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**Concept Inventories in Engineering Science and Design**

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Submitted by:

James Nicolora

Daniel Rosado

Raymond Gasper

Reinaldo Ross Fonseca Vieira Lopes

William Bugden

Faculty Advisor:

Professor Holly K. Ault

## ABSTRACT

The purpose of this IQP is to assess the use of conceptual learning at WPI within two separate disciplines: Engineering Science and Engineering Design. After comprehensive literature research, the team was subdivided into two groups. The first group focused on the possible implementation of Concept Inventories (CI) in the engineering sciences. This was carried out by interviewing professors and administering a CI to senior mechanical engineering students. The second group focused on the possible development of a design CI by interviewing department heads, design professors, and surveying senior students. The first group found that CIs could be useful tools to aid in the improvement of engineering education at WPI. The second group set up the foundation for further research that could lead to the development of a design CI.

# ACKNOWLEDGEMENTS

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# AUTHORSHIP

This report is the combined effort of two groups. The engineering science chapters were written by Raymond Gasper, James Nicolora, and Daniel Rosado. The engineering design chapters were written by Reinaldo Ross Fonseca Vieira Lopes, and William Bugden IV. All five group members collaborated equally to write the front matter, the Introduction, the Conclusion, and the Recommendations.

The Background chapter was divided into the following sections:

- Definition of a Concept Inventory, by Raymond Gasper
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## EXECUTIVE SUMMARY

The engineering science group began this project with the intention of investigating the feasibility of implementing Concept Inventories (CIs) into the WPI curriculum. We initially did extensive literature research in order to gain a good background on all of the work completed on CIs prior to the start of our project. Some of the findings included a list of all of the engineering CIs with detailed articles explaining their history, development, analysis, and implementation. With this background information we were able to move on to the data collection phase.

The data collection was split up into two sections: Faculty Interviews and Student Assessments. Before engaging any professors, we first identified the engineering science courses we wanted to focus on. We chose to focus on Fluid Mechanics, Thermodynamics, Heat Transfer, and Materials Science. After attempting to contact several professors, we were able to interview five professors (three of whom teach materials science and two that teach the thermofluids courses). The goal of the interviews was to gauge faculty awareness of CIs as well as their outlook on conceptual learning. In addition to the interview, one of the thermofluids professors agreed to allow us to administer a CI to his senior thermofluid design course. The CI was administered in two trials: one at the beginning of the course and one at the end of the review process. Because the course covers all three of the thermofluid subject areas, rather than having the students take all three CIs, the professor chose sections of each CI to form a combined assessment. This combined assessment covered concept areas in Fluid Mechanics, Thermodynamics, and Heat Transfer.

After the first trial, we were able to identify Bernoulli principles and radiation to be the two concept groups where students had the most difficulty. This information proved to be useful to the professor as he was able to implement this knowledge, of which he was previously unaware, into a focused review. This review process prepared the students for the second trial as its results as approximately 33% of the questions showed significant improvement. The results from the faculty interviews showed that all of the professors value conceptual learning on some level. Only two of them had any previous experience with CIs. While they do not use them currently, they still use conceptual questions in their respective courses. One of the biggest criticisms of the materials CI was that the majority of the questions do not apply to the introductory materials science course at WPI. Other than that, the professors liked the overall structure of the CIs and are interested in gaining more information about them.

With the faculty in support of conceptual learning along with the proven usefulness of the combined CI, we can conclude that using CIs within the WPI curriculum would be of much benefit. We suggest that some of the CI questions be reworded for clarity and that a new materials science CI be constructed which applies more towards WPI students. In addition, some type of lecture or seminar should be held to increase faculty awareness of these tools.

From our analysis of professor interviews and student surveys, we were able to get a good look at how design is taught at WPI. Biomedical Engineering (BME) has a very simple design structure that focuses on the BME 3300 course to teach both the biological and mechanical aspects of the major. BME adheres to a standard design methodology that covers the full design process. BME offers a very large assortment of Major Qualifying Projects[1] (MQP) for seniors to choose from, and seniors within BME adhere to the design model well. Mechanical Engineering (ME) offers a broader range of concentrations and spreads design learning among many classes with varying methodologies. However, many students do not take a more advanced design class before their MQP and thus do not follow as strict a design methodology. The Aerospace Engineering (AE) program lacks a specific design class before C-Term of the senior year, and expects students to pick up the methodology through their courses and during the MQP. Electrical and Computer Engineering (ECE) requires students to take an advanced design class; however, the class has a very experiential approach, and utilizes a methodology that does not incorporate the iterative nature of design. Therefore, the focus of the class is to provide ECE students with the opportunity to figure out how to design on their own.

We learned that the design requirements of the MQP vary from department to department and from project to project. In general, the MQP allows for a much more in-depth look into design that is not necessarily available at other

[1] Senior capstone design requirement

institutions, but the MQP does not always cover as many kinds of design as might be offered at other universities. Particularly, the MQP has a surprising weakness in modeling the design.

# INTRODUCTION

Every year tens of thousands of engineering students graduate from institutions all over the country. Upon graduation, many of these students enter the most technologically advanced industries in the world. Given the competitive nature of these industries, there is little room for error in the work of these engineers. In order to remain competitive, it is necessary maintain improvement in the education of upcoming engineers. A recent initiative towards achieving this objective is an increased focus on conceptual learning in universities nationwide.

This initiative is in response to the perceived lack of conceptual learning in engineering education (Hestenes 1992). In order to address this, concept inventories (CIs) were created by faculty from universities across the country as a means to identify the misconceptions of students within the engineering sciences. As well, these faculty members created exercises designed to correct these misconceptions (Nottis 2008). Despite this enthusiasm shown by many faculty members, many institutions, including WPI, have not yet implemented these tools into their curriculum. For engineering design education, the situation is even worse as concept assessment tools have not yet been developed in this field.

Although professors at WPI have expressed interest in this type of tool, the use of CIs remains extremely limited at WPI. The group believes this is primarily due to a lack of awareness among professors; however, on the few occasions where professors did use CIs, they had issues with their structure and content. The group believes that when in the right format, CIs could be used on an extensive basis as a valuable tool in improving the quality of WPI's education in both the engineering sciences and design.

The possibility of creating a design CI is explored in this project by identifying the design models used by faculty at WPI. However, after a thorough analysis, these models proved insufficient to develop a universal list of design concepts. We continued to conduct personal research in attempt to broaden our knowledge of engineering design beyond the scope of the models found in the literature.

Currently, there are thirteen completed engineering CIs in use at other universities. Our goal is to increase faculty awareness of these CIs and investigate the feasibility of implementing them at WPI. To achieve this objective we have selected four CIs in which to focus. In addition, as a first step in creating a design CI, the group attempted to identify a list of design concepts based upon the textbooks design professors use at WPI. It is our intention that this project will benefit the engineering education at WPI and help develop more knowledgeable engineers.

# CONCEPT INVENTORIES: BACKGROUND

Before the group could begin the data collection, it was necessary obtain a better understanding of concept inventories. Through a comprehensive literature research phase, the group explored the historical development and purpose of concept inventories. The group found articles detailing the construction and reliability of concept inventories, as well as their use in various institutions. In order to begin compiling a list of design concepts, the group searched for articles relating to the history and development of design education.

## Definition of a Concept Inventory

Concept inventories are an alternative form of academic assessment which resemble traditional multiple-choice exams, but are fundamentally different from them in structure, development, and purpose. A clear separation between these two assessment methods which is conducive to the understanding of a concept inventory is that scoring well on a concept inventory should require little to no memorization of any formulas, equations, or factual information. The intention behind this is that a concept inventory is not meant to gauge skill level in the knowledge group being studied. Instead, a concept inventory is "not a test of intelligence, it is a probe of belief systems" (Hestenes 1992). The quote is from David Hestenes' seminal paper, *Force Concept Inventory*, one of the first and most successful concept inventories.

## Purpose of a Concept Inventory

Hestenes effectively summarized the purpose of the *Force Concept Inventory* in his statement; this purpose can be expanded into a few specific goals that are common to all concept inventories. The most important distinction between a concept inventory and a traditional examination is that a concept inventory is not designed for the students in a specific course or class offering. Rather, a concept inventory should be able to be taken by anyone. As such, a concept inventory should contain questions addressing such a breadth of understanding of the material that any student who has taken a course covering some portion of the material should be able to take the concept inventory and produce both a meaningful score and, through careful examination of results, a profile of their strengths and weaknesses in understanding of the material.

The foregoing discussion also sheds some light on another purpose of a concept inventory. To be useful, a concept inventory must have questions constructed carefully so as not only to assess whether a student understood the concepts required to answer the question correctly, but also to assess the particular misunderstandings a student may have regarding the subject material. This makes questions in a concept inventory much more purposeful than questions asked in a traditional examination. For this reason, many concept inventories include seemingly 'common sense' answers to questions. These answers are sometimes referred to as distractors, as they are often incorrect. They play on common misconceptions students will have, and if a student 'falls for' the distractors of multiple related questions, it is a good indication that the student has not properly learned and come to an understanding of the concept being tested. This serves the important use of highlighting the gaps in course instruction, if the concept inventory were to be given at the end of a related course. Similarly, if a student has a good understanding of the concepts being assessed by the concept inventory, then the correct answers should appear to be rather obvious, and the distractors should be clearly incorrect.

## History of Concept Inventories

For several decades, academic researchers have worked to develop a systematic approach to assess student understanding of concepts in various disciplines. This work led to the creation of the first true concept inventory in 1992. It was developed and published by David Hestenes, and became known as the Force Concept Inventory, or FCI. It would soon achieve widespread popularity and use. The FCI specialized in concepts related to Newtonian Mechanics, which deals with force and kinematics. This concept inventory was modeled after its precursor, the Mechanics Diagnostic Test, which was created by Hestenes in 1985. The FCI was very similar to the Mechanics Diagnostic Test, however, the FCI provides a “more systematic and complete profile of the various misconceptions” (Hestenes 1992) that students may hold, which has since become a crucial element of concept inventories (Savinainen 2002).

The ability to identify common misconceptions in the classroom has played a large role in engineering education reform. Because concept inventories such as the FCI provide such a straightforward profile of a student’s understanding, including both topics they have mastered and areas of confusion, professors can effectively adapt their teaching strategy to suit the students' needs and focus on areas where scores are lowest. The FCI was one of the first exams to give teachers a fuller understanding of their students' thought processes and beliefs, which can enhance the teacher's instructional approach, and thereby improve the students' learning. By giving teachers insight into which prior misconceptions their students hold, concept inventories can have a beneficial impact on courses and improve the quality of a course in subsequent years.

The simple yet effective nature of the FCI, along with its clear-cut analysis of a student's strengths and weaknesses, contributed to its rapid popularity gain in the 1990s. Its effect in education was inspirational, and it led to the rise of many more concept inventories in several basic science and engineering disciplines. There was a surge of effort devoted to the development of concept inventories in the early 2000s that spanned a wide range of engineering topics from fluid mechanics and heat transfer to systems and signals, circuits, and electromagnetics. Other inventories in non-engineering subjects have been created as well, covering topics such as chemistry, calculus, and statistics (Evans 2003).

## Reliability, Validity, and Continuity of Concept Inventories

A paramount characteristic of a concept inventory is its reliability. To be useful, a concept inventory must be extremely reliable. Concept inventories go through a period of statistical analysis during preliminary trials, eliminating questions which create an undesirable effect on the test results. A good indicator of the test's value is the test-retest reliability. This is a simple method of analysis such that students taking a test with strong test-retest reliability would tend to perform the same if they took the test twice within a period of time short enough not to forget the concepts, but long enough to forget the exact questions - roughly a few weeks (Hestenes 1992). Other, more intensive, methods of statistical analysis are used, such as equivalent form reliability which "[measures] the correlation of the score on an instrument with the score of the same group of students on a second instrument that measures the same construct"(Lasry 2011), or internal consistency reliability which is a mathematical way of checking the reliability between questions on the test. These methods evaluate results compared to some form of random choice result (Martin 2004, Steif 2007).

Along with the creation of new concept inventories in the last decade, many developments and improvements have been made that have increased the accuracy, validity, and overall effectiveness of these inventories. An inventory is considered to be valid if the conclusions drawn from the results are accurate. Ideally, the results of a valid inventory will accurately portray both the student's understanding of the material, and also their misconceptions based upon the distractors they chose. Thus, it is important to update the inventories and create revisions that clarify ambiguities and eliminate false positives and other potential causes of distorted results, such as the language and format used. The FCI went through revisions in 1995. Revising an assessment preserves the face validity and content validity of the inventory. An inventory has face validity if the language and diagrams used are clear and easily understood, and has content validity if, for example, correct answers are chosen for the correct reason (Savinainen 2002). To eliminate false positives, distractors are included within the multiple choice answers to prevent students using flawed logic from answering correctly. Because the distractors represent certain misconceptions that students commonly hold about the topic in question, they are a useful tool in understanding why students struggle with certain topics and where their logic has gone astray. Teachers can use this knowledge of student misconceptions to review areas of confusion and shape their course in the future. When developing a concept inventory, it is vital to identify the concepts involved in the subject and research popular student misconceptions (Martin 2003). Including distractors to represent these misconceptions will aid professors and improve the validity of the results (Savinainen 2002). Because of these factors, the development of a concept inventory is a timely process that involves research and an awareness of the challenges that will arise.

## Development of a Concept Inventory

Developing a concept inventory comes with unique challenges beyond those of generating conventional tests. Concepts need to be identified and separated from the facts, and then common misconceptions must be developed. These concepts must then be ranked to reflect their importance, and questions must be drawn up and evaluated to ensure that concepts are effectively tested. This process often requires several iterations of critique and revision that eventually leads to the finished Concept Inventory test.

Since a concept inventory is designed to evaluate a student's understanding of theory and concept within a field, the first challenge that is presented is how to identify the concepts in a field. A concept is an abstract construct of ideas that has been derived from many facts, but this very nature makes it difficult to separate the concept from the factual knowledge that defined it (Danielson 2004). Besides personal experience, a common method to gather this information is to survey professors and students about their beliefs. Such surveys will yield many false positives or vague answers that pertain more to skills than concepts, but they provide an important base from which the researchers can refine the concepts (Martin 2003). Once a list of concepts is generated, the test developers must rank the concepts by order of importance. This is necessary because most tests are limited to about an hour, and so the number of questions that can be put into a given test is also limited. Therefore, it is important to prioritize concepts to ensure the main topics are fully covered (Martin 2003). This involves another round of surveys of professors and students. It is important to rank concepts by both importance in the field and understandability (i.e. the ease with which a given concept is usually grasped) (Martin 2003).

The challenge is to create questions that ask a student to identify the fundamental principles behind a given situation. To exemplify, we can look at a question that asks about a ball thrown straight up in the air. The question asks the student to identify the direction of the acceleration of the ball at the highest point in its trajectory. The student is then given the choice of upward, zero or downward acceleration at the peak. The question deliberately asks only for the direction of the acceleration to avoid testing the student's knowledge of the numeric value of the gravitational constant (a fact), and thereby tests the student's understanding of the effect of gravitational acceleration on a body (the concept). Other choices are given to distract the student from the correct answer and see if the student harbors a common misconception about gravitational acceleration. For example, if the student had answered zero, he or she may be confused about the difference between acceleration and velocity (Danielson 2004). It is important to determine such common misconceptions so that someone analyzing the results of a concept inventory would not only know what the student did and did not understand, but exactly which concepts they misunderstood and the basis for the misconception.

Now a preliminary concept inventory can be drafted; however, this draft must be checked for reliability. Specifically, the test must be checked for the ability of questions to rate the understanding of a concept, rate the distractor answers for effectiveness, and reliability (Martin 2004). After several iterations of these evaluations and reform processes have been completed, a first edition of the concept inventory can be presented.

## Engineering Concept Inventories

During the beginning of the twenty-first century, several concept inventories relating to engineering began to emerge. Much of this recent emergence of concept inventories in engineering disciplines is due to the work done by the Foundation Coalition with funding from the National Science Foundation (Concept Inventory Assessment Instruments 2012). The following table lists concept inventories that have been developed or are currently in development.

| **Concept Inventory (CI)** | **Stage in Development** |
|---|---|
| Circuits | Second revision; Given at the University of Maryland in the Spring of 2003 |
| Computer Engineering | First version of CI still under development |
| Electromagnetics | First version was completed in the Summer of 2001 and was administered at the University of Massachusetts Dartmouth. Currently being shared by other institutions around the country. |
| Electronics | The first version of this exam was released for official use in the Fall of 2004. |
| Signals and Systems | A fifth version of this CI was developed and available for use in February 2010. |
| Waves | Unknown |
| Dynamics | First version became available in Spring 2005. |
| Fluid Mechanics | Developed and administered in the University of Wisconsin and the University of Illinois. Current revision unknown. |
| Heat Transfer | First revision became available in January 2004. |
| Strength of Materials | Fourth version became available for distribution at the beginning of 2002. |
| Thermodynamics | Now in its fifth revision. |
| Chemistry | Progress on this CI has been reported to the Share the Future IV Conference Panel and at a Frontiers in Education conference in 2003. |
| Materials | Second version is currently available and being administered at Texas A&M and Arizona State University. |

*Table 1: Foundation Coalition concept inventories and their stage in development (Concept Inventory Assessment Instruments 2012).*
*The blue highlights indicate that the CI is still under development.*

In the year 2000, Clark Midkiff of the Department of Mechanical Engineering at the University of Alabama, began working on a Thermodynamics Concept Inventory (TCI) (Midkiff 2003). Its development followed the same model as Hestene's FCI. The goal of this assessment was to inform the professors of the pre- and post- performances of their course (by administering the assessment at the beginning and end of the class). While the TCI was initially aimed at mechanical engineering students, with slight modification it became applicable to students of other engineering majors. At most institutions (unlike Worcester Polytechnic Institute [WPI]), thermodynamics is taught in a two course sequence, one at the sophomore level and one at the junior level. The TCI was constructed to accommodate this two course progression by dividing the inventory into two parts. The first TCI was aimed at assessing the "initial knowledge state" of students taking their first thermodynamics course and the second TCI was obviously aimed at those taking their second course. Both versions, however, cover the same concepts: systems and systems diagrams, work and heat, concepts of state, thermodynamic balances, cycles and processes, and reversibility and irreversibility. The TCI is now in its fifth revision. The first four versions were focused on preparedness whereas the fifth version holds a heavier emphasis on material taught and thermodynamics terminology.

Another engineering concept inventory developed during this time period was in the field of fluid mechanics. This CI was developed by Jay Martin in collaboration between the faculty of the Universities of Wisconsin and Illinois in 2003 (Martin 2003). Fluid mechanics generally comes after thermodynamics in the sequence of engineering sciences. The first step was to identify the key concepts in fluids. The developers of this concept inventory found that the identification of these concepts was a much more difficult task than was done for the FCI as its application to engineering was much more complex. The concepts identified for this concept inventory were boundaries and boundary layers, laminar incompressible steady flow, conservation of mass and momentum, drag force, similarity, and pressure/velocity/area flow relations. After compiling a set of concepts they were content with, the professors involved began to write up the conceptual questions. The questions followed the typical concept inventory format wherein no calculation was needed. In addition, they included graphic and visual representation of each concept. After the inventory was completed, it was given to students at these two universities to ensure that all misconceptions were accounted for. Professors of fluid mechanics also evaluated this new instrument to check its validity.

Other inventories were developed in the fields of heat transfer and materials. The Materials Concept Inventory (MCI) was developed by Stephen Krause and tested at Arizona State University and Texas A&M University (Krause 2003). The concepts identified for the MCI were atomic structure and bonding, band structure, crystal geometry, defects/deformations, microstructure, phase diagrams/solubility, and performance of metals, polymers, ceramics, and semi-conductors. The Heat Transfer Concept Inventory, of unknown origin, identified the following as core heat transfer concepts: conduction, convection, radiation, thermal resistance, temperature versus hot and cold, and heat transfer rate versus amount (Knottis 2008). Both of these concept inventories follow the same development procedure outlined earlier in this chapter. Important concepts in the field are identified along with common student misconceptions and the assessments were developed based on those results. Ultimately, what comes to matter the most is the actual effectiveness of these assessments.

This recent surge of development of engineering concept inventories is due to the resurgence of interest in engineering education. In addition, there have been many changes in the accreditation process in engineering institutions which also sparked some interest in improving the quality of teaching engineering concepts. The MCI, for example, was targeted to be useful specifically for maintaining Accreditation Board for Engineering and Technology (ABET) accreditation (Krause 2003). Concept inventories in physics, biology as well as other subjects have been developed and have had a lot of notoriety and success. Engineering is a field where a great number of concepts have to be learned and often the focus for many students is to memorize the necessary equations and ultimately pass the course. For instance, the TCI identifies energy and energy transfer as one of the main concepts in thermodynamics (Midkiff 2003). Students will often try to memorize the work and heat transfer equations rather than actually understanding the given problem. This can become troublesome because there are usually unique circumstances that require one to approach the problem differently. Without a complete understanding of the concepts, students will be likely to misuse equations and other tools used to solve various problems. If students fail to learn these concepts, they will carry these misconceptions with them into their professional careers. In order to produce well-rounded professionals, the quality of the courses taught at the undergraduate level must be improved, which is the ultimate goal of these assessments.

The concepts needed constantly by professionals in the working world are usually the concepts identified as most important. If those concepts are among those which are commonly misconceived then the objective of the concept inventory is to identify sources of these misconceptions. The assessment becomes effective when its results help professors to alter the way they teach their courses to clarify better what the students tend not to understand.

While there have been multiple concept inventories in these engineering science subjects, little has been done regarding engineering design. This is partially because it is currently unknown whether or not the necessary design concepts can be measured through a concept inventory. Design concepts are so abstract that it is unknown whether an assessment can be made to test a student's understanding of design concepts the same way it can be done with fluid mechanics or thermodynamics. We intend to research these design concepts in order to find out whether this can be done.

## Design Education Background

In order to adapt a design curriculum to the current demands of engineering education, many universities undertook reform to review their engineering curricula. This section defines the purpose of design and gives a historical background on design education.

### Definition/Purpose of Design:

Design is a central activity in engineering. As Herbert A. Simon has argued, it is *the* central activity that defines engineering - or at the very least that distinguishes it from "pure" sciences (Dym 1994). It is something the engineer does. If an engineer is designing something, one should be able to look at the individual and observe him or her actively doing something. This behavior may be looking at blueprints, making decisions, collecting information, holding meetings, generating alternatives, brainstorming, following a specified geometry, etc. Design is doing something (Koen 1994). While designing, the engineers are fully engaged in an "intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym 2005).

Dym further states that "The purpose of design is to derive from a set of specifications a description of an artifact sufficient for its realization. Feasible designs not only satisfy the specifications but take into account other constraints in the design problem arising from the medium in which the design is to be executed (e.g., the strength and properties of materials), the physical environment in which the design is to be operated (e.g., kinematic and static laws of equilibrium) and from such factors determine the cost and the capabilities of the manufacturing technology available" (Dym 1994).

In order to realize an artifact, engineers participate in a systematic, "innovative and methodical use of scientific knowledge" (Oakes 2004). This practice, consisting in the development and the selection from alternative solutions, is called the engineering design process. It is general set of steps or phases that allow for effective and efficient generation and evaluation of solutions to problems from the simplest to the most complex problems (Oakes 2004). However, there is no consensus on what exactly constitutes the engineering design process. Similarity across various models exists in that the engineering design process is not simply sequential, but rather an iterative process. Specific terms for steps, the order of the steps, and the available pathways through the models vary from one model to another (Carberry and Lee 2010).

For instance, this iterative nature of the design process is illustrated by a design process called *Prescriptive model of the design process* in Figure 1 below, (Dym 1994). This model comprises four phases: Clarification of the task, Conceptual design, Embodiment of design, and Detailed design.

The *clarification phase* has as input the tasks presented by the customer and as output the design specification. During this phase, the engineers clarify customer's requirements, elaborate detailed specifications, and define specific targets toward which design effort is to be aimed and against which success or failure is to be measured.

The *conceptual design phase* uses the requirements and targets previously established to generate concepts as a result. Here, the engineers identify the most crucial problems, establish a function structure, formulate solution procedures, prepare concepts schemes, evaluate candidate schemes against relevant economic and technical metrics. This is the most open-ended phase of the design process. It includes high level abstract discussions, and several negotiations among participants.

The *embodiment of design phase* inputs candidate schemes to output a definitive design solution. The engineers refine the candidate schemes by evaluating and ranking them against design specifications and choose the best option as preliminary design. They also optimize the preliminary design and prepare preliminary parts' lists and specification fabrications.

In the *detailed design phase* the engineers input the definitive design solution, check results and document design in final fabrication specifications.

Furthermore, in this design model there is another prescription. In each phase, the engineers perform synthesis, analysis, and evaluation of each candidate solution. During *synthesis*, they assemble primitive design elements or partial designs into one or more configurations that satisfy key objectives. In *analysis*, they perform needed calculations to assess the behavior of current synthesis. And finally, in *evaluation*, they compare analyses of attributes and behavior of current design against design specifications and constraints to determine if synthesis is acceptable. These characteristics make this design model particularly iterative and repetitive.

After this brief overview, on the definition and the purpose of design and also on how engineers do their craft, the following section further explores some shifts and reforms, in the past two decades, which occurred within engineering curricula of many institutions across the country as an attempt to incorporate engineering design in their academic program. And thus, engineering students with ever increasing quality emerge.

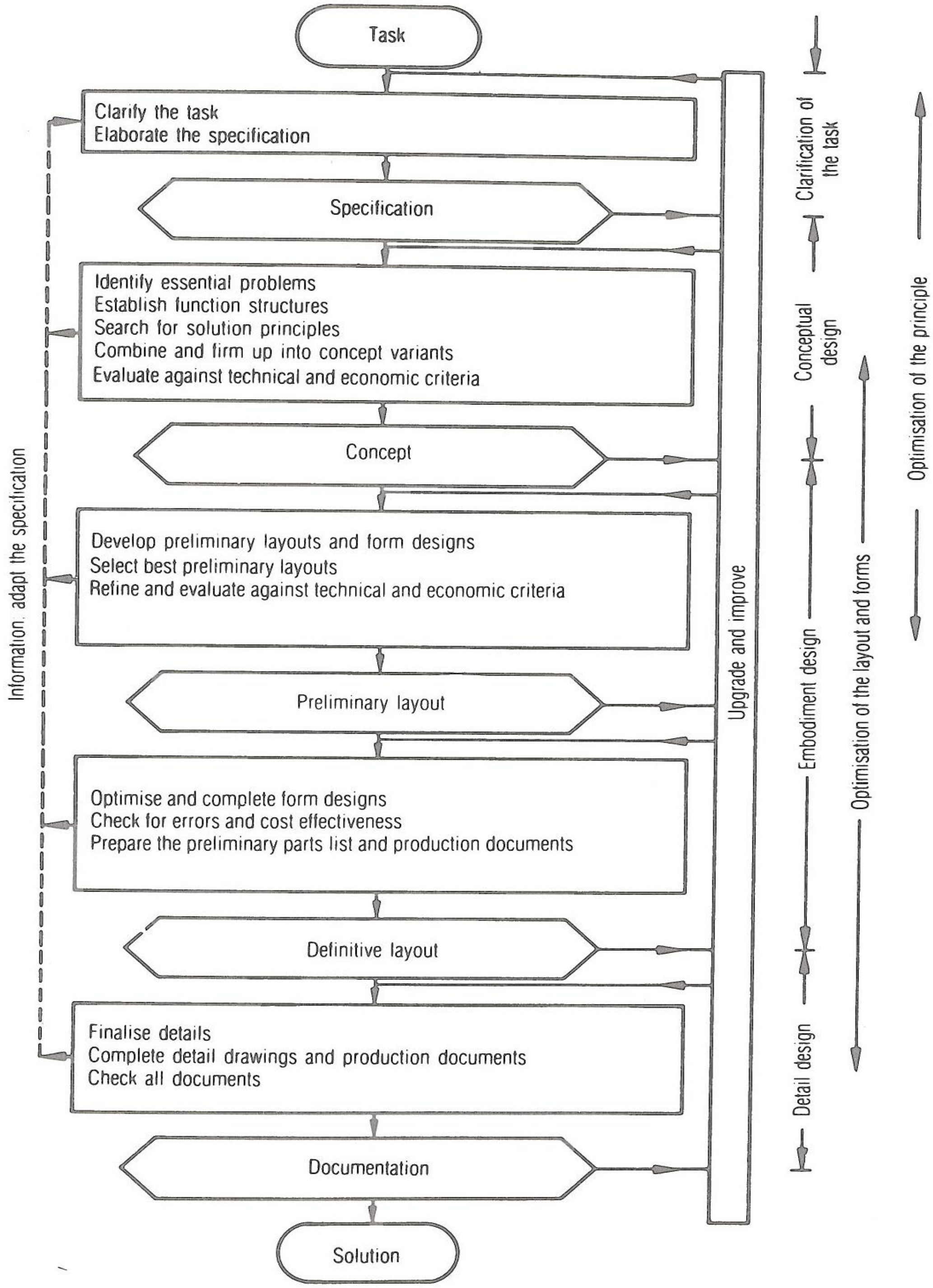



*Figure 1- Prescriptive model of the design process (Pahl and Beitz, 1984). Source: Dym, 1994*

## Historical Background:

Early engineering curricula focused on practical skills that could be applied immediately in the field, but shortly after the middle of the century the emphasis changed to providing a solid foundation in engineering science, leaving the practical training to the employer (Tryggvason 2001). In the late 1950s, engineering curricula have been based in many respects on an “engineering science” model, in which engineering design courses were taught only after the two first years of solid basis in basic science, engineering science and mathematics. Only then, could students take their *capstone (design) courses*. This focus on the theoretical rather than on the practical (drawing and shop) side directly resulted in entry-level engineering graduates being perceived as unable to function effectively in industry. In response, capstone courses were subject to many changes over the years including “made up” projects ranging from faculty to industry-sponsored projects where companies provided “real” problems, along with expertise and financial support (Dym 2005). Moreover, in the 1990s, *cornerstone (design) courses*, i.e. project and design courses started being offered to first-year engineering students in order to bring them closer to their engineering faculty, but also to provide them with means of exposure to what engineers actually do and, finally, to teach them the basic elements of the design process by doing real design projects (Dym 2005).

Among other significant changes made to engineering curricula nationwide was the introduction during the 1990s of a pedagogical approach to teaching design in the classrooms called Project-Based Learning (PBL). The need for PBL, and other changes in engineering education, stemmed from industrial and market requirements. Today, industry is in need of graduates that not only possess a solid foundation of engineering knowledge, but also have good communication skills, the ability to work in a team, the ability to solve problems both critically and creatively, and a desire to learn for life. In other words, ultimately to provide industry with designers who are equipped with the essential characteristics and skills required in real-life situations (Gadala 2005).

In parallel to PBL, a product-life cycle-based initiative called Conceive, Design, Implement and Operate (CDIO) was developed in the late 1990s, at the MIT, with the objective to offer an alternative educational framework for producing better-prepared and highly skilled engineering graduates (Lynch 2007). The initiative aims to provide students with an education that stresses engineering fundamentals based on the life cycle of a product. During the life cycle of any product it goes through clearly defined stages. The CDIO initiative applies this framework to the education of its undergraduate engineers. The students learn to solve problems and complete projects following the same stages i.e. Conceive, Design, Implement and Operate (Lynch 2007).

However, despite these major structural changes in the realm of engineering design education very little published quantitative assessment for PBL programs in the literature. The evaluations that have been undertaken have been almost entirely along the lines of student interviews or responses to open-ended questions. This qualitative research has generally found students in favor of the program although they generally believe that it adds more work on the part of the students. The limited assessment for PBL in the literature indicate that the approach significantly improves important skills such as solving open-ended, real-world problems; finding, evaluating, communication skills, team work and using appropriate learning resources. On the other hand, available assessments indicate that there was no gain in students' performance on standard tests and exams. Also, no apparent decline in student's performance was reported. In the area of PBL assessment, it is obvious that more research is needed. Proper assessment measures and avenues for obtaining assessments are required. Also, assessment of PBL graduates in the work place is crucial to reach proper conclusion for this approach. As the practice in industry, it may be constructive to consider various methods of assessment such as final product, presentations, portfolios, peer reviews, self-assessments, and competitions (Gadala 2005).

Therefore, though the improvement in the presence, role, and perception of design in the engineering curriculum has been considerably marked in recent years, it is undoubtedly true that future improvements are necessary (Dym 2005).

# ENGINEERING SCIENCE: METHODOLOGY

This chapter focuses on the methods and procedures used in this project in order to meet project goals. The project began with an extensive literature research to gain a strong background on the subject matter. The bulk of the work done throughout this project was personally collecting data through faculty interviews and administering student assessments. This portion, as well as the methods used to analyze this data, is covered in detail throughout the chapter.

## Project Goals

There are two primary goals of our IQP work:

- To benchmark the awareness of concept inventories among WPI engineering professors
- To encourage potential implementation of concept inventories as a valuable educational tool for WPI engineering courses

In pursuit of these end goals, the project was broken down into four main stages: the literature research, faculty interviews, student testing, and data analysis. Each stage required a distinct approach and execution, but all contribute towards the primary goals.

## Literature Research Goals

Extensive literature research into concept inventories was conducted in order to understand our IQP material, and also to be able to effectively communicate with professors in those topic areas regarding concept inventories. Extensive understanding of the concept inventories assists in implementation and data analysis of the assessments.

## Interview Goals

We decided to investigate the level of awareness that professors have of concept inventories here at WPI. This is because concept inventories are a growing tool for educators in engineering, and increased awareness among professors could lead to more creative, more personal, and better education through their implementation. In order to investigate we conducted interviews with five professors. The interviews also reveal how professors use concepts and concept inventories in their courses if they have had past experience with them. Some questions we ask attempt to bring out information about courses, teaching philosophies, and related material, in order that we could attempt to find places where concept inventories could be useful for the professors.

## Student Assessment Goals

A primary goal of our IQP is to investigate the possibility of the use of concept inventories at WPI. From our research we know that concept inventories have been used in a proactive educational approach to the improvement of courses for both students and professors (Hestenes 1992). By testing students with concept inventories before, after, or during courses, a professor can see what concepts students understand, not just their class performance. We hope to see that professors at WPI would be interested in utilizing this functionality, or others, of concept inventories. We facilitated this process for two professors. To promote this goal, we have administered a concept inventory to a senior mechanical engineering design course in C-term 2012.

## Data Analysis Goals

The data analysis was an ongoing process through the IQP. The concept inventories taken by students required grading and analytical examination in order to determine any common misconceptions among WPI students. We also intend to demonstrate the effectiveness of concept inventories through their performance at identifying these misconceptions, potentially creating an avenue for course improvement by professors here at WPI. Also requiring examination are the results of the faculty interviews, through which we were able to benchmark concept inventory awareness among WPI engineering professors, and identify new approaches towards using concept inventories, and new reasons to use them or not to use them.

## Literature Research

The first stage of this project was conducting research through articles and journals. Many of these sources were found online using resources provided by the WPI Gordon Library. From these articles the group learned what concept inventories are, as well as their history and purpose. Further research gave insight into the development process and reliability testing. This knowledge is essential to understand concept inventories, their benefits, and how to administer an assessment and analyze the results.

Eventually the group began researching a more narrowed field concerning only concept inventories related to engineering science courses taught at WPI, including Material Science, Thermodynamics, Heat Transfer, and Fluid Mechanics. The group members used the Material Science and Thermodynamics concept inventories as self-assessments. After grading these, the group performed an analysis of the concept inventories. The group identified the concepts covered by analyzing the questions in the assessment. The incorrect choices were examined for distractors to identify the misconceptions. Once this was done, the group continued researching these fields to affirm that the concepts and misconceptions identified were correct. This knowledge was useful when interviewing professors and eventually administering a concept inventory to a class.

## Faculty Interviews

At the end of B term, the group sent out pitch emails to the WPI professors who teach the engineering science courses specified above. These emails described the IQP and the project goals and explained how and why concept inventories can benefit a course. Also included in this email was a request to set up an interview with the professors at the beginning of C Term to measure their awareness of concept inventories and evaluate their interest in administering one to their class. The pitch emails proved to be successful, as the group got positive responses from multiple professors. Three Materials Science professors responded, and the group interviewed all three. Because none of them were teaching Materials Science C Term, they were unable to consider administering an inventory to their class; however their interviews were still very insightful. A thermodynamics professor responded also, and was very interested in administering a concept inventory to his class.

The interviews ran no longer than thirty minutes. The group began the interviews by determining whether or not the professor was aware of concept inventories. If not, the group gave a description of concept inventories including their layout, purpose, and potential to benefit a course. If the professor was aware of them, we asked if he or she had implemented them into a course and whether or not they were successful. The professors were then read a list of concepts covered by the inventory and asked if they agreed with the list. This information was used to identify any overlap between concepts covered in the CIs and in their courses. The group next asked questions involving the professor's teaching philosophy. The professors were asked if they used any sort of conceptual questions in their class, and how much emphasis they put on concept understanding versus equation usage and memorization. The group also asked what textbook the classes used, and how the professors selected them. These interviews were very useful in gauging the use of concept inventories by WPI professors.

## Student Testing

In addition to faculty interviews, we also obtained experimental data by administering a combined concept inventory to a senior level mechanical engineering design course. We will refer to the instructor of this course as Professor A. Because this course covers heat transfer and fluids concepts as well as thermodynamics, we extracted a sub-set of questions from each of those respective CIs (chosen by Prof. A) and combined them into one assessment.

We administered the combined CI to the students enrolled in this course at the beginning of C term. The data obtained from this course indicated whether or not concepts from the Introduction to Thermodynamics (ES3001), Introduction to Fluid Mechanics (ES3004), and Heat Transfer (ES3003) courses had been retained by the students. After the initial round of testing, we administered the assessment again during the second half of the term after Prof. A had enough time to review the material (indicated by our first round of testing). With the second round scores we were able to see if there was any improvement from the first round, and in what areas. Combined with knowledge of how Prof. A used the data from the first test to change his review process, we could show this approach as a potential use of CIs by instructors.

During the testing process, student confidentiality and test security was enforced. We administered the assessments through the myWPI Blackboard site for the course. The only scores reviewed by the group were the two combined CI tests. The results were taken in for analysis. The test is secure, as students never had direct access to an answer key.

## Data Analysis and Recommendations

The methods used to analyze these data have been divided into two sections: Student Testing Analysis and Faculty Interview Analysis. This is because the analysis required for each section is very distinct. In the student testing section, we analyzed the collected data to gain information on the usefulness of CIs as a teaching tool. The faculty interviews were analyzed to gauge professor awareness of and interest in CIs, as well as their philosophy on conceptual learning as a whole.

### Student Testing Analysis

Because the inventory administered to Prof. A's class was done so through Blackboard, the answers were graded and stored electronically. This allowed the group to access and to analyze the scores, while still keeping them confidential. The group consulted with Prof. F of the math department in order to conduct a statistical analysis of the scores. He recommended using the SAS program to run McNemar's Test to determine which of the changes in score can be considered significant. This test analyzes each question individually, showing how many students changed their answer between the two trials and whether they improved or not. The data are outputted in tables that show the question responses and resulting P-values. An example is shown below in Table 2.

In the first table, the top number of each white cell indicates the number of responses with that result. In the gray boxes, the number 0 indicates an incorrect response and the number 1 indicates a correct response. In the second table, the Exact P-value indicates the significance of the change in score. A P-value approximately equal to or less than 0.05 indicates a significant change. In the example below, the low P-value demonstrates that the majority of students who changed their answer improved. The frequency missing value indicates the number of students who did not answer the question in both trials. All other numbers in the tables are not used for this analysis.

| Table of test1q5 by test2q5 | | | |
|---|---|---|---|
| test1q5 | test2q5 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 4<br>6.35<br>19.05<br>66.67 | 17<br>26.98<br>80.95<br>29.82 | 21<br>33.33 |
| 1 | 2<br>3.17<br>4.76<br>33.33 | 40<br>63.49<br>95.24<br>70.18 | 42<br>66.67 |
| Total | 6<br>9.52 | 57<br>90.48 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

| McNemar's Test | |
|---|---|
| Statistic (S) | 11.8421 |
| DF | 1 |
| Asymptotic Pr > S | 0.0006 |
| Exact Pr >= S | 7.286E-04 |

*Table 2: The table to the left shows the number of students who answered question 5 correctly and incorrectly for each trial. The table above shows the results of McNemar's test and the P-Value for this question.*

The group sorted through the scores to determine which questions, and in turn, which concepts the students do and do not understand. The group then examined the questions involving concepts students struggled with to find any common distractors. Because these distractors represent misconceptions that students hold, this analysis provided insight into which particular topics the students do not understand and the sources of their confusion.

## Interview Analysis

After all the interviews were conducted, the group looked for commonalities between each of the professors' thoughts on conceptual learning and concept inventories. We looked to see whether the faculty supported the idea of concept inventories or implementing a similar concept-based assessment into their course. The group also searched for overlap in concepts taught in their courses and the concepts covered by the corresponding concept inventory.

# ENGINEERING SCIENCE: RESULTS AND ANALYSIS

The findings of this IQP can be divided into two categories. The first is the set of information collected through faculty interviews, and the second is the data collected from student assessments. Both were useful in isolation; however they are significantly more revealing when considered together in light of the primary IQP goal. This goal is to determine whether concept inventories could potentially be useful as an instruction tool at WPI, particularly in the Engineering Sciences.

## Faculty Interview Findings

The professors will be referenced anonymously, and grouped by department as shown:

| Identity | Contribution | Department | Specific Field |
|---|---|---|---|
| Professor A | Interviews and Student Testing | Mechanical Engineering | Thermofluids |
| Professor B | Interview | Mechanical Engineering | Materials Science |
| Professor C | Interview | Mechanical Engineering | Materials Science |
| Professor D | Interview | Mechanical Engineering | Materials Science |
| Professor E | Interview | Mechanical Engineering | Heat Transfer |
| Professor F | Statistical Analysis | Mathematics | Statistics |

*Table 3: The anonymous name each professor will be referred to as, their contribution to this project, their department, and their specific field of study*

### Faculty Awareness of and Experience with Concept Inventories

Of the five professors interviewed, only two had heard of CIs prior to our meeting with them. Those professors were Prof. B and Prof. E. They both used CIs over two years ago as a teaching tool for their Materials Science and Heat Transfer courses respectively. However, despite their previous experience with CIs, both professors found that the CIs in their original form were not as useful as they had anticipated. Prof. B in particular thought that the majority of the questions found in the Materials Science CI did not apply to her course. However, their experience was not entirely negative. Both professors have continued to focus on conceptual learning in their courses even though they have stopped using CIs.

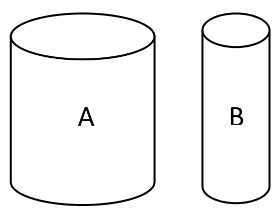
The remaining three professors had not heard of CIs prior to our interviews. Those professors were Prof. A, Prof. C, and Prof. D. After explaining to each of them the purpose of a CI, they were all interested in learning more about them to possibly integrate them into their courses.

### Faculty Use of Conceptual Questions

All of the professors we spoke to agreed that conceptual learning is important on some level. Prof. B and Prof. E, however, both agreed that conceptual understanding is more important than calculation skill. Their reasoning behind this belief is that they understand that the majority of students taking their class are not going into their respective fields; there is no materials engineering major at WPI, and thermofluids is not a popular direction of study. That being said, they believe that it is more important for their students to walk away from their courses with a good understanding of core concepts that the students can apply to their field rather than memorization of a few equations.

In order to reinforce her students' conceptual knowledge, Prof. B used in-class student-response questions (clicker questions), many of which were entirely conceptual. She would challenge the students with these questions, review the proper thought process to answer the question, and then hold student discussion. She feels that students respond very well to the conceptual clicker questions. An example of one of these questions is shown below. Like many of the clicker questions she uses, this question is similar in purpose and structure to those found in CIs.

- Pieces A and B are cut from the same metal plate that has uniform mechanical properties. They have different diameters, as shown, but their heights are equivalent. *The same tensile force, F, is applied to each cylinder along its axis.* Which cylinder will elongate more?




  A. Cylinder A
  B. Cylinder B
  **C. A and B will elongate equal amounts (Correct)**
  D. It is not possible to say without more information.
- Provide one or two sentences of explanation to justify your answer:

*Figure 2: Sample conceptual student-response question used by Prof. B*

The other materials science professors, Prof. C and Prof. D, also use conceptual questions in their courses. They did not respond with such a strong emphasis towards conceptual knowledge as Prof. B, however. Along with conceptual questions, Prof. D uses multiple choice student-response questions involving quick calculations. She has the answers structured in a similar way to CI questions, with wrong answers hinting at how the student made a calculation mistake.

Prof. A, Prof. C, and Prof. D responded that they value calculation skill with equations just as much as conceptual understanding. Prof. A in particular found that one of the questions in the Heat and Energy CI, shown below, could yield a different result with different input parameters.

- You wish to cool a stream of mineral oil from 100°C to 90°C in a heat exchanger using identical volumetric flow rates of either 10°C air or 20°C water. Assume that the volumetric flow rates of both water and air are great enough that neither the water nor air temperature increases significantly through the process. Which stream is more likely to transfer heat from the process stream more quickly?
    A. Water, primarily because it has the higher heat transfer coefficient
    B. Water, primarily because it has the higher heat capacity
    **C. Air, primarily because it is colder (Correct)**
    D. Water, primarily because it will provide evaporative cooling
    E. Either will cool the oil equally because of the high flow rates used

*Figure 3: Heat and Energy CI question*

When conceptually considering this question, the proper thought process is to consider that the convective constant of the oil is so much greater than the convective constant of either water or air, that the difference in convective properties of water and air will not make a difference in the heat transfer. Therefore, the slightly lower temperature of the air will cause a faster heat transfer. This is counterintuitive as normally one would consider that water, having better convective properties than air, would cool the oil stream more quickly.

The problem with this question that Prof. A found is that, choosing a light oil and a heavy oil, the former actually produces the result that water would cool better, and the latter produces the “correct” result. This is an example of why Prof. A believes that having strong calculation skills is as important as conceptual knowledge. Because of the interaction of two different concepts, convection and thermal gradient, students performed so poorly on this question that we gained no useful information about student misconceptions. However, it does indicate that students have a difficult time with higher level conceptual analysis.

### Concept Groups Found in Concept Inventories

All of the professors agreed that there was some overlap between the concepts presented in the CIs and the concepts they teach in their courses. There were, however, concepts presented in the CIs that these professors do not cover in their classes and vice versa. Below is a table that illustrates the alignment between concepts presented in the assessments in their original form and their corresponding course:

| Thermodynamic Concepts | Prof. A's Course | TCI |
|---|---|---|
| Systems and System Diagrams | Yes | Yes |
| Energy and Energy Transfer (work and heat) | Yes | Yes |
| Concept of State | Yes | Yes |
| Thermodynamic Balances | Yes | Yes |
| Cycles and Processes | Yes | Yes |
| Reversibility and Irreversibility | Yes | Yes |

*Table 4: Alignment of concepts taught in Prof. A's course and the TCI*

| Fluid Mechanics Concepts | Prof. A's Course | Fluid Mechanics CI |
|---|---|---|
| Boundaries and Boundary Layers | Yes | Yes |
| Laminar Incompressible Steady Flow | Yes | Yes |
| Conservation of Mass and Momentum | Yes | Yes |
| Drag Force | Yes | Yes |
| Similarity | Yes | Yes |
| Pressure/Velocity/Area Flow Relations | Yes | Yes |

*Table 5: Alignment of concepts taught in Prof. A's course and the Fluids Mechanics CI*

| Heat Transfer Concepts | Prof. E's Course | Heat Transfer CI |
|---|---|---|
| Convection | Yes | Yes |
| Conduction | Yes | Yes |
| Radiation | Yes | Yes |
| Thermal Resistance | Yes | Yes |
| Temperature vs. Hot and Cold | Yes | Yes |
| Heat Transfer Rate vs. Amount | Yes | Yes |
| Mixed Systems | Yes | No |
| Heat Capacitance with Unsteady Conditions | Yes | No |

*Table 6: Alignment of concepts taught in Prof. E's course and the Heat Transfer CI*

| Materials Science Concepts | ES2001 | MCI |
|---|---|---|
| Atomic Structure and Bonding | Yes | Yes |
| Band Structure | No | Yes |
| Crystal Geometry | Yes | Yes |
| Defects/Deformations | Yes | Yes |
| Microstructure | Yes | Yes |
| Phase Diagrams/Solubility | Yes | Yes |
| Performance of Metals, Polymers, Ceramics, and Semi-conductors | Yes | Yes |
| Failure | Yes | No |
| Fatigue | Yes | No |
| Stress and Strain | Yes | No |

*Table 7: Alignment of concepts taught in ES2001 and the MCI*

The discrepancy between the materials science CI and the materials science course is rooted in a difference of objective. The materials science CI is focused towards students working towards a materials science major, and they should have a very strong grasp of concepts such as band structure and atomic structure and bonding. Many of the questions in the MCI cover corrosion and conductivity (physical behaviors under the band structure concept group) which are topics not covered in depth in ES2001. Engineering students at WPI will most likely not be implementing this knowledge in their careers. Instead, they gain more by covering topics such as stress, strain, and failure.

Because of these differences in material covered, the materials science professors who used CIs in their courses found them most useful when they only implemented selected sections, as opposed to a CI in its original format. It does not appear that professors in fluid mechanics, thermodynamics, and heat transfer will have to make many changes to the respective CIs because due to the strong alignment of concepts. Prof. A constructed a test with questions from four CIs combined in order to cover all the material in a senior design course. He found the results useful, and the resulting test was significantly less time consuming than four CIs taken together.

### Alignment of Misconceptions

In the literature research, we found lists of topics of difficulty that students often hold in materials science and heat transfer (Krause 2003). The professors all agreed with these misconceptions, saying they had often encountered them while teaching introductory courses; however, they also had encountered misconceptions that are not covered by the CIs. The table found below includes the original misconceptions in materials science and the ones added by Prof. B, Prof. C, and Prof. D:

| Concepts of Difficulty | Identified by Literature | Identified by Professors |
|---|---|---|
| Geometry of Points, Lines and Planes in Crystal Structures | Yes | Yes |
| Phase Diagrams | Yes | Yes |
| Mechanism of Plastic Deformation of Metals | Yes | Yes |
| Force vs. Stress | No | Yes |
| Crystal Structures of Metals and Ceramics | No | Yes |
| TTT Graphs (Temperature-Time-Transformation) | No | Yes |

*Table 8: Alignment of materials science misconceptions identified by the literature and WPI professors*

Prof. B has created conceptual questions that are directed at identifying the additional misconceptions in her students, in the same style as CI questions. The example student-response question (Figure 2) is one of these.

| Concepts of Difficulty | Identified by Literature | Identified by Professors |
|---|---|---|
| Heat Rate vs. Amount | Yes | Yes |
| Temperature vs. Hot and Cold | Yes | Yes |
| Temperature vs. Energy | Yes | Yes |
| Radiation Rate vs. Color | Yes | Yes |

*Table 9: Alignment of heat transfer misconceptions identified by the literature and WPI professors*

There were no misconceptions explicitly identified by the literature that we could access in regards to Thermodynamics and Fluid Mechanics. However, after administering the combined CI to Prof. A's students, we were able to identify Bernoulli Principles, specifically the relation between pressure and velocity of a fluid, as a common area of difficulty in Fluid Mechanics. In Trial 1, most students demonstrated that they understood the effect that a change in pipe diameter has on the velocity of a fluid, however many incorrectly answered that pressure would increase or decrease with velocity. In fact, according to Bernoulli Principles, the pressure and velocity of a fluid are inversely proportional. The misconception that the pressure of the fluid is directly proportional to its velocity was addressed by Prof. A in his review session. As indicated by the results of Trial 2, this misconception was properly repaired.

## Miscellaneous Professor Responses

The professors had criticisms of the CIs in their existing form. All of the professors interviewed are interested in using CIs or conceptual questions, but with their own revisions. Prof. A believed that many of the questions were phrased in a misleading or inaccurate manner. He intends to use CIs and conceptual questions in the future, but has said he will change the wording of many of the CI questions to avoid ambiguity. Prof. A also had objections to a few questions which included higher level analysis of multiple interacting concepts, such as the question in Figure 3. This directly conflicts with one of Prof. B's objections, which was that she felt the materials science CI was primarily "factoids", and that the students would benefit more from conceptual questions which include analysis.

The primary criticism of Prof. B, Prof. C, and Prof. D was that the concepts covered by the materials CI did not entirely intersect with the topics covered in their introductory course. Prof. A also had this issue, and resolved it using the combined CI.

## Student Assessment Findings

After conducting the two student assessments, we constructed an overall summary of the key information we found. This summary concisely explains the data acquired from the student assessments.

By compiling and comparing the two trials of the combined CI employed in the senior thermofluids design course, we found some interesting data which we believe to be useful for the instructor of the course. After a review including topics identified as student conceptual weaknesses by the first application of the assessment, the average score rose by about ten percent. According to the results from the McNemar's Statistical Test, ten out of thirty-two questions experienced a significant increase in percentage correct. This doesn't, on its own, point to the usefulness of the assessment; any review would hopefully cause an increase in performance on any related test. However, when the questions are broken down initially into CI categories, and even more into individual concept groups, the results demonstrate how the students profited from the review section of the course.

The class was fairly large, yielding a good sample size. Seventy students participated in the first test, sixty-eight participated in the second, and sixty-four participated both times. The scores of students who did not take the test both times were discounted.

### Fluid Mechanics Section

In Fluid Mechanics, the first trial highlighted a concept gap when students dealt with Bernoulli principles (questions 43 and 39). Prof. A found this to be surprising as he expected senior mechanical engineering students to have a basic understanding of this core concept. During the review section of the course the instructor made sure to cover these basic concepts. These questions (43 and 39) saw the highest score increase between the two tests (as shown below), demonstrating that this part of the review process was particularly effective. The McNemar's Test results show that the respective p-values for both of these questions are 2.46E-5. Such a low p-value indicates a significant increase and reflects that nearly all students who changed their answer from the first trial improved. Student performance significantly improved between test trials in the Fluid Mechanics section, more so than the test as a whole.

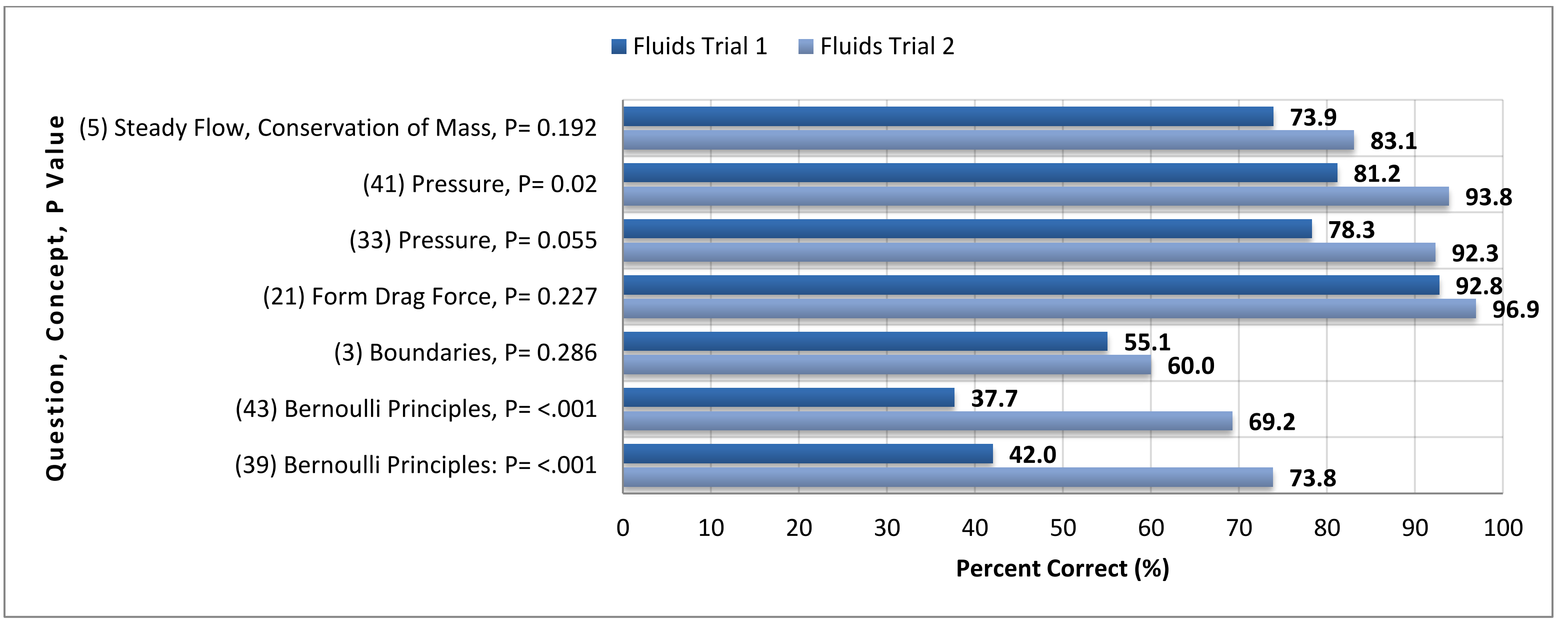



*Figure 4: Difference in percent correct between trial 1 and 2 of the Fluid Mechanics CI questions administered to Prof A's students.*

### Heat Transfer and Heat and Energy Section

After the first trial, the heat transfer section initially looked promising as it had a high average score, suggesting that the students had a good understanding of heat transfer concepts. This is discounting question fifty-three which the instructor decided was misleading (for explanation of the issues with this question, see the faculty interview results). The overall increase in this section between tests was quite low, though this can be expected given that the majority of students were already answering the questions correctly before the review.

Student responses to two specific questions revealed some useful information. In the first trial, students performed somewhat worse than expected on the two radiation questions (9 and 51), similar to the Bernoulli principle concept group. During the review the instructor made sure to focus on radiation, and student performance on these questions, like the Bernoulli principle questions, showed a significant improvement over the test average. The statistical p-values for these two questions, respectively, are $< .001$ and 0.0576. This indicates a significant improvement on these two questions.

There are two other questions which one might note as starting with unusually low scores- questions 45 and 1. Prof. A did include conduction, convection, and thermal resistance in his review, but he did not intentionally focus on these concepts as much as he did on radiation and the Bernoulli principles. Question 1 requires some analysis of the interaction between conduction and convection, which he noticed causing difficulty among the students. He did not mention any objections with the low score on question 45, and did not say he would specifically review the concept of thermal resistance. It is not surprising then that the score increase on both these questions was not significant, with p-values well over the 0.05 limit.

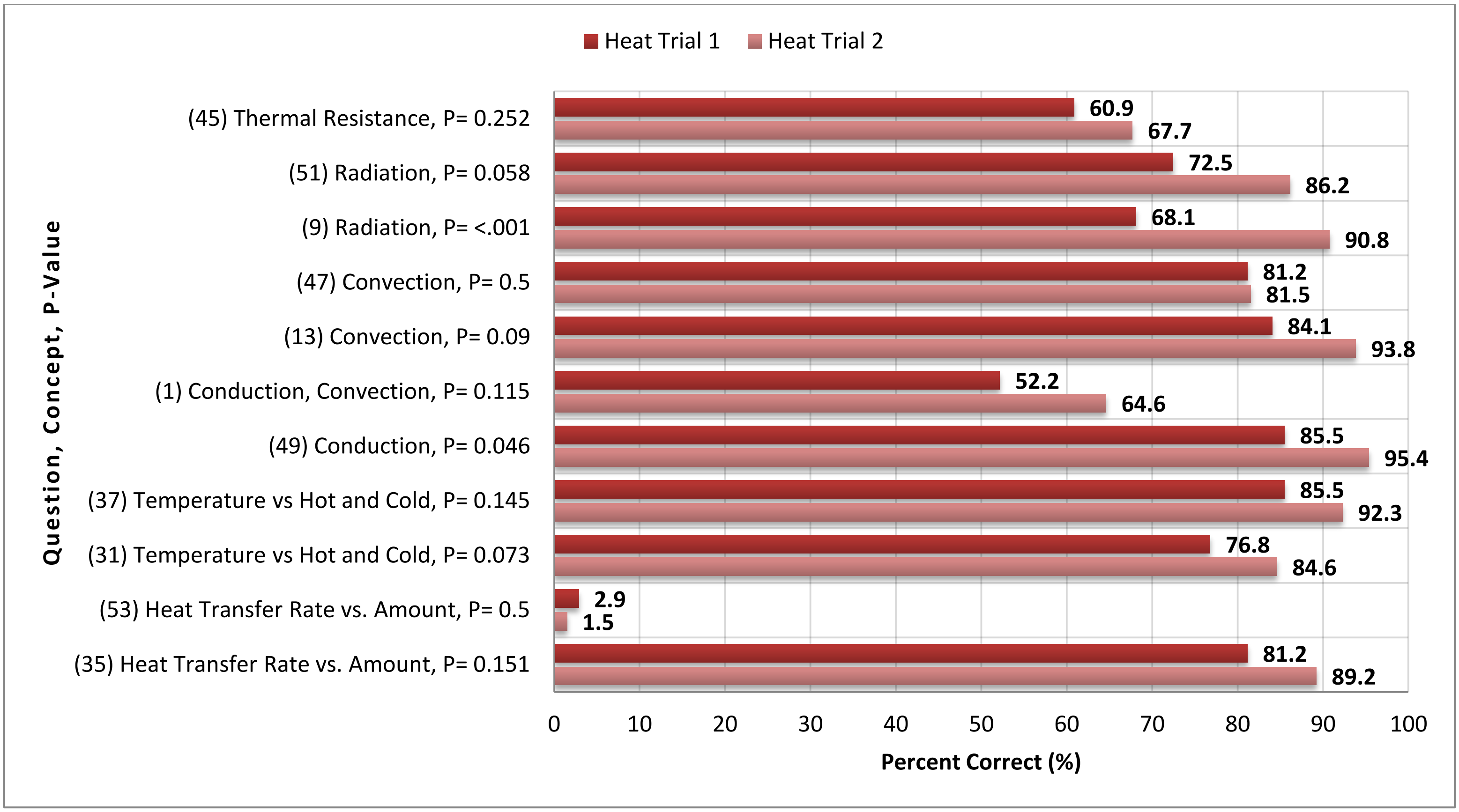



*Figure 5: Difference in percent correct between trial 1 and 2 of the Heat Transfer and Heat and Energy CI questions administered to Prof A's students.*

### Thermodynamics Section

Many of the questions experienced small increases in student performance, but not enough to be statistically significant. The McNemar's Test showed that three questions, all in the Work and Heat concept group, showed a significant increase in percent correct (57, 59, and 63) with their p-values as shown below. As well, students performed worse on five of the questions in this section in the second testing. An intriguing part of this is that four of these five questions (17, 23, 29, and 55) were also in the Work and Heat concept group. However, the decrease in performance on these questions was shown to be insignificant by the McNemar's Test. Their respective p-values are shown below, and all are well above the 0.05 threshold. This suggests that students who changed their answers on these four questions did so in a random fashion. Also, it was no surprise that three Work and Heat questions experienced significant increases, despite this concept not having been included in Prof. A's focused review. This is because the course already integrates Work and Heat as a primary concept, and students reviewed it and performed more complicated analysis with the concept in the normal progression of the course.

| Work and Heat Concept Question | P-value |
|---|---|
| 17 | 0.778 |
| 23 | 0.709 |
| 29 | 0.5 |
| 55 | 0.833 |
| 57 | 0.039 |
| 59 | <.001 |
| 63 | 0.005 |

*Table 10: Work and Heat concept questions and corresponding p-values.*
*Red p-values indicate questions which went down in score*

The question with the highest drop in score is question twenty-seven. This question was concerning the concept of state properties. This is a concept group that was not covered by any other question in the test, and was also mentioned in discussion with Prof. A to be a concept group in which he had noticed students frequently having difficulty. However, despite the relatively large decrease in student performance, the McNemar's Test showed that it is insignificant with a large p-value of 0.885.

The most important parts of the pretest-posttest analysis for this IQP are the Bernoulli Principle and Radiation concept groups. In both of these concept groups, students (seniors in ME) performed significantly below the expectation of the professor on the pretest. He made sure to do a focused study of these concept groups during the review section of the course, and these two sections improved significantly more than the test average. This demonstrates how implementing these tests could be very useful for instructors: as the questions are simple, well-constructed, and easily available, a professor can assemble a test relevant to his/her course with little difficulty. With analysis it is possible to identify student misconceptions, even ones the professor did not expect the students to hold.

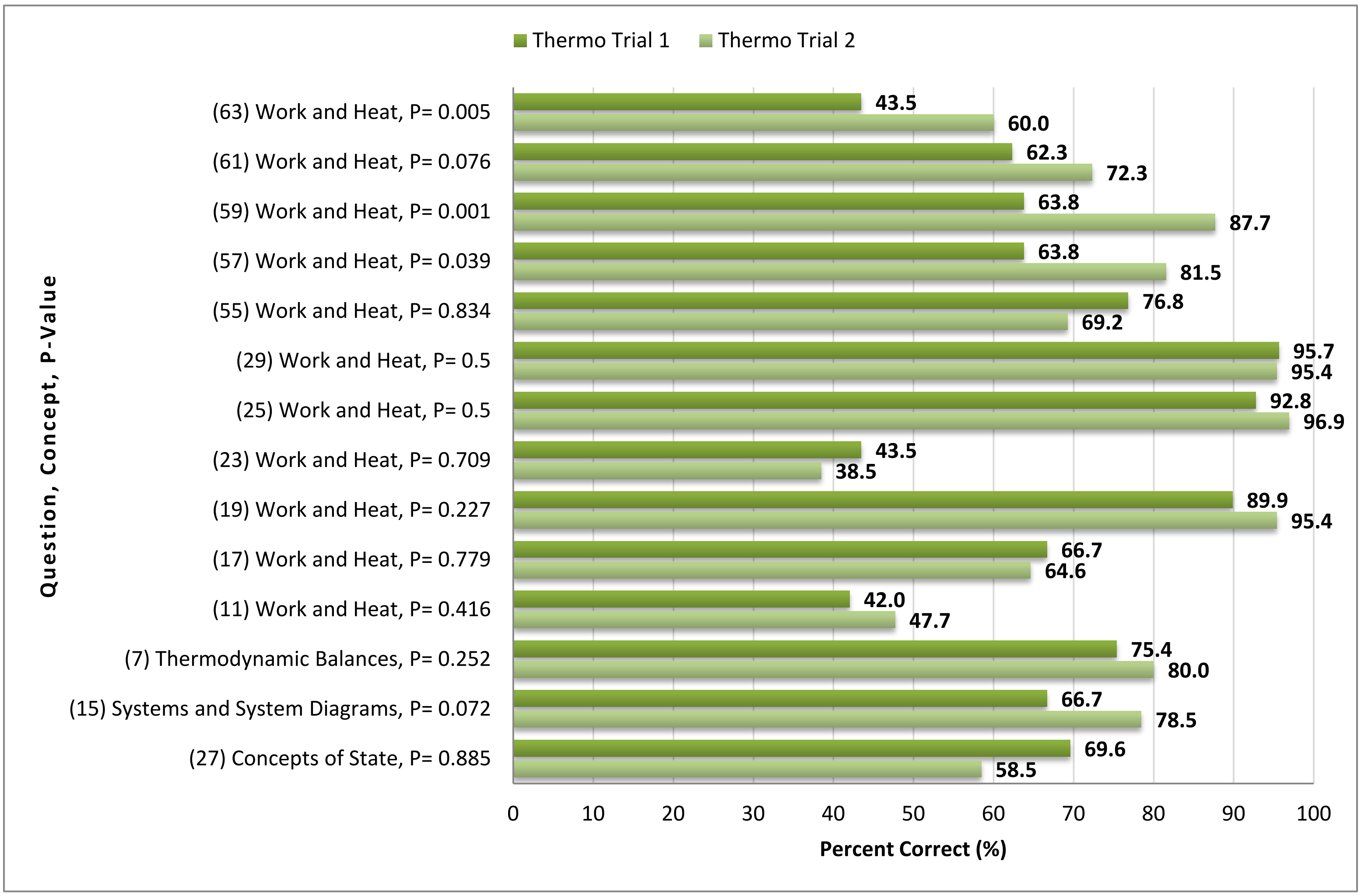



*Figure 6: Difference in percent correct between trial 1 and 2 of the TCI questions administered to Prof A's students.*

## Combined Analysis

The use of conceptual questions received a positive response from all the faculty interviewed. An initiative within materials science professors has already begun implementing conceptual questions in their courses. Although they were not identified as such, they hold a similar purpose as CI questions. While many of the materials science professors did not like the MCI in its original form, they all were interested in using some of the questions in addition to their own. Prof A. thought the concept inventories related to thermofluids have a good set of questions that do apply directly to the introductory courses taught at WPI. His only critique was that he thought some needed to be reworded to improve clarity.

An advantage of CI questions over the conceptual questions used currently is the use of organized distractors. Each distractor points out a different misconception which is a valuable tool for professors to use. With the knowledge of which misconceptions their students hold, professors can construct more focused reviews similar to the one done by Prof. A after we first administered the combined CI. After the first trial, Prof. A was able to identify two concept groups, Bernoulli principles and radiation, in which students performed very poorly. Based on which distractors students chose he was able to create a review which focused on repairing their misconceptions of those two concept areas. After our second trial, it was those two concept groups in which students showed the greatest improvement, which is supported by our statistical analysis. Prof. A indicated that if it were not for the surprisingly low performance in those two concept groups in the first trial, he would have assumed his students had a good understanding of them and would not have reviewed them as in depth.

The usefulness of the combined CI given to Prof. A's students, in addition to the materials science professors' strong support for conceptual learning show that the use of CIs or similar concept-based assessments would have a positive impact on the WPI curriculum. This is because CI questions are structured such that professors can obtain a large amount useful information on student understanding from their responses. Although all of the professors interviewed were supportive of the use of conceptual questions, the materials science professors were not supportive of using the MCI in its current form. This was mainly due to differences in concepts covered in the MCI as compared to the introductory materials science course at WPI.

# ENGINEERING DESIGN: METHODOLOGY

This chapter outlines the methods used in the course of the project. We first began by defining the purpose of study for the engineering design group. This purpose of study was strongly influenced by the findings of the background research which indicated to us that personal data collection was necessary. The primary methods of data collection were faculty interviews and student surveys. These results were analyzed in an attempt to compile a list of concepts used in engineering design.

## Project Goals

The main purpose of this study is to identify the design concepts being taught in the Engineering Departments at WPI offering design oriented MQPs and to examine how well the groups of students that are the object of this study understand those concepts. To do so, the following questions will be addressed:

- What design concepts are taught at WPI?
- How are they taught?
- Describe strength and weaknesses of WPI curricula of interest to this study
- Advantages/disadvantages to taking a design course prior to MQP
- If students are using design concepts in MQPs prior to taking design classes, where did they learn them?
- Are design concepts independent from the domain knowledge? i.e., are they independent from the classes in which they're being taught?

## Project Protocol

The investigation was carried out in two phases: an interview stage and a survey stage. The interview stage will serve as an identification process during which we hope to extract valuable information regarding the design concepts that department heads and professors that teach design classes at WPI expect students to learn throughout the curriculum. The second stage focuses on surveying students of interest in order to shed some light on how they are absorbing the design concepts that department heads and design professors expect them to learn.

**a. Interview Process:**

The interview stage focused on interviewing several WPI engineering department heads and professors who are involved in teaching design. In particular, we looked at Mechanical, Biomedical, Aerospace, and Electrical & Computer engineering because they are disciplines that are known to have strong use of design in their curricula. We asked a series of questions to determine how design is taught at WPI and particularly, what concepts are focused on. Answers were recorded in written notes from the interview without the use of video/audio devices. We also asked for information on current MQP groups that are using a high degree of design in their project. This information was used in the survey phase of our research.

**i. Tools:**

Two different sets of questions have been set up: one for Department Heads; and the other for Professors Teaching Design Classes. For interview questions, see Appendix.

**ii. Target Groups (Reinaldo):**

*Group I:* Department Heads for ME, AE, BME, and ECE departments;

*Group II:* Professors teaching Design classes in ME, AE, BME, and ECE departments.

**b. Survey Process:**

Two surveys were generated and sent to students who are currently working on, or have recently submitted, their MQP. The first survey round focused more on general questions regarding the students own experience with design. The second survey round was generated by using information from the interviews. In this phase, we used information on design concepts and notes from interviews to refine the survey and ask more specific questions about their use of design. Surveys were conducted using Google Docs.

i. **Tools:**

The first survey round, literature research based, was an online questionnaire issued using Google Docs, varying from multiple-choice to paragraph text answers. As for the second round survey, it was a combination between literature research and information from the faculty interviews. For the survey questions, see the Appendix.

## Design Models

The design model used in both round I and round II student surveys is based on the Dym and Little design model (Dym 2002), as shown in Figure 8 below. Another model that was also considered for this project is the Voland design model, as shown in Figure 9 below. Both models are currently taught at WPI. For instance, the Voland model is taught in ME 2300 (Mechanical engineering design course) and ECE 2799 (Electrical and computer engineering design course) according to professors J and L. The Dym and Little design model is taught in BME 3300 (Biomedical engineering design course), as explained by prof. I. Besides, other design models such as the EPICS design process (EPICS 2009) and the Kosky-Keat design model (Kosky 2009) were also investigated.

However, these design models are more oriented toward mechanical design. Therefore, the concepts therein relate more to students in ME, BME, and AE departments then they do to ECE students. Given that the chief enterprise of this project is to compile a list of design concepts that can be applied to any department, we found the necessity to explore several ECE MQPs in order to include the concepts that electrical engineering and computer science students were using while designing.

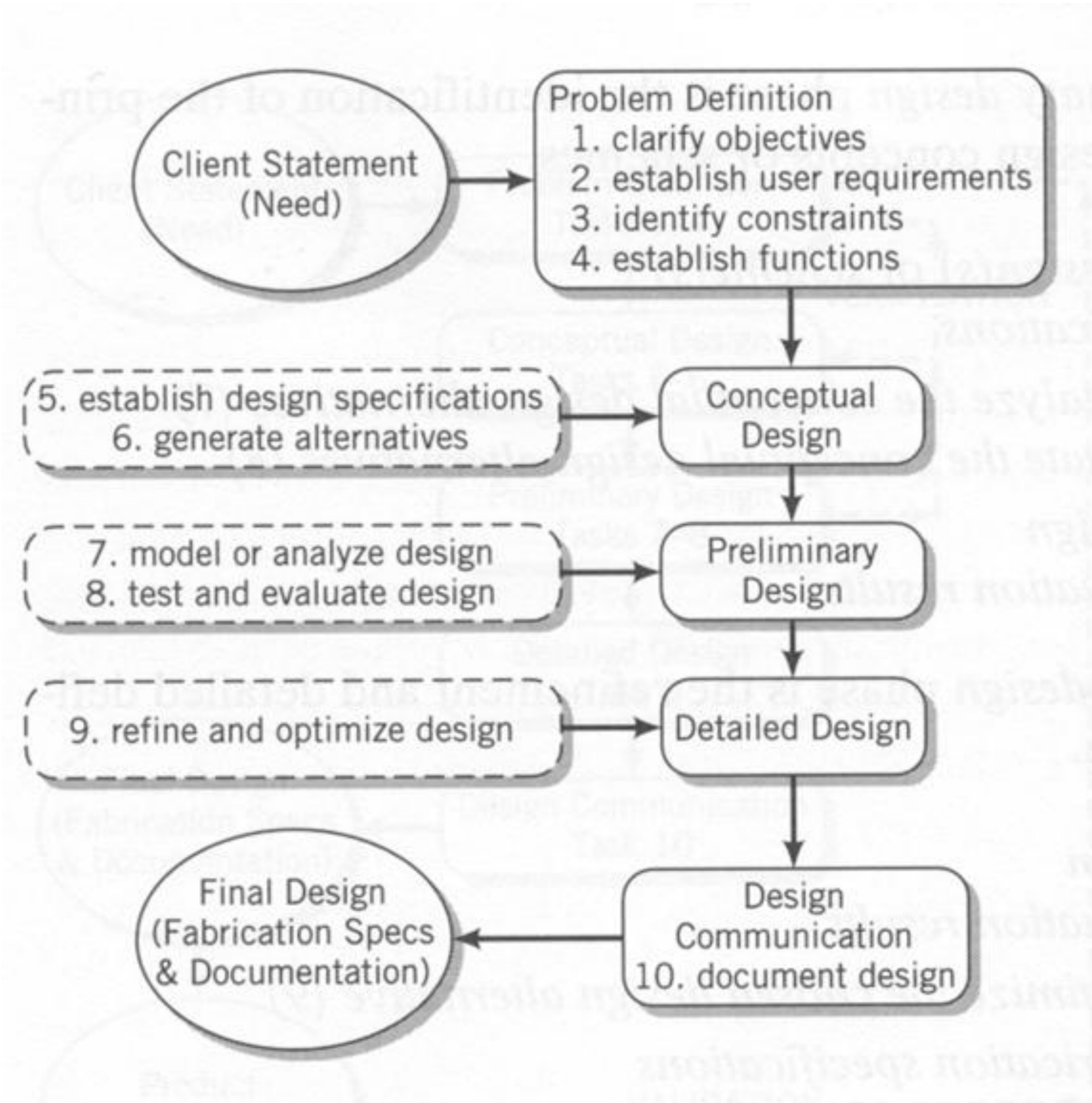



*Figure 7: Dym and Little design model, Introduction to Engineering Design, 2002*

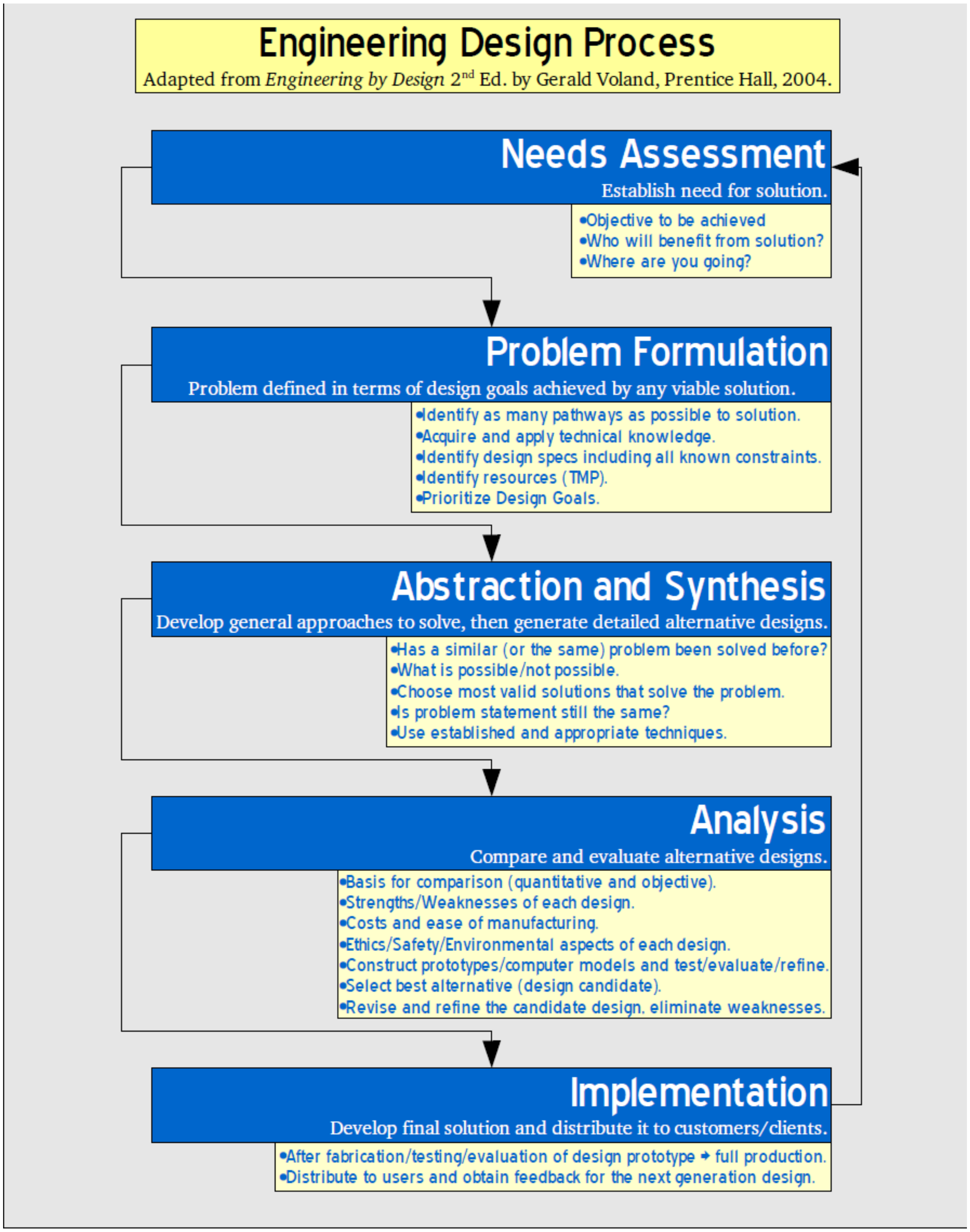



*Figure 8: Voland design model, Engineering by Design, 2004*

# ENGINEERING DESIGN: RESULTS AND ANALYSIS

The findings relative to the design portion of this IQP are divided in two categories. These are the sets of information collected through interviews, and through two rounds of student surveys. Both sets of information were useful in isolation; however they are significantly more revealing when considered together in light of the primary IQP goal. This goal is to determine whether concept inventories (CIs) could potentially be useful as an instruction tool at WPI, particularly in the Engineering Sciences.

## Faculty from WPI and other institutions, Interview Findings

The professors will be referenced anonymously, and grouped by department as shown:

| Identity | Contribution | Department | Participated as |
|---|---|---|---|
| Professor G | Interview | Mechanical/Aerospace Engineering | AE Capstone Design Course professor |
| Professor H | Interview | Mechanical/Aerospace Engineering | AE Capstone Design Course professor |
| Professor I | Interview | Biomedical Engineering | Department head and Design course professor |
| Professor J | Interview | Mechanical Engineering | Former Department head and Design course professor |
| Professor K | Interview | Electrical and Computer Engineering | Represented department head and MQP advisor |
| Professor L | Interview | Electrical and Computer Engineering | Design course professor |
| Professor M | Interview | University X ME/AE/Materials department | Thermal design professor and ME/AE/Materials department head |
| Professor N | Interview | University Y ME/AE department | ME/AE department chairman |

*Table 11: The anonymous name each professor will be referred to as, their contribution to this project, their department, and role related to the project*

### Analysis of Engineering Design Curriculum at WPI

In order to gain a better understanding of the design curriculum at WPI, we decided to interview department heads and design professors from each of the departments on which we focused. A total of eight professors were interviewed, representing the BME, ECE, ME, and AE departments of WPI. From these interviews we were able to gain a good understanding of the design methodologies employed by each department that we examined. All departments employ a project driven experiential design class structure as the core of their design class. BME, ECE, and ME departments have courses that are recommended design courses to be taken before senior year and the MQP; while AE has its design classes during C-term of the senior year, which coincides with the MQP for most students in the AE major.

BME 3300 Biomedical Engineering Design is offered in junior year as an unofficially required design course that all BME majors must take prior to MQP (with very rare exceptions under special circumstances). The course contains two sections, a textbook based section that teaches the design process, followed by the project based section, which gives students the experiential side of design. The project section is split into two halves, to reflect both the biological and mechanical focuses within BME. To allow for this, the class is taught by a senior and a junior professor, each focusing in one of the two aspects of BME. In this way, the BME department has merged two design classes into a single hybrid class. For senior year, BME offers a very large number of MQP projects, approximately 35 projects for about 75 seniors, in hopes that everyone finds a project that they are interested in.

For the ME department, ES 1020 Introduction to Engineering, ME 2300 Introduction to Engineering Design, and ME 3506 Rehabilitation Engineering are all design classes that are offered before the MQP. Although they are suggested, the ME program does allow flexibility for when/if these classes are taken. ES 1020, available to all first year students, provides a general introduction to the design process. ME 2300 and ME3506 focus on the entire design process in significantly more depth, and are set up so that the classes integrate a design project into the course of the class. Projects are often current or recent client needs, and ME2300 is set up such that the class reflects the project bid system that engineers encounter in the business world. In order to fulfill the capstone design requirement, the ME department also offers ME 4429 Thermofluid Application and Design and ME 4320 Advanced Engineering Design.

For the AE program, the only major-specific design classes are offered in C term of the senior year. This usually means that the vast majority of students with AE majors or concentrations take their capstone design class during their MQP. Therefore, most students must either take one of the ME design classes or take one of the capstone design classes during the junior year, if they plan to have a design class before the MQP. ME 4471 Spacecraft Mission and Design focuses very specifically on the analysis and modeling, as well as documentation phases of the design with some cursory consideration of the other phases because of time constraints and the complexity of spacecraft design. ME 4470 Aircraft Design covers more of the design process, but must exclude the testing and evaluation process due to cost of prototype and time constraints of the 7 week term. Despite these exclusions, AE design professors believe that students are able to pick up on the design process from what professors mention in other classes, or can pick it up easily in the course of the MQP.

ECE design is primarily taught in ECE 2799 Electrical and Computer Engineering Design, which employs the Voland Design Model (Voland 2004), as its basis, but without a specific textbook. This model does have several significant drawbacks; while it is a simple model, it over simplifies the design process and misses the iterative nature of design, and neglects necessary feedback between phases of the design process. The coursework centers on a project that is very open-ended. Professors encourage groups to focus on very specific design needs within niche markets to simplify the design needs. Students are free to choose their project's themes, and then focus heavily on problem identification, where it is up to research and determine the specifications that meet the customer's needs. However, most students do not fully meet the needs of the customer because of this lack of iteration in their design. While students are told to initially begin with brainstorming, they are encouraged to spend a fair amount of time looking at previous and related designs as a basis for their designs. This emphasis on previous work does help students to better see how similar projects have been done in the past, but this can be a double-edged sword that also reduces creativity and innovation in student design. It is important to note that ECE uses this class to expose students to the design process and give them experience working with design, and to learn from both their successes and failures.

### Engineering Design Curriculum at University X

We were presented the unique opportunity to interview a professor, who we will call Professor M, who has recently held a senior position at University X. This allowed us to compare the design teaching methodologies of WPI to those of University X. University X has ME, AE, and Materials Engineering (MTE) as a single merged department, so this allowed us to compare both ME and AE programs. University X has a much more rigid schedule of classes for its engineering students with very little room for schedule changes or free electives. Also, University X has recently modified its design curriculum to include a mandatory design class during the sophomore year that gives students a general knowledge of the design process and engineering practices. This class is primarily lecture-based, but is designed to help students connect material from the various classes they will take to common, real-world applications. Most notably, University X has two required senior design projects, called interprofessional projects, in place of WPI's MQP. Each of these design projects is semester long, with one focusing in thermal design, and the other focusing on the mechanical aspect of design. This covers both ABET requirements for thermal and mechanical design in the form of projects. The thermal project is focused on the design process and usually precedes the mechanical design project. The thermal project asks students to solve a real world problem with no information about project specifics. The example used by Professor M was a project that asked students to design a natural gas line from New Orleans to Chicago, but the students were asked to find any further information or requirements themselves by researching or asking the professor. Students would then take the design up to the blueprint stage of design, and defend it as if they were bidding on the project. Professor M was less familiar with the mechanical project, but told us that a similar, but smaller scale, project brief was given and students were asked to design and build a prototype for the final result. This is interesting to compare to the MQP, which usually focuses on mechanical design and relies on a separate course to fulfill the thermo-fluid aspect of design. However, the MQP does allow for longer term projects since the timescale is not limited to a single semester. This means that for ME students, the MQP allows for a more extensive project that can cover much more of the design process, but at the cost of only covering either mechanical or thermo-fluid design, leaving the other to a much less significant class project. University X values both mechanical and thermo-fluid design equally, but it does not cover either in as much depth as the MQP, and therefore, does not encourage specialization between these types of ME design in the senior projects.

### Engineering Design Curriculum at University Y

We were also given the opportunity to have a brief interview with a professor in a senior position in the ME/AE department of University Y. From this interview, we were able to get a brief overview of the design coursework at university Y. The design curriculum is structured such that students take an Introduction to Engineering class during freshman year that is a full year course. Then, during junior year, students take a Design of Machine Elements class and an Electrical Engineering class called Programming of Micro-processors. In senior year, students take a lecture-note-based design class called Design Methodology that is aimed at providing a more structured look at the design process. Seniors also complete their capstone design project, wherein concepts learned in Programming of Micro-processors are fully used.

## Analysis of Student Survey responses

This section contains the analysis of both rounds of student surveys, and the conclusions we drew from them.

### Round I Student Survey Analysis

This first survey was aimed at getting a better understanding of when and where seniors and graduate students learned about the design process in their undergraduate programs. For this purpose, the survey asked for brief descriptions of the students' MQPs, in which classes they learned design, and what phases of the design process the students used in the MQP. The design model used in the survey was based on Dym and Little design model (Dym and Little 2002) because it was fairly generalized for multiple majors, was commonly used by various institutions, and specified seven design phases (which represented a fair average, since most models specify between 5 and 10). The respondents included 35 undergraduates in the ME, AE, BME, and ECE departments with 10, 2, 14, and 19 responses respectively.

Comparing our survey to what professors have told us, we find some interesting discrepancies. Most notable of these is that students believe that the current MQP does not focus on either the Analysis and Modeling (A&M), or the Identification of Environment (IDE) steps, as shown in Figure 9 below. It is interesting that such key parts of the design process would appear to be missing from the MQP. According to students, IDE was weakest in BME and ME based MQPs, Figure 10 - Figure 11, and A&M was weakest in the ME and ECE based MQPs, Figure 11- Figure 12.

The number of responses from AE, Figure 13, was too low to draw any conclusions. It is interesting that these differences exist here considering that 94% of the students of both departments said that they took a design course prior to MQP that, according to the professors, covers the entire process. The low number of respondents who included IDE in their MQPs may be due to student misconception of the survey question, or it could be that many MQP project descriptions provided by the advisor/sponsor adequately specify the environment of the project.

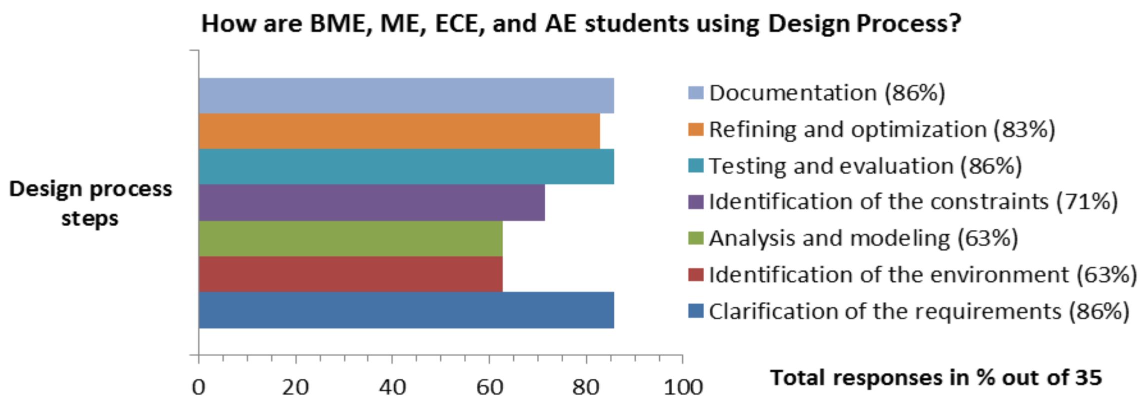



*Figure 9: Total responses from BME, ME, ECE, and AE students*

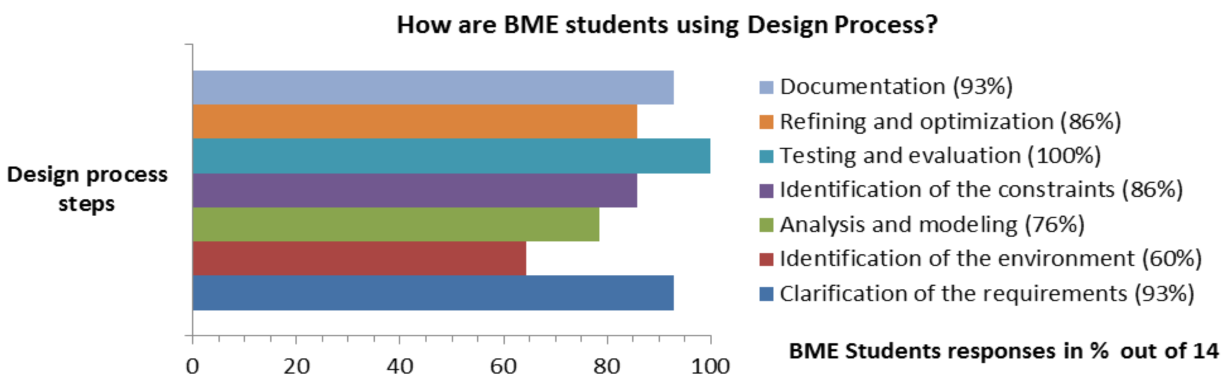



*Figure 10: BME responses*

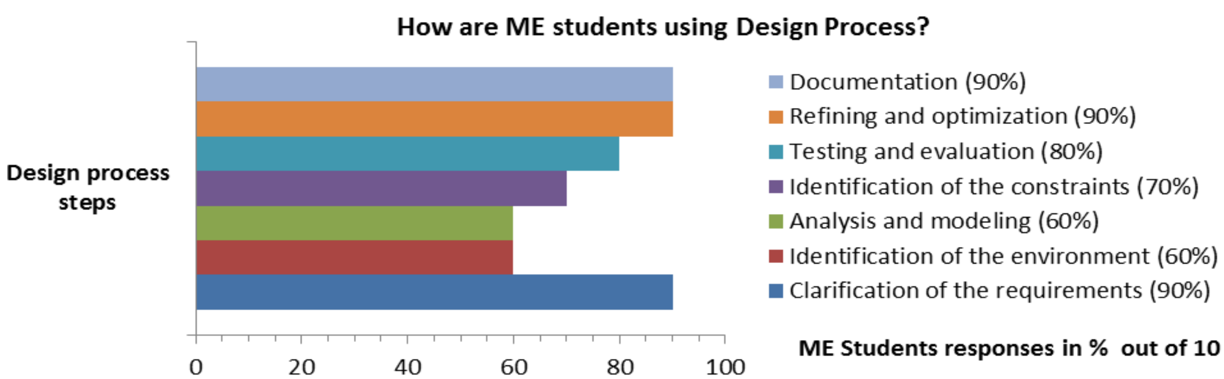



*Figure 11: ME responses*

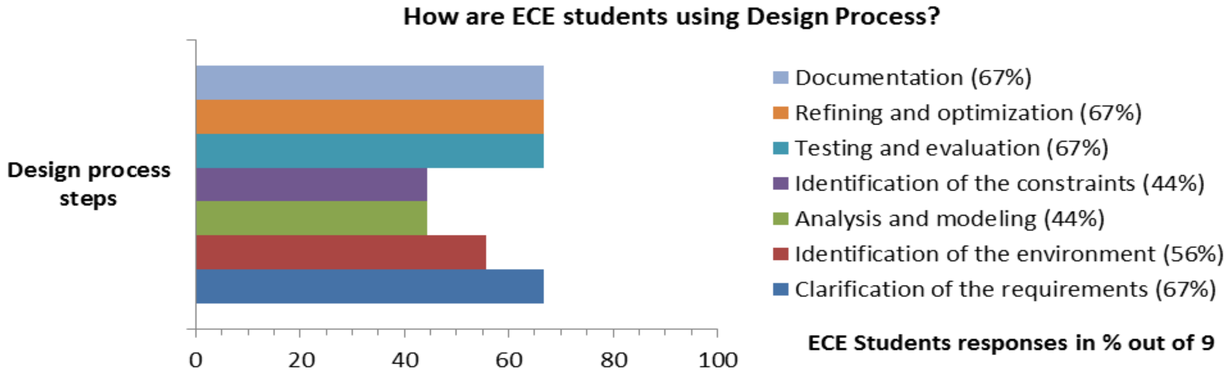



*Figure 12: ECE responses*

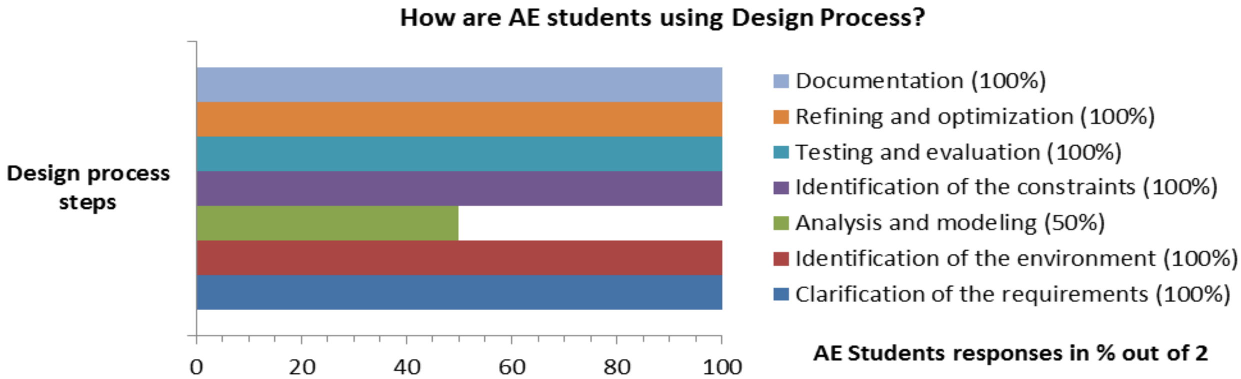



*Figure 13: AE responses*

These results led us to launch our second survey, which broke up these general phases into more specific activities that are within these general phases to examine more closely how design was being used in the MQP. We shifted our general design model to reflect several design methodologies (see Figure 1, Figure 7, and Figure 8) and focused on their commonalities. We re-grouped our specific processes into five phases, instead of the seven phase model used in our first survey, and asked seniors to select which processes within the phases they used in their MQP. These phases were as follows: Problem Definition, Conceptual Design, Preliminary Design, Detailed design, and Design Documentation (see Appendix: Round II Survey Questions for processes within each of these phases). This would allow us to glean which activities were being completed in the MQP.

## Round II Student Survey Analysis

The second survey yielded 36 responses from seniors in the same departments, representing 32 different MQPs, with the largest number of responses from the BME and ME departments (12 and 17 responses respectively). ME responsiveness increased drastically; however, ECE participation dropped down to only 3 responses. It is important to note that roughly one-fifth of total MQPs for these departments are represented, despite the low number of responses, if one assumes that only one student per project responded to the survey. (See Appendix: Survey II results for results of the survey).

Looking into the responses for the problem definition phase, we find interesting results for each design activity. All the departments had a small number of responses for creating a list of solution independent design specifications. This weakness could indicate that students favored one design solution, rather than investigate multiple solutions in order to find the most appropriate solution. Use of pairwise comparison was strong in BME, but fairly weak in ME and very weak in AE and ECE. This result matches our predictions based on professor interviews. The ME program is flexible and thus the classes that teach pairwise comparison are not required. The AE program is much less flexible than other ME programs, and as such, does not currently require a class that teaches pairwise comparison, and a student would have to make a special effort to take one of the ME classes that does. The ECE design class teaches a much more flexible design methodology that does not focus on the use of this design tool. ECE had one more area with low response, creating a list of specifications for the design to satisfy. This may also be due to the more flexible methodology learned in ECE 2799, which allowed for a much more open and experimental design process. Customer needs assessment and identification of target values for specifications had high scores for all departments, even in ECE, which does not emphasize it as part of their design class. We further investigated the categories that each department included in their design specifications. BME focused primarily on performance, materials, time, cost, manufacture, and safety with minor focuses in geometry, standards and adjustability. ME focused on performance, weight, and materials with less emphasis on cost, manufacture, and adjustability. AE concentrated in performance, geometry, and cost with less focus on most of the other specifications. ECE focused on performance, energy, time, cost, and adjustability. It is interesting to note that ME has a higher consideration for ergonomics than BME, but the reason for this is unclear.

We defined the conceptual design phase as the initial generation and selection of solution techniques. BME was fairly strong in most of the steps, but focused mostly on the generation of several solutions and ranking them with a decision matrix, rather than dividing the task into subsystems and eventually recombining them. ME appears to use all processes equally, but did not have very high results for any single process. AE focused greatly on breaking down and eventually combining subsystem designs to form the end concept. Interestingly, ECE has low responses for all phases except for combining subsystems. It may be that this is because ECE projects often have to design a subsystem to interface with an existing or larger product.

Preliminary design was broken down into using mathematical and physical models to predict design behavior, experimenting with aspects of the design that are uncertain, and documenting the results of testing the design. In particular, we were interested in the breakdown of the modeling in the MQP since our first survey yielded such low results for Analysis and Modeling. BME is strong in physical modeling and experimenting with uncertain aspects. ME uses each of these processes fairly equally, but responses average around a moderately low value of 50%. AE has very strong documentation and fairly strong mathematical modeling and experimentation. It is to be expected that AE would have low physical model results since aerospace products are often very expensive and complicated to manufacture. ECE is strong in all fields with the exception of the physical model, which matches our expectations based on professor interviews. Looking more in depth at the modeling processes, we find that BME and ME tend to use both physical and mathematical models, with emphasis on the physical model, where AE and ECE tend to lean towards the mathematical models. Oddly, there is a significant portion, a full 25%, that does not use either modeling technique. Some of these MQP students are testing existing equipment, or have projects that did not have any prototype phase, but this discrepancy between professor expectations requires further investigation.

In the detailed design phase, we look at the specifics of the design. We find that, again, BME has strong results for all aspects of detailed design. ME had strengths in building a prototype and specifying parts and materials, but was weaker in the other 6 activities. In particular, ME students do not frequently utilize design optimization and specifying design metrics of their design; however, ME students did say that they provided detailed drawings, so it is possible that the distinction was not clear between these specifying design metrics and providing a detailed drawing. AE had high results for specifying the design metrics, using detailed diagrams, and performing optimization studies. As expected, AE students scored low on building, evaluating, and refining their prototype. ECE students scored surprisingly high for building and evaluating their prototype despite lower scores for the creation of a physical model. In addition, ECE had high scores for specifying design metrics and using repeated analysis to refine their design. However, ECE students did not appear to have done any refining of the prototype parameters or optimization studies.

As a final step, we asked students what phases of the design process they used at the beginning and end of our survey to see how the students changed their perspective after seeing more specifically what each step entailed. Initially, we had strong results for all five phases in each department, except for detailed design for ME and ECE, and documentation for ECE. However, after taking the rest of the survey, we find that BME remained largely unchanged outside of a minor drop in communication. ME had more drastic changes since 2 students dropped the problem definition phase, 2 students added conceptual design while one dropped it. ME also had 2 students add detailed design and 3 students drop communication. AE evidenced several drops; primarily from one particular student that believed his project did not contain conceptual, preliminary or detailed design. ECE did not have significant change except for one student who switched from having conceptual design to having detailed design. From this, we can conclude that overall, some students did not fully understand what was entailed by each of the phases. The phases with the most significant degree of uncertainty were communication and conceptual design. From total responses, we don't see a tremendous difference in the total phases present in a project, since the net change is only a drop of 2 responses for all five phases.

## CONCLUSION

The project team has been broken up into two groups; however, both groups ultimately share the same conclusion. The project goal at the inception was to identify the level of conceptual learning at WPI and to see if a greater level of conceptual learning can improve the WPI curriculum in both engineering science and design. From the engineering science perspective, we now see that many of the WPI professors support conceptual learning and are eager to implement it into their courses. In addition to faculty support of CIs, we were able to identify student misconceptions, of which the professor was previously unaware, by administering a CI assessment to students. This new information allowed the professor to improve the overall quality of his course. Given the level of improvement in performance, as well as the faculty support for conceptual learning, we can conclude that CIs would be an effective teaching tool at WPI.

Given the effectiveness of CIs within Engineering Science courses, it seems reasonable to apply this tool to the Engineering Design curriculum. However, a list of concepts for Engineering Design has not yet been compiled, so the group decided to take first steps towards generating this list. Through interviews with design professors and surveys of students actively using design in their MQPs, we determined that design does not follow a set of concepts in the same sense that ES courses do because some aspects of the design process can be domain specific. Nevertheless, during this project we determined a list of common steps that students from BME, ME, AE, and ECE departments share when using the design process in their MQPs.

Because of faculty support for conceptual learning, the demonstrated usefulness of CIs as educational tools, and the potential benefits of a design CI, the group believes that applying CIs to the WPI curriculum could improve the level of student conceptual learning.

# RECOMMENDATIONS

The engineering science group found that there was a large gap between the materials science curriculum taught at WPI and the concepts covered in the MCI. In order to advance conceptual learning in the engineering science department, we recommend that WPI materials science professors create a new CI that aligns with the concepts taught at WPI. It was also found that a number of questions in the thermofluids CIs (Thermodynamics, Heat Transfer, Heat and Energy, and Fluid Mechanics) were worded in a misleading or ambiguous manner. We suggest that WPI professors interested in using these CIs rephrase these questions to improve clarity. We recommend that CIs see more use at WPI. In order to achieve this, faculty awareness needs to be increased. It would benefit education at WPI to hold some form of lecture or seminar to spread the awareness of these new educational tools.

In order to identify design concepts we recommend that much more data be collected by increasing the number of participants in future studies. This can be achieved by including more WPI departments, and other institutions, in surveys and interviews. Student participation could be enhanced through use of incentives from design professors and MQP advisors. Also, during the literature research for this project it was found that most of the textbooks teaching design were very biased towards mechanical design. Therefore, we recommend that more research be done to universalize the design process and make it applicable to various engineering disciplines.

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# APPENDIX

## Engineering Science Professor Interview Outline and Summaries

- Introduction
  - Name, general overview of the project
  - "Thanks for being willing to see me"
- Concept inventory awareness?
  - If so
    - Have you used a concept inventory as a professor?
      - Why/Why not?
      - Example use: Finals review misconception guide
        - Pros: quick (20-30 minutes), direct, multiple choice so easy to grade
  - If not
    - Explain concept inventory
      - Concepts
      - Misconceptions
        - Value of the concept inventory
          - Provides in-depth analysis of students' misconceptions and understandings
        - Example use: Finals review misconception guide
- Education awareness
  - Common Student misconceptions you consider/encounter as a professor?
    - List of misconceptions
      - Additional misconceptions he/she would like to add?
  - Teaching Philosophy
    - Would you agree that an emphasis on concept understanding is at least as important as skill in equation use and equation memorization?
      - Why?
- Textbooks
  - How do you select a textbook to use for your course?
    - Concept explanations
    - Diagrams
    - Equations
    - Readability
- Future Intentions for the IQP
  - Discuss Plan/development of surveying students directly on their misconceptions and understanding using the concept inventories
- Closing

- "Thanks for your time"
- If we have further questions, may we contact you again?
- If you have any further interest, feel free to contact us (only makes sense to say this if he/she expressed interest in using the concept inventories).

### Prof. A Follow up Interview Summary

- Wasn't surprised by students' performance
  - He questions the students' effort when taking this because it it didn't count for a grade
  - The majority of the students in his class are ME students with interest in mechanical design
    - The majority only take his class because it is a requirement not because they're good at the material and want to learn more about thermo
  - He wants to have his students retake the skills test to see if there is any improvement after 3 weeks of review
- Will use the results from the fluids and heat transfer section to emphasize different concept areas when he does additional review
  - Found that students did not grasp the Bernoulli principle and so will go over it more when he teaches fluids in D Term
  - Will go over the heat transfer concept of convection more with his current class
- Gender issue
  - According to ASEE literature, males are more confident in their knowledge than females which could have contributed to the confidence statistics since there are only 7 females in his class
- Thinks that overall there were a good set of questions
  - Students tend to do poorly with liquids (incompressible flow) but do better with saturated gases (ideal gas properties)
    - In a large class he doesn't have the time to meet with students individually to help them understand the concepts
- Found that some of the concepts listed in the TCI literature were not all covered in the CI itself
  - Ex. Concepts of state
    - Thinks that concepts of state is a calculation concept which is why it is hard to implement in a conceptual exam
- Some of the CI questions are higher level questions not covered in introduction course
  - Ex. Radiation question

### Prof. B Interview Summary

- Her Experience
  - Used it 5 years ago
  - Believes that CIs can be used in two ways
    - During a course to give student/instructor feedback on misconceptions
    - For research purposes
  - Creates her own conceptual questions
- Agree/Disagree with CI Structure?

- Not at all aligned with what she teaches in her class
    - The MCI does not always test conceptual understanding but tests little "factoids" which she does not really teach
    - She teaches students from a wide variety of majors, many of which her class will be their only materials class
    - Only a small percentage of the MCI questions match the objectives of her class
    - MCI works in the lower levels of Blumes Taxonomy
- Misconceptions?
    - The misconceptions identified by Krause, the creator of the MCI, are common with her students as well
        - She would also add to the misconceptions: the difference between force and stress
        - She doesn't teach corrosion and electrical properties in detail because she doesn't have enough time
    - She feels that the MCI focuses too much on atomic structure which the average engineer in the workplace won't need to know unless they are material scientist
        - She begins her course with material properties and performance as opposed to atomic structure because it is more important to the general population of WPI students
- Conceptual understanding more important than equations?
    - She believes conceptual understanding is more important
    - Students at WPI are more exposed to challenging calculations and have the misconception that conceptual multiple choice questions are easier
        - A good concept question should be difficult
        - She has seen many students do well on calculations but do poorly on concepts because they simply rehearse the steps
- Textbook selection
    - She would look at homework problems when choosing a textbook
    - WPI materials professors make a group decision on which book to use and have been using the same one for years
        - It has better readability
        - Better homework problems
        - She's not sure how well it explains concepts because she hasn't read it in a while
- Clicker questions
    - Has 2-3 clicker questions per class
        - The most successful ones are the conceptual questions
        - Has questions that would normally be calculation questions but sets up the multiple choices that will let her know what the students did wrong based on their answer
        - Gets a lot of positive student feedback from clicker questions
- Her class
    - Students are more likely to prepare for class when she integrates concepts into her lecture
    - She encounters the same misconceptions every time she teaches the class
        - She becomes better prepared for dealing with them but hasn't noticed a change in performance or structure of her class
- Recommendations

        - Wants us to talk to Prof. E, Director of K-12 outreach
            - She teaches Heat Transfer occasionally and uses concept inventories/conceptual questions in her class

### Prof. C Interview Summary

- Awareness
    - Never heard of CIs before nor has used them
- Conceptual Questions
    - Uses conceptual questions in her class
    - Thinks that CI could be useful to prepare for review for her exams
    - Believes that conceptual understanding is just as important as skill in solving equations
    - Students have appreciated having conceptual questions because it points out gaps in their understanding
- Misconceptions
    - Agrees with the misconceptions identified in the literature
    - Would also add crystal structure of ceramics and metals
    - Students get confused with what the phase diagram curves mean
    - Agrees with Prof. B's point on confusion with force and stress
    - Students also don't understand that strain is unitless
- Concepts
    - Touches on electrical conductivity but doesn't go in depth
    - Agrees with the concepts identified in the literature
    - Would also add failure and fatigue
- Textbook
    - Easier to have a standardized textbook
    - Current textbook has a good balance of concepts
- Very interested in looking into CIs for her class in D Term

### Prof. D Interview Summary

- Awareness
    - Had not heard of CIs before
    - Interested in looking into them further
- Conceptual Questions
    - Uses student response system to give conceptual questions to her class
    - Assumes that students don't know anything at the beginning of the course
    - Gives a quiz, similar to a CI, to identify certain misconceptions
        - Most don't require calculation
    - Materials professors at WPI have already implemented a similar idea in their classes
        - Choose their own questions based on what they expect their students to know
        - Uses distractors as well
    - Different professors have different approaches
    - Conceptual understanding and calculation skill are equally as important
- Concepts

    - All WPI professors teach the concepts mentioned in the literature
    - Don't cover electrical conductivity
- Misconceptions
    - Phase diagrams
    - Crystal structure
        - Gives hands on extra credit assignment to create their own crystal structure
    - TTT graphs (Temperature-Time-Transformation)
    - Her students don't have trouble with force vs stress
- Frustrated with the insufficient preparation in math for her class
- Likes the current textbook
    - Easy to read
    - Good set of problems

### Prof. A Final Interview Summary

- Class performance
    - Disappointed that the class didn't improve more even after making the assessment worth 5% of their grade
    - Thinks that his class' calculation skill are far greater than their conceptual understanding
    - Thought the thermo section would have improved
    - Doesn't understand why students did so poorly with work concepts
- CI
    - Would rephrase some of the questions
    - Would consider giving fluids CI in his class during week 6
        - Thinks it would carry over better in intro courses
    - The questions in the TCI, which focus on control masses, aren't consistent with what they learn in his class which focuses on control volumes
    - Still likes the idea of using CI but thinks that getting well worded questions is the most important thing
- Review
    - Ideal gases
    - Incompressible materials
    - Specific heats
    - Cycles
- MQPs
    - The quality of MQPs about 20 years ago were so high that almost all of them could be published
        - Very concept driven

## Combined Skills Test Results

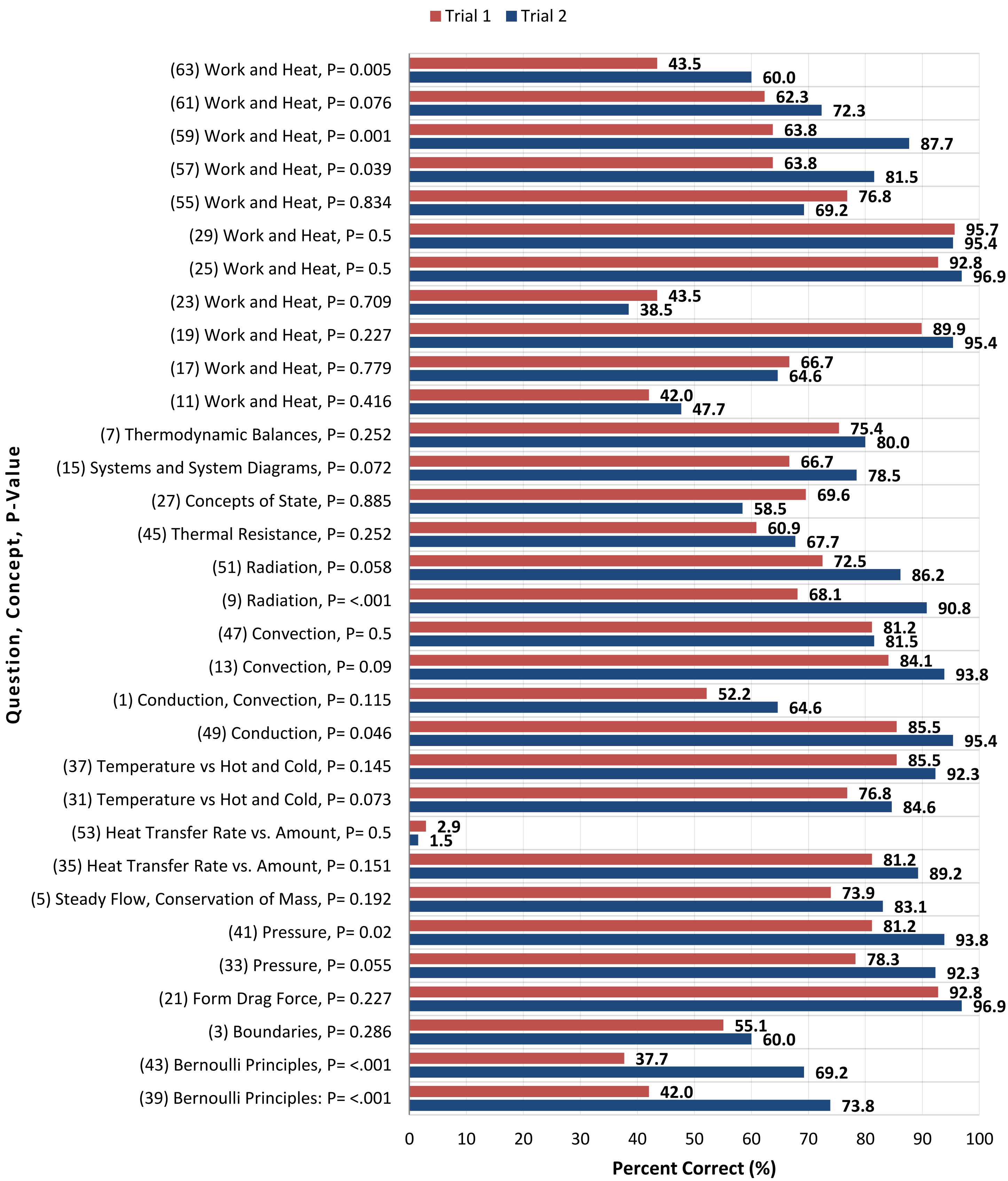


*Figure 14: Combined skills test results grouped by concept areas*

| | Percent Correct | | | | |
|---|---|---|---|---|---|
| **Question** | **Trial 1** | **Trial 2** | **Delta (%)** | **Inventory** | **Concepts** |
| 39 | 42.0 | 73.8 | 31.8 | Fluid Mechanics | Bernoulli Principles |
| 43 | 37.7 | 69.2 | 31.5 | Fluid Mechanics | Bernoulli Principles |
| 3 | 55.1 | 60.0 | 4.9 | Fluid Mechanics | Boundaries |
| 21 | 92.8 | 96.9 | 4.2 | Fluid Mechanics | Form Drag Force |
| 33 | 78.3 | 92.3 | 14.0 | Fluid Mechanics | Pressure |
| 41 | 81.2 | 93.8 | 12.7 | Fluid Mechanics | Pressure |
| 5 | 73.9 | 83.1 | 9.2 | Fluid Mechanics | Steady Flow, Conservation of Mass |
| 35 | 81.2 | 89.2 | 8.1 | Heat and Energy | Heat Transfer Rate vs. Amount |
| 53 | 2.9 | 1.5 | -1.4 | Heat and Energy | Heat Transfer Rate vs. Amount |
| 31 | 76.8 | 84.6 | 7.8 | Heat and Energy | Temperature vs Hot and Cold |
| 37 | 85.5 | 92.3 | 6.8 | Heat and Energy | Temperature vs Hot and Cold |
| 49 | 85.5 | 95.4 | 9.9 | Heat Transfer | Conduction |
| 1 | 52.2 | 64.6 | 12.4 | Heat Transfer | Conduction, Convection |
| 13 | 84.1 | 93.8 | 9.8 | Heat Transfer | Convection |
| 47 | 81.2 | 81.5 | 0.4 | Heat Transfer | Convection |
| 9 | 68.1 | 90.8 | 22.7 | Heat Transfer | Radiation |
| 51 | 72.5 | 86.2 | 13.7 | Heat Transfer | Radiation |
| 45 | 60.9 | 67.7 | 6.8 | Heat Transfer | Thermal Resistance |
| 27 | 69.6 | 58.5 | -11.1 | Thermodynamics | Concepts of State |
| 15 | 66.7 | 78.5 | 11.8 | Thermodynamics | Systems and System Diagrams |
| 7 | 75.4 | 80.0 | 4.6 | Thermodynamics | Thermodynamic Balances |
| 11 | 42.0 | 47.7 | 5.7 | Thermodynamics | Work and Heat |
| 17 | 66.7 | 64.6 | -2.1 | Thermodynamics | Work and Heat |
| 19 | 89.9 | 95.4 | 5.5 | Thermodynamics | Work and Heat |
| 23 | 43.5 | 38.5 | -5.0 | Thermodynamics | Work and Heat |
| 25 | 92.8 | 96.9 | 4.2 | Thermodynamics | Work and Heat |
| 29 | 95.7 | 95.4 | -0.3 | Thermodynamics | Work and Heat |
| 55 | 76.8 | 69.2 | -7.6 | Thermodynamics | Work and Heat |
| 57 | 63.8 | 81.5 | 17.8 | Thermodynamics | Work and Heat |
| 59 | 63.8 | 87.7 | 23.9 | Thermodynamics | Work and Heat |
| 61 | 62.3 | 72.3 | 10.0 | Thermodynamics | Work and Heat |
| 63 | 43.5 | 60.0 | 16.5 | Thermodynamics | Work and Heat |

*Table 12: Combined skills test delta scores grouped by CI*

## Combined Skills Test Statistical Analysis

| Table of test1q1 by test2q1 | | | |
|---|---|---|---|
| test1q1 | test2q1 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 14<br>22.22<br>46.67<br>60.87 | 16<br>25.40<br>53.33<br>40.00 | 30<br>47.62 |
| 1 | 9<br>14.29<br>27.27<br>39.13 | 24<br>38.10<br>72.73<br>60.00 | 33<br>52.38 |
| Total | 23<br>36.51 | 40<br>63.49 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q1 by test2q1***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.9600 |
| DF | 1 |
| Asymptotic Pr > S | 0.1615 |
| Exact Pr >= S | 0.2295 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1960 |
| ASE | 0.1209 |
| 95% Lower Conf Limit | -0.0409 |
| 95% Upper Conf Limit | 0.4329 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q2 by test2q2 | | | |
|---|---|---|---|
| test1q2 | test2q2 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 13<br>20.63<br>44.83<br>52.00 | 16<br>25.40<br>55.17<br>42.11 | 29<br>46.03 |
| 1 | 12<br>19.05<br>35.29<br>48.00 | 22<br>34.92<br>64.71<br>57.89 | 34<br>53.97 |
| Total | 25<br>39.68 | 38<br>60.32 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q2 by test2q2***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.5714 |
| DF | 1 |
| Asymptotic Pr > S | 0.4497 |
| Exact Pr >= S | 0.5716 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.0963 |
| ASE | 0.1247 |
| 95% Lower Conf Limit | -0.1481 |
| 95% Upper Conf Limit | 0.3407 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q3 by test2q3 | | | |
|---|---|---|---|
| test1q3 | test2q3 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 2<br>3.17<br>13.33<br>20.00 | 13<br>20.63<br>86.67<br>24.53 | 15<br>23.81 |
| 1 | 8<br>12.70<br>16.67<br>80.00 | 40<br>63.49<br>83.33<br>75.47 | 48<br>76.19 |
| Total | 10<br>15.87 | 53<br>84.13 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q3 by test2q3***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.1905 |
| DF | 1 |
| Asymptotic Pr > S | 0.2752 |
| Exact Pr >= S | 0.3833 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | -0.0376 |
| ASE | 0.1161 |
| 95% Lower Conf Limit | -0.2652 |
| 95% Upper Conf Limit | 0.1899 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q4 by test2q4 | | | |
|---|---|---|---|
| test1q4 | test2q4 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 5<br>7.94<br>29.41<br>38.46 | 12<br>19.05<br>70.59<br>24.00 | 17<br>26.98 |
| 1 | 8<br>12.70<br>17.39<br>61.54 | 38<br>60.32<br>82.61<br>76.00 | 46<br>73.02 |
| Total | 13<br>20.63 | 50<br>79.37 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q4 by test2q4***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.8000 |
| DF | 1 |
| Asymptotic Pr > S | 0.3711 |
| Exact Pr >= S | 0.5034 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1298 |
| ASE | 0.1327 |
| 95% Lower Conf Limit | -0.1303 |
| 95% Upper Conf Limit | 0.3900 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q5 by test2q5 | | | |
|---|---|---|---|
| test1q5 | test2q5 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 4<br>6.35<br>19.05<br>66.67 | 17<br>26.98<br>80.95<br>29.82 | 21<br>33.33 |
| 1 | 2<br>3.17<br>4.76<br>33.33 | 40<br>63.49<br>95.24<br>70.18 | 42<br>66.67 |
| Total | 6<br>9.52 | 57<br>90.48 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q5 by test2q5***

| McNemar's Test | |
|---|---|
| Statistic (S) | 11.8421 |
| DF | 1 |
| Asymptotic Pr > S | 0.0006 |
| Exact Pr >= S | 7.286E-04 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1739 |
| ASE | 0.1092 |
| 95% Lower Conf Limit | -0.0401 |
| 95% Upper Conf Limit | 0.3879 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q6 by test2q6 | | | |
|---|---|---|---|
| test1q6 | test2q6 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 23<br>36.51<br>65.71<br>69.70 | 12<br>19.05<br>34.29<br>40.00 | 35<br>55.56 |
| 1 | 10<br>15.87<br>35.71<br>30.30 | 18<br>28.57<br>64.29<br>60.00 | 28<br>44.44 |
| Total | 33<br>52.38 | 30<br>47.62 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q6 by test2q6***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.1818 |
| DF | 1 |
| Asymptotic Pr > S | 0.6698 |
| Exact Pr >= S | 0.8318 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2979 |
| ASE | 0.1203 |
| 95% Lower Conf Limit | 0.0621 |
| 95% Upper Conf Limit | 0.5336 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q7 by test2q7 | | | |
|---|---|---|---|
| test1q7 | test2q7 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 0<br>0.00<br>0.00<br>0.00 | 10<br>15.87<br>100.00<br>16.95 | 10<br>15.87 |
| 1 | 4<br>6.35<br>7.55<br>100.00 | 49<br>77.78<br>92.45<br>83.05 | 53<br>84.13 |
| Total | 4<br>6.35 | 59<br>93.65 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q7 by test2q7***

| McNemar's Test | |
|---|---|
| Statistic (S) | 2.5714 |
| DF | 1 |
| Asymptotic Pr > S | 0.1088 |
| Exact Pr >= S | 0.1796 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | -0.0998 |
| ASE | 0.0380 |
| 95% Lower Conf Limit | -0.1742 |
| 95% Upper Conf Limit | -0.0253 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q8 by test2q8 | | | |
|---|---|---|---|
| test1q8 | test2q8 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 9<br>14.29<br>42.86<br>64.29 | 12<br>19.05<br>57.14<br>24.49 | 21<br>33.33 |
| 1 | 5<br>7.94<br>11.90<br>35.71 | 37<br>58.73<br>88.10<br>75.51 | 42<br>66.67 |
| Total | 14<br>22.22 | 49<br>77.78 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q8 by test2q8***

| McNemar's Test | |
|---|---|
| Statistic (S) | 2.8824 |
| DF | 1 |
| Asymptotic Pr > S | 0.0896 |
| Exact Pr >= S | 0.1435 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3377 |
| ASE | 0.1253 |
| 95% Lower Conf Limit | 0.0921 |
| 95% Upper Conf Limit | 0.5832 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q9 by test2q9 | | | |
|---|---|---|---|
| test1q9 | test2q9 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 8<br>12.70<br>42.11<br>33.33 | 11<br>17.46<br>57.89<br>28.21 | 19<br>30.16 |
| 1 | 16<br>25.40<br>36.36<br>66.67 | 28<br>44.44<br>63.64<br>71.79 | 44<br>69.84 |
| Total | 24<br>38.10 | 39<br>61.90 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q9 by test2q9***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.9259 |
| DF | 1 |
| Asymptotic Pr > S | 0.3359 |
| Exact Pr >= S | 0.4421 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.0534 |
| ASE | 0.1252 |
| 95% Lower Conf Limit | -0.1919 |
| 95% Upper Conf Limit | 0.2988 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q10 by test2q10 | | | |
|---|---|---|---|
| test1q10 | test2q10 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 1<br>1.59<br>16.67<br>33.33 | 5<br>7.94<br>83.33<br>8.33 | 6<br>9.52 |
| 1 | 2<br>3.17<br>3.51<br>66.67 | 55<br>87.30<br>96.49<br>91.67 | 57<br>90.48 |
| Total | 3<br>4.76 | 60<br>95.24 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q10 by test2q10***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.2857 |
| DF | 1 |
| Asymptotic Pr > S | 0.2568 |
| Exact Pr >= S | 0.4531 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1695 |
| ASE | 0.1894 |
| 95% Lower Conf Limit | -0.2016 |
| 95% Upper Conf Limit | 0.5406 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q11 by test2q11 | | | |
|---|---|---|---|
| test1q11 | test2q11 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 0<br>0.00<br>0.00<br>0.00 | 5<br>7.94<br>100.00<br>8.20 | 5<br>7.94 |
| 1 | 2<br>3.17<br>3.45<br>100.00 | 56<br>88.89<br>96.55<br>91.80 | 58<br>92.06 |
| Total | 2<br>3.17 | 61<br>96.83 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q11 by test2q11***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.2857 |
| DF | 1 |
| Asymptotic Pr > S | 0.2568 |
| Exact Pr >= S | 0.4531 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | -0.0475 |
| ASE | 0.0252 |
| 95% Lower Conf Limit | -0.0968 |
| 95% Upper Conf Limit | 0.0018 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q12 by test2q12 | | | |
|---|---|---|---|
| test1q12 | test2q12 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 29<br>46.03<br>85.29<br>78.38 | 5<br>7.94<br>14.71<br>19.23 | 34<br>53.97 |
| 1 | 8<br>12.70<br>27.59<br>21.62 | 21<br>33.33<br>72.41<br>80.77 | 29<br>46.03 |
| Total | 37<br>58.73 | 26<br>41.27 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q12 by test2q12***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.6923 |
| DF | 1 |
| Asymptotic Pr > S | 0.4054 |
| Exact Pr >= S | 0.5811 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.5815 |
| ASE | 0.1028 |
| 95% Lower Conf Limit | 0.3801 |
| 95% Upper Conf Limit | 0.7829 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q13 by test2q13 | | | |
|---|---|---|---|
| test1q13 | test2q13 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 0<br>0.00<br>0.00<br>0.00 | 4<br>6.35<br>100.00<br>6.67 | 4<br>6.35 |
| 1 | 3<br>4.76<br>5.08<br>100.00 | 56<br>88.89<br>94.92<br>93.33 | 59<br>93.65 |
| Total | 3<br>4.76 | 60<br>95.24 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q13 by test2q13***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.1429 |
| DF | 1 |
| Asymptotic Pr > S | 0.7055 |
| Exact Pr >= S | 1.0000 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | -0.0576 |
| ASE | 0.0227 |
| 95% Lower Conf Limit | -0.1020 |
| 95% Upper Conf Limit | -0.0131 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q14 by test2q14 | | | |
|---|---|---|---|
| test1q14 | test2q14 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 11<br>17.46<br>55.00<br>40.74 | 9<br>14.29<br>45.00<br>25.00 | 20<br>31.75 |
| 1 | 16<br>25.40<br>37.21<br>59.26 | 27<br>42.86<br>62.79<br>75.00 | 43<br>68.25 |
| Total | 27<br>42.86 | 36<br>57.14 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q14 by test2q14***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.9600 |
| DF | 1 |
| Asymptotic Pr > S | 0.1615 |
| Exact Pr >= S | 0.2295 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1627 |
| ASE | 0.1226 |
| 95% Lower Conf Limit | -0.0777 |
| 95% Upper Conf Limit | 0.4031 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q15 by test2q15 | | | |
|---|---|---|---|
| test1q15 | test2q15 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 1<br>1.59<br>33.33<br>33.33 | 2<br>3.17<br>66.67<br>3.33 | 3<br>4.76 |
| 1 | 2<br>3.17<br>3.33<br>66.67 | 58<br>92.06<br>96.67<br>96.67 | 60<br>95.24 |
| Total | 3<br>4.76 | 60<br>95.24 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q15 by test2q15***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.0000 |
| DF | 1 |
| Asymptotic Pr > S | 1.0000 |
| Exact Pr >= S | 1.0000 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3000 |
| ASE | 0.2561 |
| 95% Lower Conf Limit | -0.2019 |
| 95% Upper Conf Limit | 0.8019 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q16 by test2q16 | | | |
|---|---|---|---|
| test1q16 | test2q16 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 7<br>11.11<br>43.75<br>70.00 | 9<br>14.29<br>56.25<br>16.98 | 16<br>25.40 |
| 1 | 3<br>4.76<br>6.38<br>30.00 | 44<br>69.84<br>93.62<br>83.02 | 47<br>74.60 |
| Total | 10<br>15.87 | 53<br>84.13 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q16 by test2q16***

| McNemar's Test | |
|---|---|
| Statistic (S) | 3.0000 |
| DF | 1 |
| Asymptotic Pr > S | 0.0833 |
| Exact Pr >= S | 0.1460 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.4264 |
| ASE | 0.1345 |
| 95% Lower Conf Limit | 0.1627 |
| 95% Upper Conf Limit | 0.6901 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q17 by test2q17 | | | |
|---|---|---|---|
| test1q17 | test2q17 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 3<br>4.76<br>27.27<br>60.00 | 8<br>12.70<br>72.73<br>13.79 | 11<br>17.46 |
| 1 | 2<br>3.17<br>3.85<br>40.00 | 50<br>79.37<br>96.15<br>86.21 | 52<br>82.54 |
| Total | 5<br>7.94 | 58<br>92.06 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q17 by test2q17***

| McNemar's Test | |
|---|---|
| Statistic (S) | 3.6000 |
| DF | 1 |
| Asymptotic Pr > S | 0.0578 |
| Exact Pr >= S | 0.1094 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2984 |
| ASE | 0.1599 |
| 95% Lower Conf Limit | -0.0150 |
| 95% Upper Conf Limit | 0.6119 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q18 by test2q18 | | | |
|---|---|---|---|
| test1q18 | test2q18 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 2<br>3.17<br>16.67<br>28.57 | 10<br>15.87<br>83.33<br>17.86 | 12<br>19.05 |
| 1 | 5<br>7.94<br>9.80<br>71.43 | 46<br>73.02<br>90.20<br>82.14 | 51<br>80.95 |
| Total | 7<br>11.11 | 56<br>88.89 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q18 by test2q18***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.6667 |
| DF | 1 |
| Asymptotic Pr > S | 0.1967 |
| Exact Pr >= S | 0.3018 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.0816 |
| ASE | 0.1361 |
| 95% Lower Conf Limit | -0.1852 |
| 95% Upper Conf Limit | 0.3484 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q19 by test2q19 | | | |
|---|---|---|---|
| test1q19 | test2q19 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 2<br>3.17<br>25.00<br>50.00 | 6<br>9.52<br>75.00<br>10.17 | 8<br>12.70 |
| 1 | 2<br>3.17<br>3.64<br>50.00 | 53<br>84.13<br>96.36<br>89.83 | 55<br>87.30 |
| Total | 4<br>6.35 | 59<br>93.65 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q19 by test2q19***

| McNemar's Test | |
|---|---|
| Statistic (S) | 2.0000 |
| DF | 1 |
| Asymptotic Pr > S | 0.1573 |
| Exact Pr >= S | 0.2891 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2717 |
| ASE | 0.1817 |
| 95% Lower Conf Limit | -0.0845 |
| 95% Upper Conf Limit | 0.6279 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q20 by test2q20 | | | |
|---|---|---|---|
| test1q20 | test2q20 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 12<br>19.05<br>33.33<br>80.00 | 24<br>38.10<br>66.67<br>50.00 | 36<br>57.14 |
| 1 | 3<br>4.76<br>11.11<br>20.00 | 24<br>38.10<br>88.89<br>50.00 | 27<br>42.86 |
| Total | 15<br>23.81 | 48<br>76.19 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q20 by test2q20***

| McNemar's Test | |
|---|---|
| Statistic (S) | 16.3333 |
| DF | 1 |
| Asymptotic Pr > S | <.0001 |
| Exact Pr >= S | 4.923E-05 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2025 |
| ASE | 0.0934 |
| 95% Lower Conf Limit | 0.0195 |
| 95% Upper Conf Limit | 0.3856 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q21 by test2q21 | | | |
|---|---|---|---|
| test1q21 | test2q21 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 3<br>4.76<br>27.27<br>75.00 | 8<br>12.70<br>72.73<br>13.56 | 11<br>17.46 |
| 1 | 1<br>1.59<br>1.92<br>25.00 | 51<br>80.95<br>98.08<br>86.44 | 52<br>82.54 |
| Total | 4<br>6.35 | 59<br>93.65 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

### *Statistics for Table of test1q21 by test2q21*

| McNemar's Test | |
|---|---|
| Statistic (S) | 5.4444 |
| DF | 1 |
| Asymptotic Pr > S | 0.0196 |
| Exact Pr >= S | 0.0391 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3384 |
| ASE | 0.1608 |
| 95% Lower Conf Limit | 0.0231 |
| 95% Upper Conf Limit | 0.6536 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q22 by test2q22 | | | |
|---|---|---|---|
| test1q22 | test2q22 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 15<br>23.81<br>38.46<br>83.33 | 24<br>38.10<br>61.54<br>53.33 | 39<br>61.90 |
| 1 | 3<br>4.76<br>12.50<br>16.67 | 21<br>33.33<br>87.50<br>46.67 | 24<br>38.10 |
| Total | 18<br>28.57 | 45<br>71.43 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q22 by test2q22***

| McNemar's Test | |
|---|---|
| Statistic (S) | 16.3333 |
| DF | 1 |
| Asymptotic Pr > S | <.0001 |
| Exact Pr >= S | 4.923E-05 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2222 |
| ASE | 0.0931 |
| 95% Lower Conf Limit | 0.0398 |
| 95% Upper Conf Limit | 0.4047 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q23 by test2q23 | | | |
|---|---|---|---|
| test1q23 | test2q23 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 13<br>20.63<br>52.00<br>61.90 | 12<br>19.05<br>48.00<br>28.57 | 25<br>39.68 |
| 1 | 8<br>12.70<br>21.05<br>38.10 | 30<br>47.62<br>78.95<br>71.43 | 38<br>60.32 |
| Total | 21<br>33.33 | 42<br>66.67 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q23 by test2q23***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.8000 |
| DF | 1 |
| Asymptotic Pr > S | 0.3711 |
| Exact Pr >= S | 0.5034 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3182 |
| ASE | 0.1219 |
| 95% Lower Conf Limit | 0.0793 |
| 95% Upper Conf Limit | 0.5571 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q24 by test2q24 | | | |
|---|---|---|---|
| test1q24 | test2q24 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 3<br>4.76<br>25.00<br>27.27 | 9<br>14.29<br>75.00<br>17.31 | 12<br>19.05 |
| 1 | 8<br>12.70<br>15.69<br>72.73 | 43<br>68.25<br>84.31<br>82.69 | 51<br>80.95 |
| Total | 11<br>17.46 | 52<br>82.54 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q24 by test2q24***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.0588 |
| DF | 1 |
| Asymptotic Pr > S | 0.8084 |
| Exact Pr >= S | 1.0000 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.0962 |
| ASE | 0.1387 |
| 95% Lower Conf Limit | -0.1756 |
| 95% Upper Conf Limit | 0.3680 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q25 by test2q25 | | | |
|---|---|---|---|
| test1q25 | test2q25 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 0<br>0.00<br>0.00<br>0.00 | 10<br>15.87<br>100.00<br>16.67 | 10<br>15.87 |
| 1 | 3<br>4.76<br>5.66<br>100.00 | 50<br>79.37<br>94.34<br>83.33 | 53<br>84.13 |
| Total | 3<br>4.76 | 60<br>95.24 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

### *Statistics for Table of test1q25 by test2q25*

| McNemar's Test | |
|---|---|
| Statistic (S) | 3.7692 |
| DF | 1 |
| Asymptotic Pr > S | 0.0522 |
| Exact Pr >= S | 0.0923 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | -0.0791 |
| ASE | 0.0369 |
| 95% Lower Conf Limit | -0.1513 |
| 95% Upper Conf Limit | -0.0068 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q26 by test2q26 | | | |
|---|---|---|---|
| test1q26 | test2q26 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 3<br>4.76<br>17.65<br>33.33 | 14<br>22.22<br>82.35<br>25.93 | 17<br>26.98 |
| 1 | 6<br>9.52<br>13.04<br>66.67 | 40<br>63.49<br>86.96<br>74.07 | 46<br>73.02 |
| Total | 9<br>14.29 | 54<br>85.71 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q26 by test2q26***

| McNemar's Test | |
|---|---|
| Statistic (S) | 3.2000 |
| DF | 1 |
| Asymptotic Pr > S | 0.0736 |
| Exact Pr >= S | 0.1153 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.0541 |
| ASE | 0.1229 |
| 95% Lower Conf Limit | -0.1869 |
| 95% Upper Conf Limit | 0.2950 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q27 by test2q27 | | | |
|---|---|---|---|
| test1q27 | test2q27 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 59<br>93.65<br>98.33<br>96.72 | 1<br>1.59<br>1.67<br>50.00 | 60<br>95.24 |
| 1 | 2<br>3.17<br>66.67<br>3.28 | 1<br>1.59<br>33.33<br>50.00 | 3<br>4.76 |
| Total | 61<br>96.83 | 2<br>3.17 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q27 by test2q27***

| McNemar's Test | |
|---|---|
| Statistic (S) | 0.3333 |
| DF | 1 |
| Asymptotic Pr > S | 0.5637 |
| Exact Pr >= S | 1.0000 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3762 |
| ASE | 0.2831 |
| 95% Lower Conf Limit | -0.1787 |
| 95% Upper Conf Limit | 0.9312 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q28 by test2q28 | | | |
|---|---|---|---|
| test1q28 | test2q28 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 9<br>14.29<br>60.00<br>45.00 | 6<br>9.52<br>40.00<br>13.95 | 15<br>23.81 |
| 1 | 11<br>17.46<br>22.92<br>55.00 | 37<br>58.73<br>77.08<br>86.05 | 48<br>76.19 |
| Total | 20<br>31.75 | 43<br>68.25 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q28 by test2q28***

| McNemar's Test | |
|---|---|
| Statistic (S) | 1.4706 |
| DF | 1 |
| Asymptotic Pr > S | 0.2253 |
| Exact Pr >= S | 0.3323 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.3327 |
| ASE | 0.1279 |
| 95% Lower Conf Limit | 0.0821 |
| 95% Upper Conf Limit | 0.5833 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q29 by test2q29 | | | |
|---|---|---|---|
| test1q29 | test2q29 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 6<br>9.52<br>28.57<br>50.00 | 15<br>23.81<br>71.43<br>29.41 | 21<br>33.33 |
| 1 | 6<br>9.52<br>14.29<br>50.00 | 36<br>57.14<br>85.71<br>70.59 | 42<br>66.67 |
| Total | 12<br>19.05 | 51<br>80.95 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q29 by test2q29***

| McNemar's Test | |
|---|---|
| Statistic (S) | 3.8571 |
| DF | 1 |
| Asymptotic Pr > S | 0.0495 |
| Exact Pr >= S | 0.0784 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1600 |
| ASE | 0.1245 |
| 95% Lower Conf Limit | -0.0840 |
| 95% Upper Conf Limit | 0.4040 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q30 by test2q30 | | | |
|---|---|---|---|
| test1q30 | test2q30 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 5<br>7.94<br>21.74<br>62.50 | 18<br>28.57<br>78.26<br>32.73 | 23<br>36.51 |
| 1 | 3<br>4.76<br>7.50<br>37.50 | 37<br>58.73<br>92.50<br>67.27 | 40<br>63.49 |
| Total | 8<br>12.70 | 55<br>87.30 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q30 by test2q30***

| McNemar's Test | |
|---|---|
| Statistic (S) | 10.7143 |
| DF | 1 |
| Asymptotic Pr > S | 0.0011 |
| Exact Pr >= S | 0.0015 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1653 |
| ASE | 0.1094 |
| 95% Lower Conf Limit | -0.0492 |
| 95% Upper Conf Limit | 0.3798 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q31 by test2q31 | | | |
|---|---|---|---|
| test1q31 | test2q31 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 9<br>14.29<br>36.00<br>52.94 | 16<br>25.40<br>64.00<br>34.78 | 25<br>39.68 |
| 1 | 8<br>12.70<br>21.05<br>47.06 | 30<br>47.62<br>78.95<br>65.22 | 38<br>60.32 |
| Total | 17<br>26.98 | 46<br>73.02 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q31 by test2q31***

| McNemar's Test | |
|---|---|
| Statistic (S) | 2.6667 |
| DF | 1 |
| Asymptotic Pr > S | 0.1025 |
| Exact Pr >= S | 0.1516 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.1581 |
| ASE | 0.1228 |
| 95% Lower Conf Limit | -0.0825 |
| 95% Upper Conf Limit | 0.3988 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

| Table of test1q32 by test2q32 | | | |
|---|---|---|---|
| test1q32 | test2q32 | | |
| Frequency<br>Percent<br>Row Pct<br>Col Pct | 0 | 1 | Total |
| 0 | 19<br>30.16<br>51.35<br>79.17 | 18<br>28.57<br>48.65<br>46.15 | 37<br>58.73 |
| 1 | 5<br>7.94<br>19.23<br>20.83 | 21<br>33.33<br>80.77<br>53.85 | 26<br>41.27 |
| Total | 24<br>38.10 | 39<br>61.90 | 63<br>100.00 |
| Frequency Missing = 4 | | | |

***Statistics for Table of test1q32 by test2q32***

| McNemar's Test | |
|---|---|
| Statistic (S) | 7.3478 |
| DF | 1 |
| Asymptotic Pr > S | 0.0067 |
| Exact Pr >= S | 0.0106 |

| Simple Kappa Coefficient | |
|---|---|
| Kappa | 0.2990 |
| ASE | 0.1083 |
| 95% Lower Conf Limit | 0.0867 |
| 95% Upper Conf Limit | 0.5113 |

***Effective Sample Size = 63***
***Frequency Missing = 4***

## WPI Department Heads/Design Professors interview questions:

1) What design classes are taught in your department?
2) Who teaches them?
3) How is design taught in your department? i.e., is any particular pedagogical method or structure used to teach design in your department?
4) What design concepts should students learn throughout the curriculum?
5) Are you aware of any reforms or studies regarding the Engineering Design Curriculum taking place at WPI or any other institution in the country that you could refer us to?
6) Can you suggest any current MQP group in your department that uses design that you think could be helpful to our project?
7) How do you teach design? i.e., do you use any particular pedagogical method or structure to teach your design class?
8) What textbook(s) do you use?
9) Is it possible to have a look into your syllabus?
10) What design concepts do you expect students to learn from your class?
11) Have you advised or are you currently advising MQP groups that include design in their project?
12) How do you think the MQP helps students have a better grasp of design concepts?

### Prof. G (AE capstone design course) 2012 interview notes:

- Project-based methodology: design of an aircraft
- Project is a term long (C term)
- Only conceptual or paper design, no fabrication involved (time constraint)
- Includes the following design process steps:
  - Specifications
  - Social-Technical aspects (economics, environment, social, political, ethical, health and safety, manufacturability, sustainability…)
  - Detailed Analysis (with design optimization/iteration)
  - Detailed Drawings (detailed three-view + isometric)
  - Deliverables (written report + oral presentation)
- Textbook: Aircraft Design: A Conceptual Approach, Daniel P. Raymer, 4$^{th}$ Edition, AIAA

### Prof. H (AE capstone design course) 2012 interview notes:

- Project-based methodology: design of a space mission
- Project is a term long
- Basic building blocks of a spacecraft
- Students propose configuration and select tools: propulsion; power; attitude
- Homework is given as stand-alone exercises serving as foundation for the project
- Design process mostly revolves around Analysis and Decision Making: selections, estimates, and iterations
- No testing and evaluation involved (time constraint)
- Use figures of merit as a comparative method of quantitative values

- 2 textbooks: "Space Systems Engineering, 4th Edition," by Fortescue, Swinerd, and Stark, (Wiley, 2011); and James R. Wertz and Wiley J. Larson (editors), *Spacecraft Mission Analysis and Design 3rd ed.*, Microcosm Press, 1999

**Prof. I (BME design professor and department head) 2012 interview notes:**

- Students first experience the design process in BME 3300 offered during junior year, which prepares them for the MQP. Students must take BME 3300 prior to taking the MQP.
- BME 3300 is a lecture-based/project-based design class. The prescribed design process is the *Dym and Little Design Model:* Problem Definition; Conceptual Design; Preliminary Design; Detailed Design; Design Communication
    - Students spend the first-half of the course learning the design process from the textbook
    - In the latter half of the course students do a project which covers all the phases in the Dym and Little Design Model:
        - They're split in 2 groups:
            - Biology
            - Technology (instrumentation)
    - Each design phase receives the same focus and is equally graded
    - Students must provide a written report for each design phase
- Textbook: *Engineering Design, A project-based introduction, 3rd edition,* by Clive L. Dym and Pratick Little

**Prof. J (ME design professor and former department head) 2012 interview notes:**

- The design curriculum in the ME department is structured in the following manner: Students are first introduced to the design process during freshman year in ES 1020, and then continue in sophomore year in ME 2300. Depending on their topic choice (Mechanical/Thermo-fluid design) students take during junior year 3000 level classes as pre-requisites to their senior year capstone design classes in either Mechanical or Thermo-fluid design.
- ES 1020 is a project-based course: students go through the entire design process. They design, build, test, work, and report (oral and written reports) their design in order to pass the course.
    - The prescribed design process is the *Voland Design Model:* Needs assessment; Problem formulation; Abstraction and synthesis; Analysis; Implementation
    - A class of 48 students is structured into 12 project groups
    - Textbook: *Engineering by Design, 2nd edition,* by Gerard Voland
- In ME 2300, students do a project to further develop the concepts introduced during ES 1020, with particular emphasis on company-based model: 4-person team with each member occupying the roles of CEO, Technical Officer, Chief Officer, Manufacturing Officer:
    - Class meets 3 times a week with 2hr labs. Each lab section has 20 students
    - Grading policy includes Peer and Self-Evaluation
    - Weekly reading-based quizzes are assigned
    - Three progress reports are presented to a Board of Directors
    - Design reports are expected
    - Oral presentation

- Written report
- Students participate in a competition established by former alumnus Robert Grant: team projects are judged by an independent jury. A sum of $ 1500USD is distributed among the teams

**Prof. K (ECE professor representing ECE department head for the occasion) 2012 interview notes:**

- Design curriculum in the ECE department is structured such that students are first introduced to design during their junior year in ECE 2799, which serves as basis/preparation to the MQP
- ECE 2799 is project-based/company-based design class
- Most of the MQPs are company sponsored
  - Progress reports are presented to the companies
  - Emphasis on creativity (Orchard analogy):
    - Background research
    - Brainstorm
    - Choose solution
    - Eliminate complexity
    - Impose time constraint
    - Implement design
  - Literature research first, then, brainstorming
  - Uses decision making methods such pair-wise comparison and decision matrix
  - Students should embrace failure and see it as a learning opportunity
- WPI is more manufacture oriented

**Prof. L (ECE design professor) 2012 interview notes:**

- Design process prescribed to this class is the Voland Design Model
- However, this design model is too simplistic because it:
  - Misses iterations, and not cyclic enough
  - Not enough feedback between design phases
- Most designs miss the needs
- Polarized design, i.e. niche markets. Less design requirements
- Not fear failure
- Students choose project themes (safety, energy harvesting…):
  - Students figure out target
  - Specifications
- Most important phase is the problem identification: customer requirements from customer's point of view. Usually, these requirements are qualitative and students are responsible for setting up technical specifications that meet customer's qualitative requirements
- Students ask customer to prioritize the specifications
- Initially, students do brainstorming. Then, they do literature review of former designs
- Students spend a fair amount of time with previous designs
- No textbook is assigned to this class. But many resources are made available to students
- Design is mostly practical, experiential

- On first day of class:
  - Students are asked to provide their commitment level
  - To determine their skill level
  - Assemble the groups
- 3 sections: 6 groups per section

## University X professor interview questions:

1) How was Engineering Design curriculum structured at University X? (E.g. design classes are taught prior to senior year projects)
2) What design classes were taught in Mechanical, Aerospace, and Materials departments at University X?
3) How was design taught in Mechanical, Aerospace, and Materials departments at University X? Was there any particular pedagogical method used to teach design classes? (E.g. project-based methodology)
4) Was there a unique pedagogical method per department or did all departments share a common methodology?
5) In general, what design concepts were taught in ME, AE, and Materials departments at University X?
6) Did each department emphasize specific design concepts?
7) What textbooks were used to teach design concepts in those departments?
8) Is there someone at University X you could direct us to for further information?
9) Are you aware of any reforms or studies regarding Engineering Design Curriculum taking place at other institutions in the country that you could refer us to?
10) Did you teach any design class at University X?
11) How did you teach design? That is, did you base your teachings on your experience as an engineer and on your understanding of design concepts (experiential approach); or, did you use a pedagogical method that is commonly accepted by the academic community (structured approach)?
12) Is it possible to obtain a syllabus of the class you taught?
13) What design concepts did you expect students to learn from your class?
14) If you used projects to teach design, how did they help students understand the design concepts?

### Prof. M (University X thermal design professor and ME/AE/MATERIALS department head) 2012 interview notes:

- In the ME/AE/MATERIALS department at University X, engineering design is embedded in a 4-year curriculum
- Intention to show good/bad design. E.g.: Design of motorcycle engine includes concepts from various fields such as Fluid mechanics, Heat transfer, Solid mechanics
- During their 3rd semester, students are exposed to topics related ME
- Every senior student is required to take both Thermal systems design and Machine design capstone courses:

- *Design of Thermal system (Fall course):* this is a lecture-oriented course where:
  - Teams of 5 members act as a consultant company
  - Students elaborate a bid/tender
  - Students provide a fully detailed design
  - Students present their design
  - Students optimize their design
- *Machine design (Spring course):* Projects with teams of 5 students where:
  - Students perform studio activities
  - Students have to determine the requirements on their own
  - They must first brainstorm before doing in depth literature research
  - Students follow the entire design process
  - Students build a prototype

➢ Also, students must take 2 IPRO's (Inter-professional Projects Program) courses, each worth 3 credit hours. An IPRO course is a team-based project that brings students from various concentrations and disciplines to work together to solve a real-world problem. Usually, IPRO's vary from sophomore to graduate levels:
  - Provide greater insight in lawful and ethical aspects of the products built by students
  - Not many off-campus IPRO's. Although, some go overseas

➢ ME 232 was included in the curriculum as an incentive to students to be more knowledgeable about global issues

## University Y Professor interview questions:

1) How is Engineering Design curriculum structured at University Y? (E.g. design classes are taught prior to senior year projects)
2) What design classes are taught in Mechanical and Aerospace departments at University Y?
3) How is design taught in Mechanical and Aerospace departments at University Y? Is there any particular pedagogical method used to teach design classes? (E.g. project-based methodology)
4) Is there a unique pedagogical method per department or do all departments share a common methodology?
5) In general, what design concepts are taught in ME and AE department at University Y?
6) What textbooks are used to teach design concepts?
7) Have there been any changes/reforms in the ME/AE design curriculum in recent years?
8) Are you aware of any similar changes to other departments such as Electrical or Biomolecular Engineering?
9) Do you teach any design class at University Y?
   a. If your answer to question 9 is yes:
      i. How do you teach design? That is, do you base your teachings on your experience as an engineer and on your understanding of design concepts (experiential approach); or, do you use a pedagogical method that is commonly accepted by the academic community (structured approach)?

ii. Do you use a particular design model for your class? What design concepts do you expect students to learn from your class?

iii. If you use projects to teach design, how do they help students understand the design concepts?

iv. Is it possible to obtain a syllabus of the design class you teach?

b. If your answer to question 9 is no:

i. Can you refer us to a design Professor who could help us in our project?

10) We understand that you were involved in a curriculum reform effort at the University of Michigan several years ago. Can you please comment on that effort, and the role of design in reshaping the curriculum?

### Prof. N (University Y professor and ME/AE department chairman) 2012 interview notes:

- In the ME/AE department at University Y, the design curriculum is structured such that students take an Introduction to Engineering class during freshman year. This is a two-semester course. Then, during junior year, students take a Design of Machine Elements class and an Electrical Engineering class called Programming of Micro-processors. In senior year, students take a lecture-note-based design class called Design Methodology. They also do their capstone design project, wherein concepts learned in Programming of Micro-processors are fully used.
- Textbooks:
  - Freshman: Introduction to Engineering: *Modeling and Problem Solving* by Jay Brockman, John Wiley & Sons, 2008
  - Junior: *Fundamentals of Machine Elements, 2nd edition,* by Bernard Hamrock, Steven Schmid, Bo Jacobson

## Round I Survey questions:

**1) Are you a senior student, or a graduate student?**

- Senior
- Graduate

**2) If you're a senior student, are you currently in a MQP group?**

- Yes
- No
- N/A

**3) If you're a graduate student, did you submit your MQP between Terms A, 2010 and D, 2011?**

- Yes
- No
- N/A

**4) What's your department?**

- ME
- BME
- AE
- ECE
- Other

**5) Provide a brief description of your MQP?**

- Paragraph text answer (300 words)

**6) Did you use design in your MQP?**

- Yes
- No

**7) If you answered yes to question 6, then, which of the following design concepts did you use during your MQP (only check those concepts below that apply specifically to your MQP)?**

- *Clarification of the requirements*, i.e. to clearly specify the purposes that the intended final product is to serve, from referring back to Customer's/Project Advisor's/Sponsor's information;
- *Identification of the environment*, i.e. to determine the environment within which the intended final product is to operate;
- *Analysis and modeling*, i.e. to describe and model the behavior of the intended final product;
- *Identification of the constraints*, i.e. to take a closer look to manufacturing, economic, marketing, and other constraints that may condition the feasibility of the intended final product;
- *Testing and evaluation*, i.e. to assess the level of performance of the intended final product;
- *Refining and optimization*, i.e. to perform a set of adjustments and refining so that the intended final product meet the requirements more efficiently;
- *Documentation*, i.e. to produce the necessary set of documents that presents the fabrication specifications to the Customer/Project Advisor/Sponsor.

**8) Have you taken any design classes prior to your MQP?**

- Yes
- No

**9) If you answered yes to question 8, please, tell us which courses did you take? And in what year were you when you took them (e.g. ME4770 – Aircraft Design, Senior year…)?**

- Paragraph text answer (300 words)

**10) If you haven't taken any design class prior to your MQP and have used during your MQP (some of or all) the design concepts mentioned in question 7, please, tell us where/how did you learn them (e.g. summer internship at GE, or through literary research, or any other source outside WPI)?**

- Paragraph text answer (300 words)

**11) If in question 10 you answered that you learned (some of or all) the design concepts listed in question 7 through literary research, please, provide us with at least one author along with the corresponding textbook/article you used?**

- Paragraph text answer (300 words)
- N/A

## Round II Survey questions:

**1) What's your department?**

- ME
- BME
- AE
- ECE
- Other

**3) Provide a brief description of your MQP.**

- Paragraph text

**4) What design phases, of the design process above, did you complete for your MQP project?**

- Problem Definition (Identification of needs, Clarification of requirements, List of specifications)
- Conceptual Design (Functional Decomposition; Generation of Design Alternatives, Evaluation of Design Alternatives)
- Preliminary Design (Analysis and Modeling, Testing and Evaluation).
- Detailed Design (Refining and Optimization)
- Design Communication (Documentation)

**5) In order to satisfy the Problem Definition phase you did the following:**

- Conducted a needs assessment, i.e. identified and validated the major needs your design must address by interviewing, surveying, or referring back to your project advisor/sponsor/customer.
- Created a list of specifications that comes in the form of categories such as performance, safety, manufacture, etc.
- Certified that the specifications were solution independent, i.e. that no bias occurred and favored one design solution over another.
- Identified measurable specifications and target values.
- Defined design objectives using pairwise comparison, i.e. prioritized the specifications in order of importance.

**6) The list of specifications determined during the Problem Definition phase of your project included (but not exclusively) the following categories:**

- Performance
- Geometry
- Weight
- Materials
- Energy

- Time
- Cost
- Manufacture
- Standards
- Safety
- Transportation
- Ergonomics
- Modularity
- Adjustability
- Robustness

**7) To satisfy the Conceptual Design phase you did the following:**

- Evaluated and selected the best design solution using a decision matrix, i.e. different design solutions were judged according to the importance of specifications and to how well they satisfied each specification.
- Decomposed the defined problem into more manageable tasks (or subsystems).
- Generated at least three fundamentally different design solutions in the form of simple sketches in order to represent how the design works.
- Combined subsystem solutions to form a total design.

**8) To satisfy the Preliminary Design phase you did the following:**

- Applied mathematical models to predict overall performance.
- Constructed scaled replicas or physical representations (such as a model or breadboard circuit) to check functionality of the component.
- Experimented on aspects of the design solution that you were unsure of, i.e. identified design aspects and their performances with high degree of uncertainty and associated them with physical variables (speed, force, time, voltage, current, program complexity…) that could be measured and varied by means of simple experiments.
- Documented testing and experimental results in form of graphs or tables.

**9) To satisfy the Detailed Design Phase you did the following:**

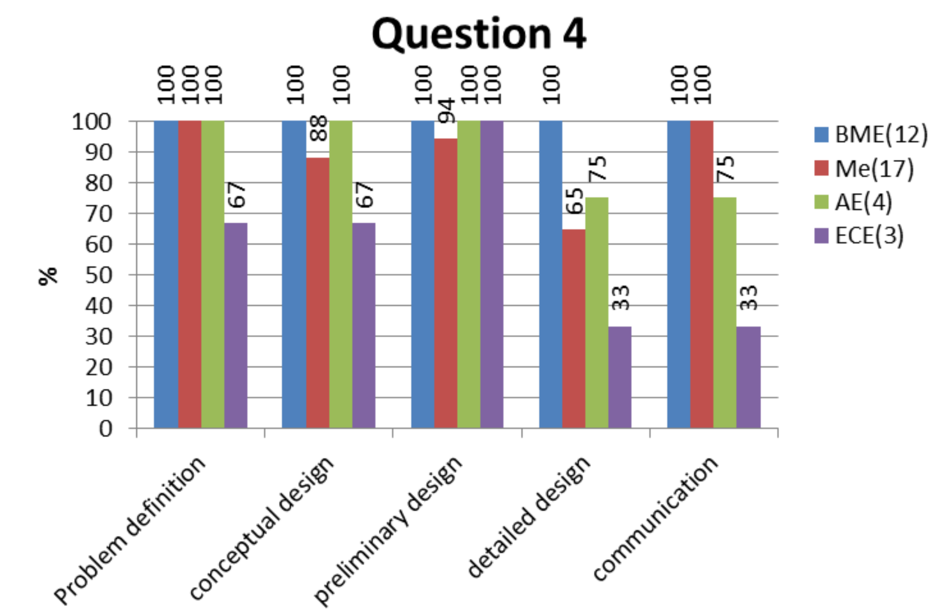
- Built/Ran (for software design) a prototype.
- Evaluated prototype performance by measuring one or more metrics, i.e. measurable quantities such as time, speed, applied force, voltage, current, program size, program complexity.
- Specified dimensions on multiple orthogonal views/ software detailed codes/ circuit voltage, current, signal type.
- Provided detailed drawings/ software-architecture/ circuit-diagrams.
- Specified materials, part types, programming languages, circuit components, interfaces, and fabrication/assembly directions.
- Refined prototype parameters.
- Performed optimization studies, i.e. determined optimum values for the parameters that best help the prototype meet design objectives.

- Repeated analysis to further refine dimensions/ number of code lines or complexity/ circuit voltage, current.

**10) After answering all the previous questions, what design phases did you actually complete for your MQP project?**

- Problem Definition (Identification of needs, Clarification of requirements, List of specifications)
- Conceptual Design (Functional Decomposition; Generation of Design Alternatives, Evaluation of Design Alternatives)
- Preliminary Design (Analysis and Modeling, Testing and Evaluation).
- Detailed Design (Refining and Optimization).
- Design Communication (Documentation).

## Round II Survey Results




**What design phases, of the design process above, did you complete for your MQP project?**

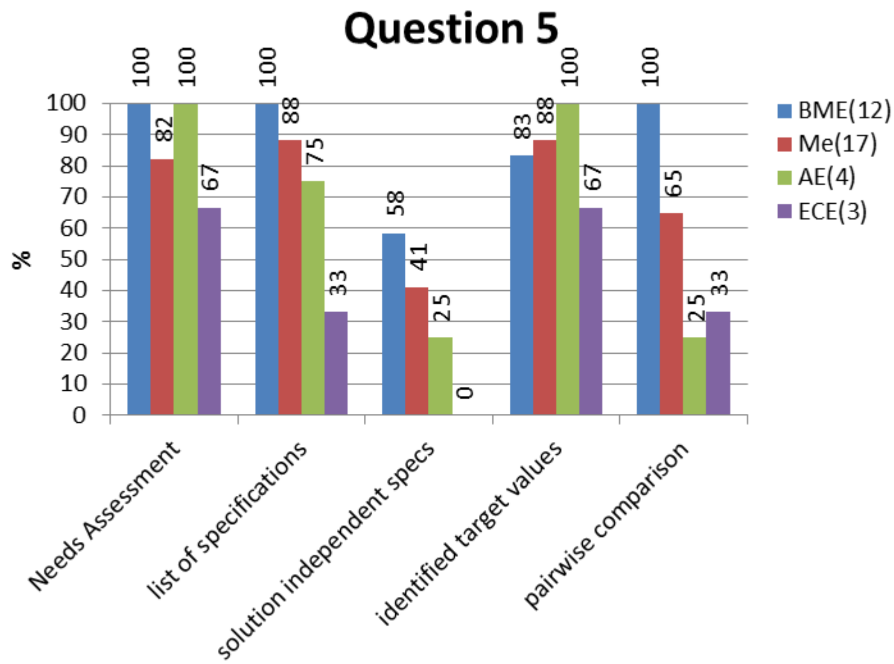
✓ Problem Definition (Identification of needs, Clarification of requirements, List of specifications).

✓ Conceptual Design (Functional Decomposition; Generation of Design Alternatives, Evaluation of Design Alternatives).

✓ Preliminary Design (Analysis and Modeling, Testing and Evaluation).

✓ Detailed Design (Refining and Optimization).

✓ Design Communication (Documentation).




**In order to satisfy the Problem Definition phase you did the following:**

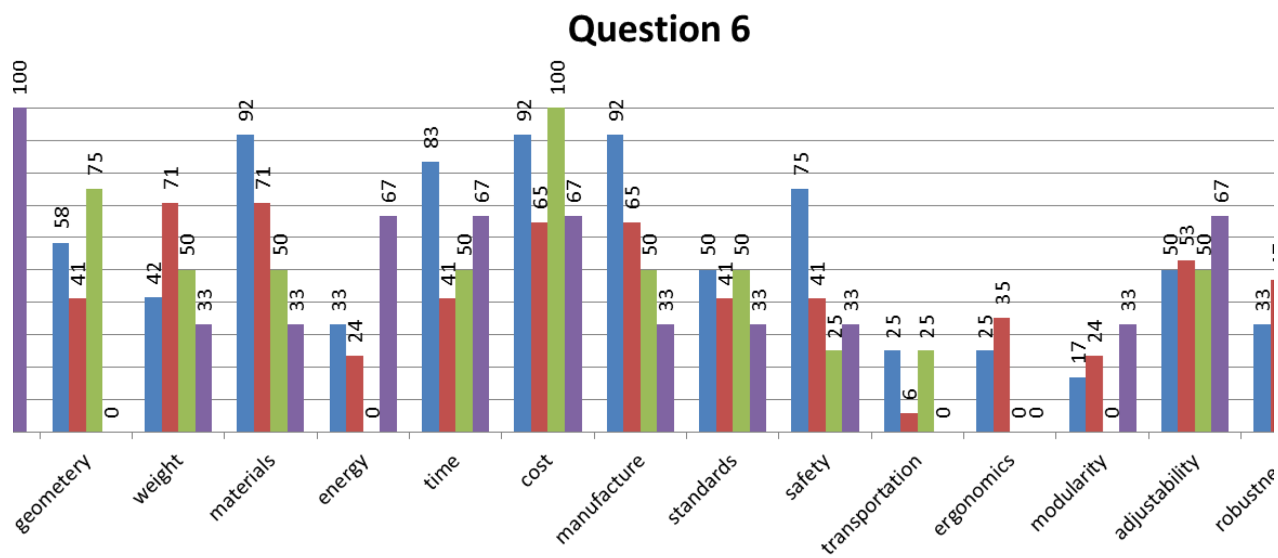
✓ Conducted a needs assessment, i.e. identified and validated the major needs your design must address by interviewing, surveying, or referring back to your project advisor/sponsor/customer.

✓ Created a list of specifications that comes in the form of categories such as performance, safety, manufacture, etc.

✓ Certified that the specifications were solution independent, i.e. that no bias occurred and favored one design solution over another.

✓ Identified measurable specifications and target values.

✓ Defined design objectives using pairwise comparison, i.e. prioritized the specifications in order of importance.




**pecifications determined during the Problem Definition phase of your project included (but not exclusively) the following**

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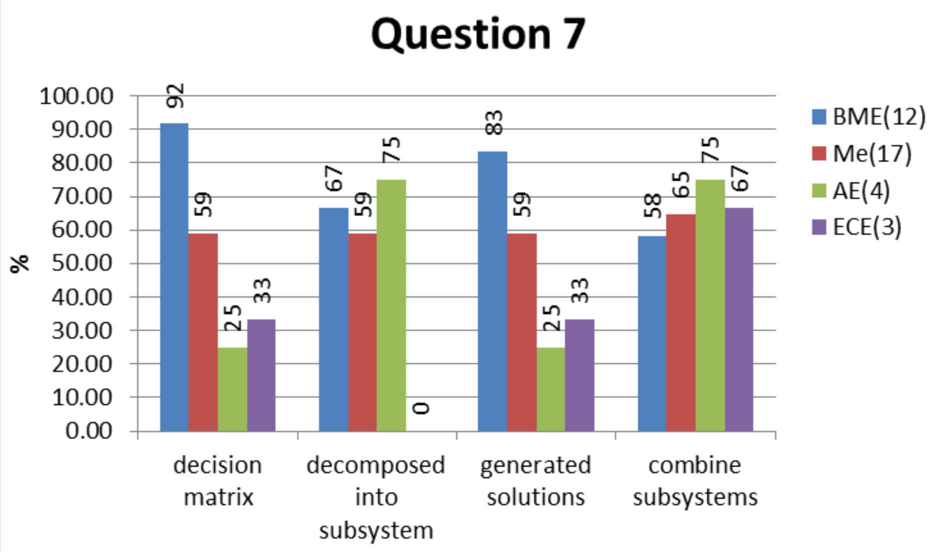


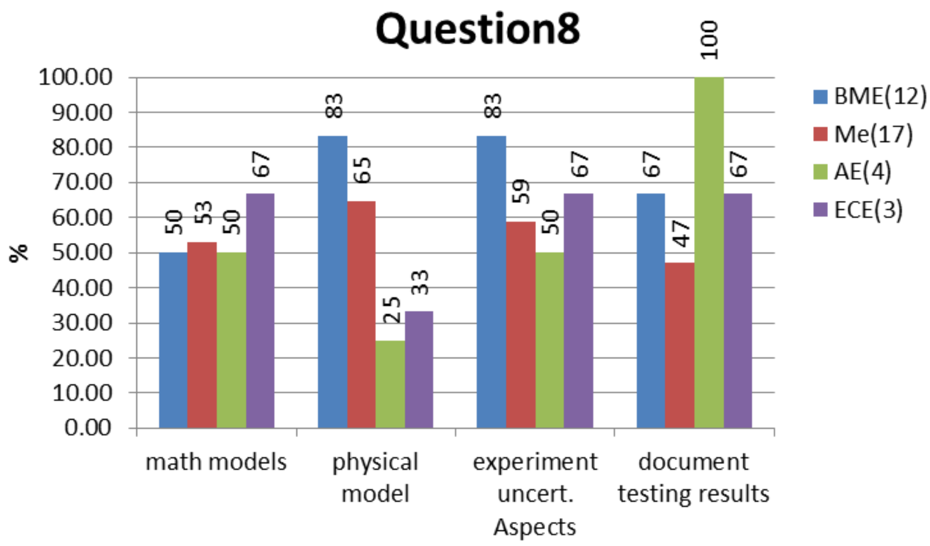

**To satisfy the Conceptual Design phase you did the following:**

✓ Evaluated and selected the best design solution using a decision matrix, i.e. different design solutions were judged according to the importance of specifications and to how well they satisfied each specification.

✓ Decomposed the defined problem into more manageable tasks (or subsystems).

✓ Generated at least three fundamentally different design solutions in the form of simple sketches in order to represent how the design works.

✓ Combined subsystem solutions to form a total design.




**To satisfy the Preliminary Design phase you did the following:**

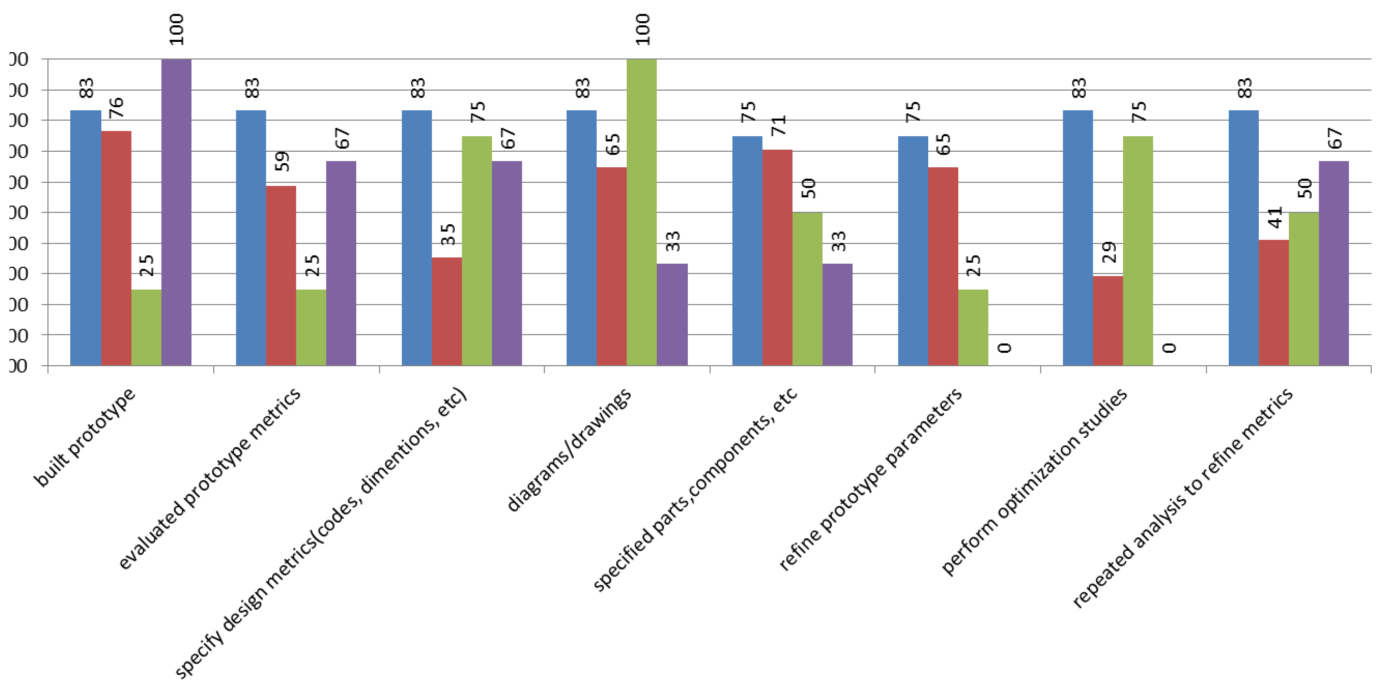
✓ Applied mathematical models to predict overall performance.

✓ Constructed scaled replicas or physical representations (such as a model or breadboard circuit) to check functionality of the component.

✓ Experimented on aspects of the design solution that you were unsure of, i.e. identified design aspects and their performances with high degree of uncertainty and associated them with physical variables (speed, force, time, voltage, current, program complexity…) that could be measured and varied by means of simple experiments.

✓ Documented testing and experimental results in form of graphs or tables.

## Question 9




**To satisfy the Detailed Design Phase you did the following:**

✓ Built/Ran (for software design) a prototype.

✓ Evaluated prototype performance by measuring one or more metrics, i.e. measurable quantities such as time, speed, applied force, voltage, cu
program size, program complexity.

✓ Specified dimensions on multiple orthogonal views/ software detailed codes/ circuit voltage, current, signal type.

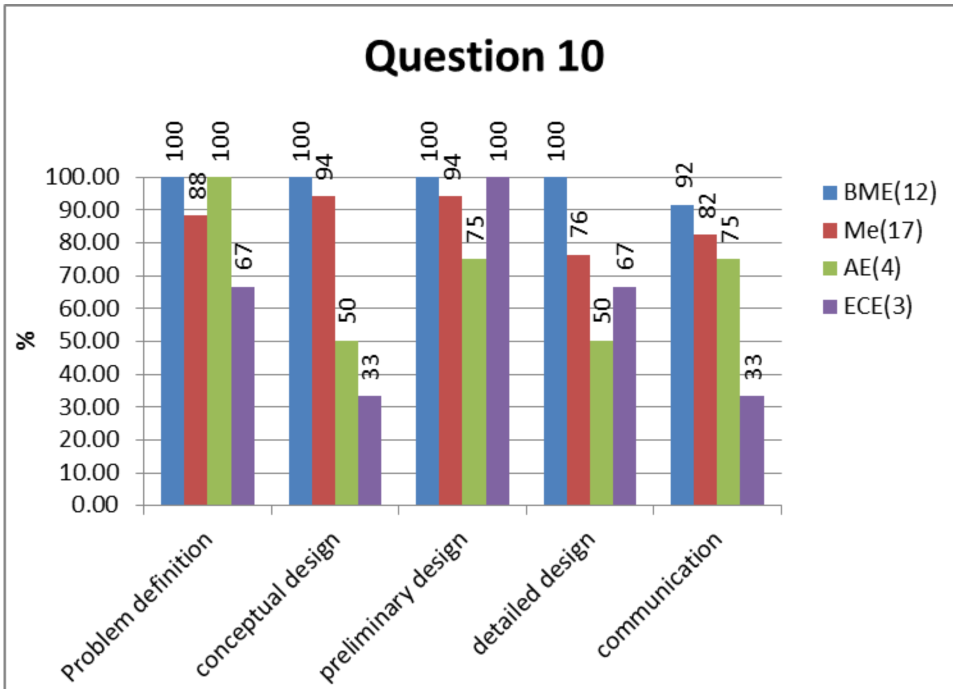
✓ Provided detailed drawings/ software-architecture/ circuit-diagrams.

✓ Specified materials, part types, programming languages, circuit components, interfaces, and fabrication/assembly directions.

✓ Refined prototype parameters.

✓ Performed optimization studies, i.e. determined optimum values for the parameters that best help the prototype meet design objectives.

✓ Repeated analysis to further refine dimensions/ number of code lines or complexity/ circuit voltage, current.




**After answering all the previous questions, what design phases did you actually complete for your MQP project?**

✓ Problem Definition (Identification of needs, Clarification of requirements, List of specifications)

✓ Conceptual Design (Functional Decomposition; Generation of Design Alternatives, Evaluation of Design Alternatives)

✓ Preliminary Design (Analysis and Modeling, Testing and Evaluation).

✓ Detailed Design (Refining and Optimization).

✓ Design Communication (Documentation).