requirements will more likely result to a high level of detail of final solution, which will then increase the probability that a high level of detail of requirements are met by the final design.

Table 6.4 summarizes the recommendations and the benefits. These may be used to help guide new faculty and advisory committees in how to evaluate early the progress of student design teams. Further, this work also provides evidentiary support for advice that may already be provided to student design teams.

Table 6.4 Summary of Recommendations

	Recommendation	Benefit
1	Students should be encourage to incorporate components such as current state, final state and some critical constraints while developing their problem statement	This may result in a greater chance of a high level of detail in the problem statement
2	Students should be encouraged to develop a high or at least a medium level of detail of problem statement and requirements	This may result in a greater chance of a high level of detail in the final solution
3	Teams with low level of detail in the problem statement and requirements may be warned early on.	This may prevent design teams from developing the final solution with low level of detail
4	Student should be encouraged to develop a detailed description of the final solution, completely label all the figures and conduct more engineering.	This may result in a greater chance of a high level of detail in the final solution
5	Students should be encouraged to develop a high or at least a medium level of detail of final solution	This may result in greater chance of a high level of percentage requirements met.

6.2 Future Work

This thesis is initial attempt to understand the influence of the level of detail of problem statement and requirements on the level of detail of final solution. The findings of this research are used to make recommendations to the students to formulate the problem statement and requirements with a high or at least a medium level of detail to achieve a high level of detail of solution and thus a high level of requirements met by the final solution. However, this research has the following limitations:

- The research focuses on the levels of detail and does not assess the quality of problem statement, requirements, and final solution. The level of detail may not necessarily be the measure of quality of problem statement, requirements and final solution. Thus, a low or medium level of detail could be a high quality or a high level of detail could be a poor quality of problem statement, requirements and final solution.
- The coding schemes for problem statement and final solution developed for the purpose of this research are not tested for stability. Here, stability refers to the reliability of the coding scheme to give similar results when used by different individuals. Testing the stability would result to a higher confidence in use of coding schemes.
- The research provides the absolute measurement of level of detail of problem statement by incorporating its components. However, though the components of final solution are used to determine the level of detail of final solution, the ranking of high medium and low is given on relative scale by comparing multiple projects. Also, the level of detail of requirements is measured on relative scale by comparing multiple projects. Thus, this research has not been able to propose absolute measurements to determine the level of detail of requirements and final solution. Moreover, this research explores the level of details of requirements as

a set rather than the level of detail of individual requirements. This was deemed out of scope for this work.

The future work for this research entails addressing the limitations of this research. Additionally, several new research questions have been identified and answering those questions will further aid in ensuring that the graduating engineering students possess the skills needed in the workforce. The new research questions derived from this thesis are:

- How does the *quality* of formulation of problem statement affect the *quality* of design solutions developed by the students?
- How does the *quality* of elicitation of requirements affect the *quality* of design solution developed by the students?
- How does the *quantity* of requirements established by the students affect their *creativity* during design process?
- How do requirements *evolve* during students' design process and what influence does this have on the final design solution?
- What could be the best practices to *teach* problem formulation and requirements elicitation to students?

In this manner, this thesis begins to lay the foundations for continued research in the form of doctoral research dissertation work.

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APPENDICES

Appendix A: Coding of Problem statement

The table in this appendix describes the detailed coding of the problem statement for all 31 reports under investigation for this research.

Year	Report	Problem Statement	Current Undesirable State	Desirable Goal State	Constraint and Criteria
1999	1	The objective of this project is to identify causes and locations of failure which limit the useful life of a charge air cooler and to develop economically competitive, conceptual solutions that yield an acceptable life.	**No**	**Yes**	**Yes**
	2	Griffin Thermal Products has asked the Clemson university senior design students to research and redesign the manufacturing process and physical design of their Charge-air-cooler (CAC) product. They would like to produce a CAC that would perform five-years. Therefore, the accepted problem of the senior design students is to define modes of failure due to thermal, vibrational, and pressure fatigue, so that the future product of Griffin Thermal products will provide outstanding service to the customer for five years.	**No**	**Yes**	**Yes**
2000	3	Currently the FG thrust bearing assembly process consists of an operator using a rubber mallet to apply the force to assemble the components and a manual spin test to determine bearing quality. Torrington seeks to improve the current assembly method of FG thrust bearing, through both a more ergonomically sound process, and an increase of the production rate to a goal of 250 parts/hour. Therefore the objective of the 402-project group was the following: to increase production rate from 100 pcs/hr to 250 pcs/hr, while removing the present assembly	**Yes**	**Yes**	**Yes**

		process of hammering the bearing components together.			
	4	The Torrington company has assigned this design group the task of increasing the production rate of this product while improving the ergonomics of the assembly process. The goals of the group are to raise the production rate of this production to a minimum of 250 parts per hour, while reducing the risk of repetitive stress injuries to the worke**r. NOTE- The current state of the process are explained in detail in one and half page long problem statement. The above statement is derived from that description.**	**Yes**	**Yes**	**Yes**
	5	To successfully redesign the bearing assembly procedure to produce more cost effective and ergonomic process, integrating a level of automation that allows for an increased output of assembled bearings	**No**	**Yes**	**Yes**
2001	6	Our objective for this project is to design a conveyor belt furnace for the heat treatment of bearing parts. The desired operating temperature range for the furnace is between 1480 to 1700 F. The furnace temperature must have a controllable atmosphere. The conveyor belt must have a minimum fatigue life of 2 years.	**No**	**Yes**	**Yes**

		Also, the belt should maintain 50-60% of the furnace temperature at the furnace entrance. It is also required that there be a cool area located near the entrance to ensure safe manual loading of parts. The belt material should have a low elasticity to minimize stretching; while at the same time have a high ductility to allow for belt adjustment. A preventive maintenance program must also be incorporated into the design to resist corrosion, scaling, etc... Economically, the design must have a maximum payback period of two years based on a $1 million capital investment			
	7	The objective is to design a conveyor belt furnace to heat treat different size bearing parts. The desired operating temperature range for the furnace is between 1480 and 1700 F. The furnace temperature must have a controllable atmosphere. The conveyor belt must have a minimum fatigue life of two years. Also the belt should maintain 50-60% of the furnace temperature at the furnace entrance. In addition to a variable speed, it is also required that there be a cool area located near the furnace entrance to ensure safe manual loading of parts. The belt material should have low elasticity to minimize its stretching; while at the same time have high ductility to allow belt adjustments. A preventive maintenance program must also be incorporated into the design to resist corrosion, scaling and other defects. Economically, the furnace should have no more than a two year payback period based on an initial $1 million capital investment.	**No**	**Yes**	**Yes**

	8	The objective of this project is to design a conveyor belt furnace for the heat treatment of bearing parts. The desired operating temperature range for the furnace is to be between 1480 to 1700 F. the furnace temperature must have a controllable atmosphere. The conveyor belt must have a minimum fatigue life of 2 years. Also, the belt should maintain 50-60% of the furnace temperature at the furnace entrance. It is also required that there be a cool area located near the entrance to ensure safe manual loading of parts. The belt material should have a low elasticity to minimize stretching; while at the same time have a high ductility to allow for belt adjustment. A preventive maintenance program must also be incorporated into the design to resist corrosion, scaling, etc... Economically, the design must have a maximum payback period of two years based on a $1 million capital investment.	**No**	**Yes**	**Yes**
	9	Design a heat treat furnace for Torrington that utilizes a conveyor belt system for transporting stock steel for bearings	**No**	**Yes**	**No**
2002	10	From the statement of need an objective was developed. To develop a prototype of a cost effective speed-controlling device that can be implemented in a residential area in a timely manner. The device will: 1. Encourage speeding motorist to obey the posted speed limit, 2. Not inconvenience motorist obeying speed limit, 3. Be harm free 4. Have no adverse effect on the neighborhood.	**No**	**Yes**	**Yes**

	11	The objective of this work is : To develop a prototype of a cost effective speed-controlling device that can be implemented in a residential area in a timely manner. The device will: 1. Encourage speeding motorist to obey the posted speed limit, 2. Not inconvenience motorist obeying speed limit, 3. Be harm free 4. Have no adverse effect on the neighborhood.	**No**	**Yes**	**Yes**
	12	While speed humps have proven to slow the average speeds in their vicinity and are much more comfortable that a speed bump, they are becoming a nuisance to all the residents that have to cross them on a daily basis. The residents that are driving at or below the speed limit have to negotiate these humps. Many of these neighborhoods contain dead ends and only one or two accesses that force the residents to negotiate the humps each and every time they leave or arrive home. Other problems noted with speed humps are that they may slow response times for emergency vehicles, considerably slow ambulances carrying patients, increase emissions due to vehicle having to accelerate after negotiating bump, and increased levels from braking and accelerating vehicles. In an effort to alleviate the problems associated with existing speed controlling devices, Hughes Investments asked ME 402 class of Clemson university to develop an alternative solution to address this active problem. Alternative solutions include existing traffic calming devices as well as designs developed by the design team. The objective of this project is to develop a prototype of a cost effective speed-controlling device that can be implemented in a	**Yes**	**Yes**	**Yes**

		residential area in a timely manner. The device will: 1. Encourage speeding motorist to obey the posted speed limit, 2. Not inconvenience motorist obeying speed limit, 3. Be harm free, 4. Have no adverse effect on the neighborhood.			
	13	The objective of this work is: To develop a prototype of a cost effective speed-controlling device that can be implemented in a residential area in a timely manner. The device will: 1. Encourage speeding motorist to obey the posted speed limit, 2. Not inconvenience motorist obeying speed limit, 3. Be harm free, 4. Have no adverse effect on the neighborhood.	**No**	**Yes**	**Yes**
2003	14	As, stated, Club car desires to develop a new design for a personal utility vehicle that allows for solo operation by mobility-impaired users. The objectives of this project is to design a solo personal utility vehicle that is safe and allows for an easy transition to the vehicle by a user having lower body impairments but sufficient upper body strength.	**NO**	**Yes**	**Yes**

	15	Physically disabled individuals desire a utility vehicle from club car to better suit their needs. Thus, the objective of this project was to modify a utility vehicle design that will increase the level of independence for a physically disabled individual, specifically one who has lost the use of their legs. The solution to this problem is limited by certain constraints and criteria.	NO	Yes	Yes
	16	Club car vehicles do not offer the needed accessibility required for independent operation by disabled persons. The problem statement is generic and extends the design for an independent disabled person to operate club car vehicles. The objective statement further defines the problem but also states what is to be done to resolve the current issues. Objective statement- Outfit a current club car production vehicle with the ability to allow a person who does not have the use of their lower body (mid-chest below) to board and disembark the vehicle.	Yes	Yes	Yes
2004	17	The current design process causes unwanted deformation to the mold sets. In addition, the process has been identified as the "bottleneck" preventing increased production rates. The bar deformation currently requires manual labor to correct the problem. A suitable design will improve all of these areas of production, implement a clear design process and be supported by quantitative data.	Yes	Yes	Yes
	18	The current process of riveting mold pins into a bar is causing deformation of the assembled mold-sets. This deformation hinders the production process and creates unnecessary cost. Possible designs are constrained by bar geometry, including straightness of	Yes	No	Yes

		the bar, and the material of the pin.			
	19	Capsugel's current process of joining mold pins and holding bars utilizes a riveting machine which, during riveting, bends the holding bars. The manual process of straightening the bar is the limiting factor in the mold making process. A design solution is to include any process which eliminates this problem by eliminating the original bending, automating the straightening process, etc.	Yes	Yes	Yes
2005	20	Design a mechanism to restrict door motion during vehicle painting	No	Yes	No
	21	The door brake used during paint production is to be redeveloped due to the fact that the current design requires costly cleaning and contributes to flaws in the paint process	Yes	Yes	No
	22	The door brake is expensive	Yes	No	No
2006	23	TTI requested the Clemson university mechanical engineering 402 design team to analyze and redesign both the clutch and speed selector switch of the model P201 cordless drill in order to obtain a less expensive and more compact drill. TTI would also like the design team to conduct patent search in order to ensure that the current and potential designs do not infringe on any existing patents.	No	YES	YES
	24	The challenge is to redesign the Ryobi cordless drill clutch mechanism and speed switch to reduce its system size, complexity and manufacturing and assembly cost, without conflicting with existing patents	No	YES	YES

	25	Redesign the clutch and speed selector in a Ryobi drill such that the drill is : less expensive to produce with an overall goal of saving Ryobi 10cent per unit, Simpler to manufacture and assemble that the existing design, Smaller in overall size than the existing design, overall less complex than the existing design. Report the outcome of the project to the advisory committee and Ryobi by submitting - a complete drawing package of the new design, any necessary engineering analysis of the new design, a physical prototype of the final design.	No	YES	YES
2007	26	The purpose of this project is to design an applicable nose gear solution specifically for the Cobra UAS that will no longer fail under load and meet all requirements and parameters specified by the manufacturer. Specifically, determine through research and analysis why the existing nose gear assembly is failing and reflect these findings in the new concept.	Yes	Yes	Yes
	27	The Clemson ME 402 Raytheon Design team D has been tasked 'to conduct a thorough dynamic analysis of the existing nose gear assembly and make recommendations to improve it based on the results'. Raytheon also expressed a desire to see new and innovative idea in order to get a fresh perspective on the problem. In order to submit an appropriately solid recommendation, a force analysis is conducted on the current system to determine the causes for failure and the design constraints for a redesigned nose gear assembly are as follows.	No	Yes	No

	28	As a result, Raytheon has requested an analysis of the failure of the existing landing gear, including the resulting design recommendation being prototyped and tested. The deliverable should be the resulting documentation as well as a functioning prototype. This problem definition has been presented to Raytheon representative Joshua Lange and approved on October 8, 2007.	**No**	**YES**	**No**
	29	To prevent the bending failure being experienced in the front nose gear of the Cobra UAS, possible improvements should be recommended to this current design and a new nose gear assembly alternative should be designed. This new nose gear assembly improvement should be driven by cost-efficiency, reduction in assembly and manufacturing time, and maintaining assembly strength. This new assembly should also function as an immediate bolt-on replacement to the existing landing gear shaft.	**YES**	**YES**	**YES**
2008	30	In order to reduce the loading time for each screw and accrue the associated cost savings a portable screw shooter apparatus will be developed for use with the Bosch Exact 6 Pistol. This apparatus must align an individual bolt, transfer the bolt to the bit end of the pistol and load the bolt into the bit in 1.75 seconds, The associate will load a minimum of 25 screws in no particular orientation into the apparatus must not be required to touch the screw before it is loaded into the bit.	**NO**	**YES**	**YES**
	31	Therefore, the objective of this project is to develop a system that will be used on the BMW X6 assembly line that will reduce the screw load time from 5.4 seconds to 1.75 seconds.	**NO**	**YES**	**YES**

Appendix B: Coding of final solution

The table in this appendix explains the detailed coding of the final solution for all 31 reports under investigation for this research.

Report		Description	Figures			Engineering		
Year	Report number	Brief/ Medium/ Detailed	Labeled	Poorly labeled	Not Labeled	Number of analysis	Number of simulation	Number of Experiment
1999	1	**NONE**	0	0	0	0	0	0
	2	Detailed	1	0	3	0	0	0
2000	3	Detailed	19	25	21	3	0	1
	4	Medium	4	7	5	3	0	4
	5	Detailed	5	1	2	2	0	1
2001	6	Detailed	1	6	1	8	0	0
	7	Detailed	3	16	19	8	0	0
	8	Detailed	10	6	0	8	0	0
	9	Detailed	14	26	5	14	0	0
2002	10	Detailed	36	13	3	5	0	0
	11	Detailed	13	14	22	3	0	0
	12	Detailed	17	41	1	3	0	0
	13	Detailed	4	8	9	4	0	0
2003	14	Detailed	107	91	44	23	1	0
	15	Detailed	35	41	26	12	1	0
	16	Detailed	15	4	15	9	0	0
2004	17	Detailed	3	2	9	2	3	1
	18	Detailed	4	3	4	3	2	0
	19	Detailed	7	0	5	1	1	1
2005	20	Detailed	19	12	4	7	3	1
	21	**NONE**	0	0	0	0	0	0
	22	Detailed	5	15	21	13	1	2
2006	23	Detailed	25	21	14	8	0	0
	24	Detailed	23	28	50	7	0	1
	25	Detailed	31	23	37	6	1	0
2007	26	Detailed	21	9	23	15	2	3
	27	Detailed	56	25	36	5	1	2
	28	Detailed	35	26	45	2	0	0

	29	Detailed	11	16	32	2	2	4
2008	30	Detailed	0	9	0	2	0	1
	31	Detailed	17	13	48	1	0	10

Appendix C: Coding of Requirements

The table in this appendix explains the detailed coding of requirements from all 31 reports under investigation for this research.

YEAR	**REPORT NUMBER**	**Total number of requirements**	**% Requirements met by final design**
1999	Report 1	7	0.00
	Report 2	4	50.00
2000	Report 3	11	9.09
	Report 4	8	50.00
	Report 5	8	50.00
2001	Report 6	19	42.11
	Report 7	20	50.00
	Report 8	17	70.59
	Report 9	24	50.00
2002	Report 10	10	10.00
	Report 11	16	6.25
	Report 12	21	4.76
	Report 13	18	16.67
2003	Report 14	24	54.17
	Report 15	13	23.08
	Report 16	18	94.44
2004	Report 17	9	77.78
	Report 18	4	25.00
	Report 19	7	42.86
2005	Report 20	11	81.82
	Report 21	28	0.00
	Report 22	10	60.00
2006	Report 23	20	65.00
	Report 24	17	41.18
	Report 25	21	61.90
2007	Report 26	8	12.50
	Report 27	16	25.00
	Report 28	13	23.08
	Report 29	13	76.92
2008	Report 30	18	16.67
	Report 31	18	100.00

Appendix D: Data compression for Problem Statement

The detailed data compression for the problem statement for all 31 reports under investigation for this research is explained in the table in this appendix.

Year	Report Number	Project Name	Number of component	Level of detail
1999	1	Failure analysis of charge air coolers	2	Medium
	2	Charge air cooler life extension	2	Medium
2000	3	Torrington/Ingersoll rand	3	High
	4	Torrington/Ingersoll rand	3	High
	5	Torrington bearing assembly	2	Medium
2001	6	Torrington Project	2	Medium
	7	Torrington Project	2	Medium
	8	Torrington Project	2	Medium
	9	Torrington Project	1	Low
2002	10	Roller pin speed bump	2	Medium
	11	Speed reduction device for residential areas	2	Medium
	12	Residential Speed control solution	3	High
	13	Speed control device	2	Medium
2003	14	Personal handicap all-terrain utility vehicle	2	Medium
	15	Tiger Club chair	2	Medium
	16	Club car capstone design project	3	High
2004	17	Redesign of bar/pinion interface to reduce bar deformation	3	High
	18	CAPSUGEL bar deformation	2	Medium
	19	CAPSUGEL bar deformation	3	High
2005	20	BMW	1	Low
	21	Paint shop door brake fixture design	2	Medium
	22	Redesign of BMW brake door brake	1	Low
2006	23	Ryobi P201 Cordless drill clutch redesign	2	Medium
	24	Redesign of clutch and switching mechanism for Ryobi hand drill	2	Medium
	25	Ryobi drill design project final report	2	Medium
2007	26	Raytheon Cobra nose landing gear	3	High
	27	Raytheon Cobra nose landing gear	1	Low

	28	Design and analysis of improved nose gear assembly for cobra unmanned aircraft system	1	Low
	29	Raytheon Cobra UAS nose landing gear design final report	3	High
Year	Report Number	Project Name	Number of component	Level of detail
2008	30	Portable screw shooter final report	2	Medium
	31	BMW X6 screw gun project	2	Medium

Appendix E: Data compression for requirements

The detailed data compression for the requirements for all 31 reports is illustrated in the table in this Appendix.

Year	Report number	Number of requirements	Level of detail of requirements	% Requirements met	Level of detail of requirements met
1999	Report 1	7	Low	0.00	Low
	Report 2	4	Low	50.00	Medium
2000	Report 3	11	Medium	9.09	Low
	Report 4	8	Low	50.00	Medium
	Report 5	8	Low	50.00	Medium
2001	Report 6	19	Medium	42.11	Medium
	Report 7	20	High	50.00	Medium
	Report 8	17	Medium	70.59	High
	Report 9	24	High	50.00	Medium
2002	Report 10	10	Medium	10.00	Low
	Report 11	16	Medium	6.25	Low
	Report 12	21	High	4.76	Low
	Report 13	18	Medium	16.67	Medium
2003	Report 14	24	High	54.17	Medium
	Report 15	13	Medium	23.08	Medium
	Report 16	18	Medium	94.44	High
2004	Report 17	9	Medium	77.78	High
	Report 18	4	Low	25.00	Medium
	Report 19	7	Low	42.86	Medium
2005	Report 20	11	Medium	81.82	High
	Report 21	28	High	0.00	Low
	Report 22	10	Medium	60.00	Medium
2006	Report 23	20	High	65.00	Medium
	Report 24	17	Medium	41.18	Medium
	Report 25	21	High	61.90	Medium
2007	Report 26	8	Low	12.50	Low
	Report 27	16	Medium	25.00	Medium
	Report 28	13	Medium	23.08	Medium

	Report 29	13	Medium	76.92	High
2008	Report 30	18	Medium	16.67	Medium
	Report 31	18	Medium	100.00	High

Appendix F:Data compression for Description

The data compression for 'Description' component of final solution is illustrated in this appendix.

Year	Report Number	Description	Level of detail
1999	Report 1	NONE	Low
	Report 2	Detailed	High
2000	Report 3	Detailed	High
	Report 4	Medium	Medium
	Report 5	Detailed	High
2001	Report 6	Detailed	High
	Report 7	Detailed	High
	Report 8	Detailed	High
	Report 9	Detailed	High
2002	Report 10	Detailed	High
	Report 11	Detailed	High
	Report 12	Detailed	High
	Report 13	Detailed	High
2003	Report 14	Detailed	High
	Report 15	Detailed	High
	Report 16	Detailed	High
2004	Report 17	Detailed	High
	Report 18	Detailed	High
	Report 19	Detailed	High
2005	Report 20	Detailed	High
	Report 21	NONE	Low
	Report 22	Detailed	High
2006	Report 23	Detailed	High
	Report 24	Detailed	High
	Report 25	Detailed	High
2007	Report 26	Detailed	High
	Report 27	Detailed	High
	Report 28	Detailed	High
	Report 29	Detailed	High
2008	Report 30	Detailed	High
	Report 31	Detailed	High

Appendix G: Data Compression for Components of Figures

The data compression for the components of figures for all 31 reports under investigation for this research is illustrated in the table in this appendix.

Year	Report Number	Labeled	Level of detail	Poorly labeled	Level of detail	Not labeled	Level of detail
1999	1	0	Low	0	Low	0	Low
	2	1	Low	0	Low	3	Medium
2000	3	19	Medium	25	High	21	Medium
	4	4	Medium	7	Medium	5	Medium
	5	5	Medium	1	Low	2	Medium
2001	6	1	Low	6	Medium	1	Low
	7	3	Medium	16	Medium	19	Medium
	8	10	Medium	6	Medium	0	Low
	9	14	Medium	26	High	5	Medium
2002	10	36	High	13	Medium	3	Medium
	11	13	Medium	14	Medium	22	Medium
	12	17	Medium	41	High	1	Low
	13	4	Low	8	Medium	9	Medium
2003	14	107	High	91	High	44	High
	15	35	High	41	High	26	Medium
	16	15	Medium	4	Medium	15	Medium
2004	17	3	Medium	2	Low	9	Medium
	18	4	Medium	3	Low	4	Medium
	19	7	Medium	0	Low	5	Medium
2005	20	19	Medium	12	Medium	4	Medium
	21	0	Low	0	Low	0	Low
	22	5	Medium	15	Medium	21	Medium
2006	23	25	Medium	21	Medium	14	Medium
	24	23	Medium	28	High	50	High
	25	31	High	23	Medium	37	High
2007	26	21	Medium	9	Medium	23	Medium
	27	56	High	25	High	36	High
	28	35	High	26	High	45	High
	29	11	Medium	16	Medium	32	High
2008	30	0	Low	9	Medium	0	Low
	31	17	Medium	13	Medium	48	High

Appendix H: Data Compression for Figures

The table in this appendix illustrates the data compression for Figures.

Year		Labeled	Poorly labeled	Not labeled	Total score for figures	Level of detail of figure
	Weight	**9**	**3**	**1**		
1999	Report 1	1	1	1	13	Low
	Report 2	1	1	3	15	Low
2000	Report 3	3	9	3	57	Medium
	Report 4	3	3	3	39	Medium
	Report 5	3	1	3	33	Medium
2001	Report 6	1	3	1	19	Low
	Report 7	3	3	3	39	Medium
	Report 8	3	3	1	37	Medium
	Report 9	3	9	3	57	Medium
2002	Report 10	9	3	3	93	High
	Report 11	3	3	3	39	Medium
	Report 12	3	9	1	55	Medium
	Report 13	1	3	3	21	Medium
2003	Report 14	9	9	9	117	High
	Report 15	9	9	3	111	High
	Report 16	3	3	3	39	Medium
2004	Report 17	3	1	3	33	Medium
	Report 18	3	1	3	33	Medium
	Report 19	3	1	3	33	Medium
2005	Report 20	3	3	3	39	Medium
	Report 21	1	1	1	13	Low
	Report 22	3	3	3	39	Medium
2006	Report 23	3	3	3	39	Medium
	Report 24	3	9	9	63	Medium
	Report 25	9	3	9	99	High
2007	Report 26	3	3	3	39	Medium
	Report 27	9	9	9	117	High
	Report 28	9	9	9	117	High
	Report 29	3	3	9	45	Medium
2008	Report 30	1	3	1	19	Low
	Report 31	3	3	9	45	Medium

Appendix I: Data Compression for Components of Engineering

The data compression for the different components of engineering such as analysis, simulation and experiments is illustrated in the table in this appendix.

Year	Report Number	Analysis	Level of detail	Simulation	Level of detail	Experiment	Level of detail
1999	1	0	Low	0	Low	0	Low
	2	0	Low	0	Low	0	Low
2000	3	3	Medium	0	Low	1	Medium
	4	3	Medium	0	Low	4	High
	5	2	Medium	0	Low	1	Medium
2001	6	8	Medium	0	Low	0	Low
	7	8	Medium	0	Low	0	Low
	8	8	Medium	0	Low	0	Low
	9	14	High	0	Low	0	Low
2002	10	5	Medium	0	Low	0	Low
	11	3	Medium	0	Low	0	Low
	12	3	Medium	0	Low	0	Low
	13	4	Medium	0	Low	0	Low
2003	14	23	High	1	High	0	Low
	15	12	High	1	High	0	Low
	16	9	Medium	0	Low	0	Low
2004	17	2	Medium	3	High	1	Medium
	18	3	Medium	2	High	0	Low
	19	1	Low	1	High	1	Medium
2005	20	7	Medium	3	High	1	Medium
	21	0	Low	0	Low	0	Low
	22	13	High	1	High	2	Medium
2006	23	8	Medium	0	Low	0	Low
	24	7	Medium	0	Low	1	Medium
	25	6	Medium	1	High	0	Low
2007	26	15	High	2	High	3	High
	27	5	Medium	1	High	2	Medium
	28	2	Medium	0	Low	0	Low

	29	2	Medium	2	High	4	High
2008	30	2	Medium	0	Low	1	Medium
	31	1	Low	0	Low	10	High

Appendix J: Data Compression for Final Solution with % Requirements met

The data compression for final solution with the component '% Requirements met' is illustrated by the table in this appendix. The table illustrates the data compression of final solution for all 31 reports.

Year	Report Number	Description	% requirement met	Figures	Engineering	Total score for solution	Level of detail of solution
1999	1	1	1	1	1	4	Low
	2	9	3	1	1	14	Low
2000	3	9	1	3	3	16	Medium
	4	3	3	3	3	12	Medium
	5	9	3	3	3	18	Medium
2001	6	9	3	1	3	16	Medium
	7	9	3	3	3	18	Medium
	8	9	9	3	3	24	Medium
	9	9	3	3	3	18	Medium
2002	10	9	1	9	3	22	Medium
	11	9	1	3	3	16	Medium
	12	9	1	3	3	16	Medium
	13	9	3	3	3	18	Medium
2003	14	9	3	9	9	30	High
	15	9	3	9	9	30	High
	16	9	9	3	3	24	Medium
2004	17	9	9	3	3	24	Medium
	18	9	3	3	3	18	Medium
	19	9	3	3	3	18	Medium
2005	20	9	9	3	3	24	Medium
	21	1	1	1	1	4	Low
	22	9	3	3	9	24	Medium
2006	23	9	3	3	3	18	Medium
	24	9	3	3	3	18	Medium
	25	9	3	9	3	24	Medium
2007	26	9	1	3	9	22	Medium
	27	9	3	9	3	24	Medium
	28	9	3	9	3	24	Medium

	29	9	9	3	9	30	High
2008	30	9	3	1	3	16	Medium
	31	9	9	3	3	24	Medium

Appendix K: Data Compression for Final Solution without % Requirements met

The data compression for final solution for all 31 reports is illustrated here.

Year	Report Number	Description	Figures	Engineering	Total score for solution	Level of detail of solution
1999	1	1	1	1	3	Low
	2	9	1	1	11	Low
2000	3	9	3	3	15	Medium
	4	3	3	3	9	Low
	5	9	3	3	15	Medium
2001	6	9	1	3	13	Medium
	7	9	3	3	15	Medium
	8	9	3	3	15	Medium
	9	9	3	3	15	Medium
2002	10	9	9	3	21	High
	11	9	3	3	15	Medium
	12	9	3	3	15	Medium
	13	9	3	3	15	Medium
2003	14	9	9	9	27	High
	15	9	9	9	27	High
	16	9	3	3	15	Medium
2004	17	9	3	3	15	Medium
	18	9	3	3	15	Medium
	19	9	3	3	15	Medium
2005	20	9	3	3	15	Medium
	21	1	1	1	3	Low
	22	9	3	9	21	High
2006	23	9	3	3	15	Medium
	24	9	3	3	15	Medium
	25	9	9	3	21	High
2007	26	9	3	9	21	High
	27	9	9	3	21	High
	28	9	9	3	21	High
	29	9	3	9	21	High
2008	30	9	1	3	13	Medium
	31	9	3	3	15	Medium