2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #36920

Design Across the Curriculum: Improving Design Instruction in a Mechanical Engineering Program.

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Introduction

Engineering design is a critical learning outcome for a mechanical engineering curriculum. ABET requires that Mechanical Engineering programs demonstrate that graduating students have "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."[1] Design has also been identified as a curricular pillar for modern engineering programs in recent reports such as in the MIT Engineering Department initiative on New Engineering Education Transformation report. [2]

Utah Valley University (UVU) recently created a new mechanical engineering Bachelor of Science degree program which has recently received full ABET accreditation. The original program structure followed a very traditional curricular model with limited input from faculty members, as the bulk of the faculty had not yet been hired at the time the program curriculum was initially developed. As new faculty have been hired and begun teaching in the program, their knowledge, and experiences at past institutions as well as a desire to improve on the traditional curriculum model has motivated the need to make curricular improvements. Specifically, there is an interest in improving how design is taught throughout the curriculum of the 4-year mechanical engineering program.

A preliminary study was previously conducted to assess the current state of how the design process was being taught in several courses across the mechanical engineering curriculum. [3] An important finding of the preliminary study was that students reported learning different design processes in their courses than they had previously seen. This showed a lack of continuity and consistency in how the design process is taught across the curriculum. Additionally, a review of different design processes was conducted to determine what model might be best suited for adoption as a standard process to be taught and referenced in courses across the curriculum.

The purpose of this study is 1) to evaluate the effectiveness of the current curriculum of a Mechanical Engineering program in helping students to learn and apply the design process and 2) to investigate and propose a curricular strategy for improving design instruction across the curriculum. A refined survey of current students in all four years of the program is presented and discussed to assess the current state of design instruction and its effectiveness in student comprehension of the design process. Additionally, a survey of faculty is included to better understand how design is incorporated into the current curriculum. Based on the survey assessments, a model for how to include and better reinforce the design process across the curriculum is proposed. This model will be implemented and evaluated in future works.

Design Process Survey

A survey was administered to students in the Fall 2022 semester in specific courses across the mechanical engineering curriculum to capture as many students in each year of the ME program as possible. One course from the freshman, sophomore, junior and senior years was identified in which to administer the survey. The courses were as follows: ENGR 1000 Introduction to

Engineering (first-year students), ENGR 2010 Engineering Mechanics: Statics (second-year students), ME 3010 Linear Systems (third-year students), and ME 4810 ME Capstone I (fourth-year students). These courses were chosen as they are required for all mechanical engineering students, and they were good indicators of how far the students had progressed through the mechanical engineering program. Also, it is very unlikely a student would be enrolled in more than one of those courses concurrently during a particular semester. Many students in this program do not strictly adhere to the suggested four-year flowchart so this classification system is intended to show how far a student has progressed rather than represent the actual number of years the student has been taking classes.

The complete survey can be found in Appendix A, totaling 15 questions. The survey was administered using Google Forms which presented each question sequentially and individually without the ability to go back and change previous answers. The first three questions are demographics questions to allow the authors to separate out non-mechanical engineering students and determine how far into the program the students are. Of the 258 total respondents, 193 were Mechanical Engineering students with 68 identified as first-year, 34 identified as second-year, 27 identified as third-year, and 64 identified as fourth-year. One plan for future improvements on the survey is to have separate surveys for each course, so students do not have to self-identify which course they are currently taking. This self-identification problem was an unexpected issue as the ME 4810 Capstone I course only had 54 enrolled students, yet 64 claimed they were currently taking ME 4810. Generally, the number of students matches the estimated enrollment for the mechanical engineering program in each year if some of the fourth-year students were actually third-year students. Note: the survey did not ask students to identify which year in the program they are in, only what course they were enrolled in, for which they were taking the survey.

The fifth question asked the students to state the design process steps in order according to how they are currently taught in the Introduction to Engineering and ME Capstone I courses. A summary of the student responses is shown in Table 1 and Figure 1. Interestingly, all four groups were able to correctly identify the first step, “Identify the Problem”, at a very high rate (more than 90%), with no other step being correctly identified by any group more than 40% of the time with one exception, fourth-year students correctly identifying “Generate Ideas” slightly over 50% of the time. Students of all groups were, however, quite good at identifying the distractors that were provided. In addition to the seven steps, four additional options were provided to the students to make sure they could differentiate between the engineering design process and the scientific method, as well as tasks generally associated with mechanical engineers. The distractors were generally identified with much more accuracy, with most groups achieving over 40%, and in many cases over 50% accuracy. Additionally, the first-year students were at or near the top for all four distractors and generally out-performed the second-year and third-year students. This result seems to support the hypothesis that students are generally learning the taught engineering design process in their first year but begin to forget the specifics in later years without any formal coverage of the design process in any courses taken during those years.

To better understand the students’ general ability to recollect the steps in the design process, a similar dataset was created by providing students credit for identifying the correct step +/- 1 spot. Students were marked correct if they were able to accurately identify a step in the engineering

design process, and listed that step in either the appropriate order, or off by only one spot. For example, a student who stated "Select a solution" as the fifth, sixth or seventh step was

Table 1 - Percent correct rates for students identifying the steps in the engineering design process

	% Correct			
Step	1st Year	2nd Year	3rd Year	4th Year
1. Identify the Problem	97.06%	91.18%	96.30%	98.44%
2. Define design criteria	16.18%	20.59%	22.22%	35.94%
3. Research/Gather data	16.18%	14.71%	11.11%	25.00%
4. Generate Ideas	19.12%	23.53%	18.52%	53.13%
5. Analyze Solutions & Test Models	17.65%	26.47%	18.52%	21.88%
6. Select a solution	13.24%	11.76%	18.52%	20.31%
7. Implement solution	16.18%	23.53%	25.93%	29.69%
State Hypothesis	69.12%	61.76%	55.56%	75.00%
Manufacturing & Assembly	47.06%	41.18%	37.04%	23.44%
Experiment to test hypothesis	60.29%	50.00%	55.56%	70.31%
Product maintenance	58.82%	44.12%	62.96%	57.81%

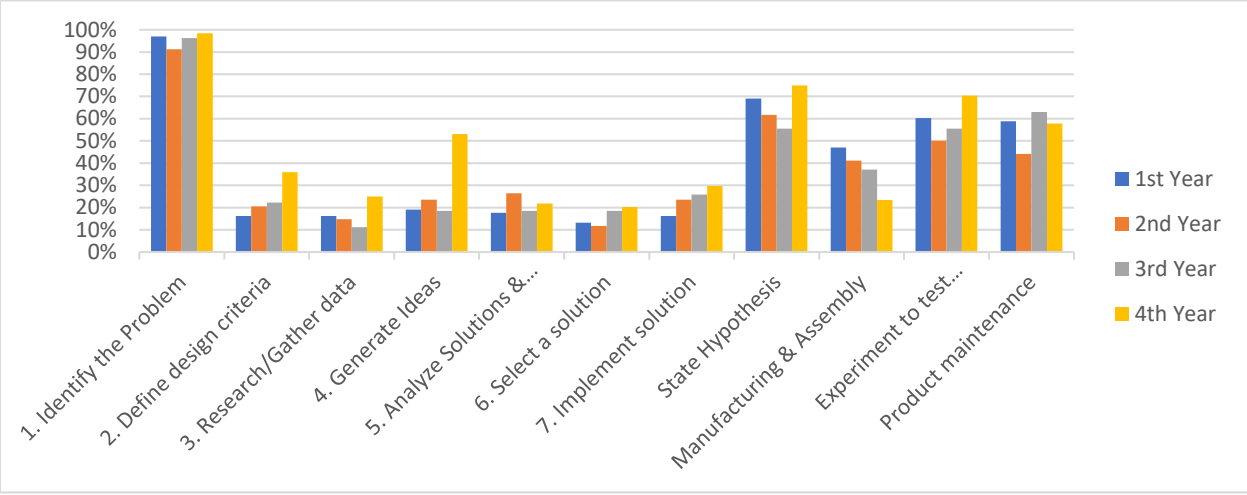

Figure 1 - Graphical representation of the student responses to identifying the engineering design process

counted as correct. These results are shown in Table 2 and Figure 2. As expected, students across all years were much more capable of identifying the steps in the design process within one spot of its correct location. The fourth-year students performed the best, with every step correctly identified to within one correct spot over 60% of the time. It would appear the majority of the fourth-year students mis-reported "Manufacturing and Assembly" as a step in the design process, causing many steps to become off by one spot. The students' general ability to understand what the steps are and roughly where they occur is encouraging, and would support the proposal of including more formal inclusion of a consistent design process across the curriculum in order to improve student understand and application of the engineering design process.

Table 2 - Percent correct rates for students identifying the steps in the engineering design process within one spot of their correct location

	% Correct			
Step	1st Year	2nd Year	3rd Year	4th Year
1. Identify the Problem	97.06%	97.06%	96.30%	100.00%
2. Define design criteria	47.06%	41.18%	59.26%	73.44%
3. Research/Gather data	63.24%	76.47%	74.07%	81.25%
4. Generate Ideas	41.18%	61.76%	55.56%	90.63%
5. Analyze Solutions & Test Models	50.00%	64.71%	51.85%	64.06%
6. Select a solution	45.59%	47.06%	55.56%	67.19%
7. Implement solution	32.35%	47.06%	55.56%	50.00%
State Hypothesis	69.12%	61.76%	55.56%	75.00%
Manufacturing & Assembly	47.06%	41.18%	37.04%	23.44%
Experiment to test hypothesis	60.29%	50.00%	55.56%	70.31%
Product maintenance	58.82%	44.12%	62.96%	57.81%

The 6th through 13th questions provided students with the correct seven steps to the engineering design process that is taught and asked to rate their opinion on statements related to that design process using a five-point Likert scale. Table 3 summarizes the students' responses by combining "agree" and "strongly agree" into one 'agree' category, as well as combining "disagree" and "strongly disagree" into one "disagree" category. Responses of "N/A" were omitted from the table. As expected, students overwhelming agreed that the design process was taught in the first- and fourth-year courses (Q6 results), whereas students in the second- and third-year courses generally agreed that a portion of the design process was taught in those courses (Q11 results). Similarly, nearly every first-year student agreed that the course improved

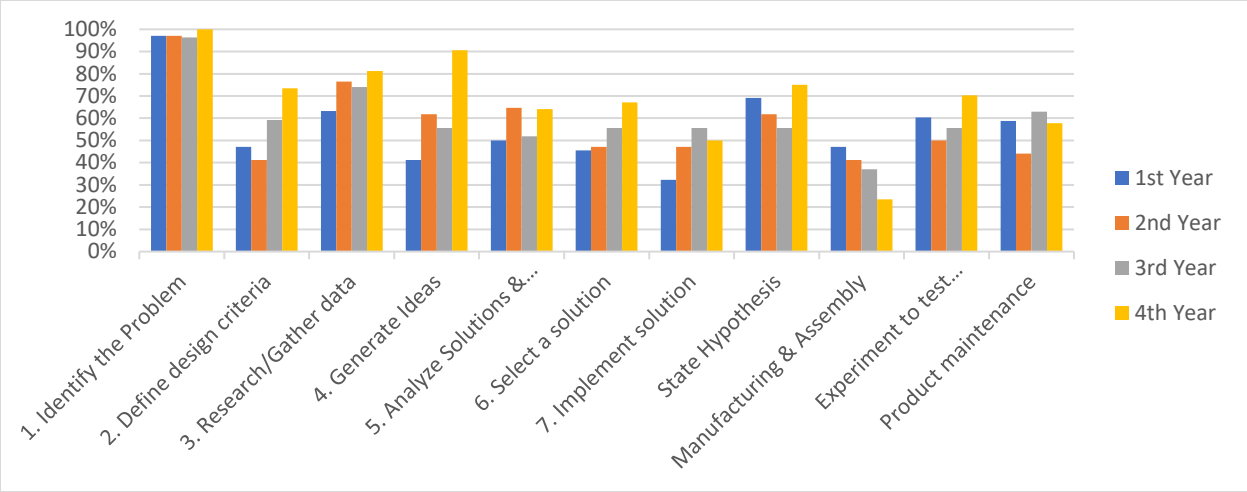

Figure 2 - Graphical representation of the student responses to identifying the engineering design process within one spot of their correct location

their understanding of the design process, along with more than 70% of fourth year students (Q12 results). Finally, a strong majority (78%) of first year students agreed that their instructor explained the engineering design process in a new way they had not seen before, with only 6% disagreeing what that statement. However, over 30% of second and third-year students and nearly 50% of fourth year students also agreed their instructor explained the design process in a new way, indicating that students are not receiving consistent instruction on the engineering design process across the curriculum (Q9 results).

Faculty Survey

The faculty of the ME program completed a survey to assess and summarize how the design process is currently being taught across the curriculum. The ME faculty is comprised of 7 full-time faculty members, 6 tenured or tenure-track and one lecturer. All faculty members completed the survey (Appendix B). The results of the survey are summarized in Table 4.

The ME program at UVU includes 23 mechanical engineering courses; 20 of these are core requirements and 3 are electives. The design process is taught in the first and fourth years of the program and faculty teaching those courses teach the same design process. The faculty were asked in which courses they currently teach the design process. They reported 10 different courses accounting for approximately 43% of the ME curriculum. Of those 10 courses, 7 are core requirements and 3 are electives. However, 3 of the 7 core classes are the introduction to design class and the two capstone design courses, all of which primarily focus on teaching and applying the design process. This leaves only 4 of the remaining 17 core courses (approximately 24%) which currently include instruction on the design process.

Of the 7 total faculty teaching courses in the ME program, 5 (or approximately 70%) reported that they specifically include instruction on the design process. However, when the faculty members were asked to describe the steps of the design process, there was little consistency to what was being taught, with one faculty member talking more generally about applications of

Table 3 - Summary results of questions 6 through 13 of the student survey

	Q6: The steps of the design process were taught in this class			Q7: The design process was presented in a way similar to one you had seen in at least one other class you took at XXXX.			Q8: You applied the majority of the design process on at least one assignment or project for this course.			Q9: Your instructor explained the design process in a new way you had not seen before.		
Year	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree
1	**94.1%**	2.9%	2.9%	39.7%	25.0%	5.9%	97.1%	0.0%	2.9%	**77.9%**	8.8%	5.9%
2	29.4%	26.5%	35.3%	35.3%	32.4%	2.9%	64.7%	17.6%	11.8%	**32.4%**	26.5%	26.5%
3	44.4%	22.2%	33.3%	40.7%	25.9%	25.9%	63.0%	14.8%	22.2%	**33.3%**	33.3%	33.3%
4	**90.6%**	7.8%	1.6%	70.3%	18.8%	9.4%	92.2%	4.7%	1.6%	**48.4%**	29.7%	20.3%

	Q10: If the design process was presented in a new way, the new process was helpful.			Q11: This class was focused on only a portion of the entire design process (i.e., analyze solutions and communicate your answers).			Q12: This class improved your understanding of the design process.			Q13: You are still confused about the steps of the design process.		
Year	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree	% agree	% Neither agree or disagree	% disagree
1	77.9%	8.8%	2.9%	32.4%	14.7%	48.5%	**97.1%**	0.0%	2.9%	7.4%	14.7%	64.7%
2	29.4%	35.3%	2.9%	**55.9%**	20.6%	14.7%	44.1%	32.4%	11.8%	14.7%	38.2%	38.2%
3	37.0%	40.7%	14.8%	**59.3%**	22.2%	18.5%	40.7%	37.0%	22.2%	29.6%	29.6%	33.3%
4	51.6%	25.0%	10.9%	26.6%	18.8%	43.8%	**71.9%**	17.2%	9.4%	14.1%	20.3%	51.6%

their classes. On average, these design projects account for 20% of the students' final grades, with a range of 10% to as much as 30%. Only one faculty member mentioned they might oppose having a standard design process taught across the ME curriculum. However, during department discussions, there were no faculty opposed. Also, 100% of faculty indicated that they would be willing to include the teaching of one or more steps of the design process in a class they teach that does not currently include instruction on the design process.

The results of the faculty survey reveal three main points about the current state of design process instruction. First, it appears that outside of the first- and fourth-year design courses, less than 25% of the core mechanical engineering courses include direct instruction on the design process. Also, while 70% of the faculty include some discussion of the design process in their courses, all faculty include some design project. This could indicate there is a need for additional and improved instruction on the design process across the curriculum. Second, there does not appear to be a common understanding across the faculty as to what the steps of the design process are or even what is meant by "the design process". And third, faculty seem open

to agreeing on a standard design process and working together on a strategy to incorporate design process instruction across the ME curriculum.

Curricular Strategy

There are three main components to the curricular strategy for teaching design across the curriculum of the mechanical engineering program. The first is to determine a standard form of the design process that will be taught to students during each year of their program. The second is to be explicit in where and how the design process is taught in each course the students take and to define design-specific learning outcomes for each course. The third is to assess student knowledge of the design process after the changes to the curriculum.

Table 4- Summary of Faculty Survey Results

Total courses in program	**23**	(20 core, 3 electives)
Courses teaching design	**43%**	(7 core, 3 electives; 3 cornerstone/capstone)
Faculty teaching design	**70%**	(Possibly 4)
Faculty incorporating design project	**100%**	(2 not teaching design process)
Weight of Design project (avg)	**20%**	(range of 10-30%)
Faculty Agreeing to standard process	**85%**	(no opposition in dept. discussion)
Willing to incorporate design process	**100%**	

In a previous work a review of a variety of design processes was presented. [3] From this and a review of other processes [4]–[11] , a basic framework was determined based on what was identified by the authors to be the key and common elements of the various processes. This basic process is shown in Figure 3. The key phases of this process are to define, ideate, model, improve and then implement. The phases of the process are organized to indicate a general order with which they are completed. Defining the problem is a key first step that students often want to rush past to get to the ideation and building activities. The graphic emphasizes problem definition happens early and before the next phases. The middle part of the graphic is organized as a Venn diagram to indicate that these phases often overlap and repeat as necessary until an adequate solution is reached. The last phase of implementation again sits outside the other phases to help students consider that at some point, a design needs to be finalized and communicated to clients or other stakeholders. However, a returning arrow is included to remind students design is an ongoing process of innovation and improvement.

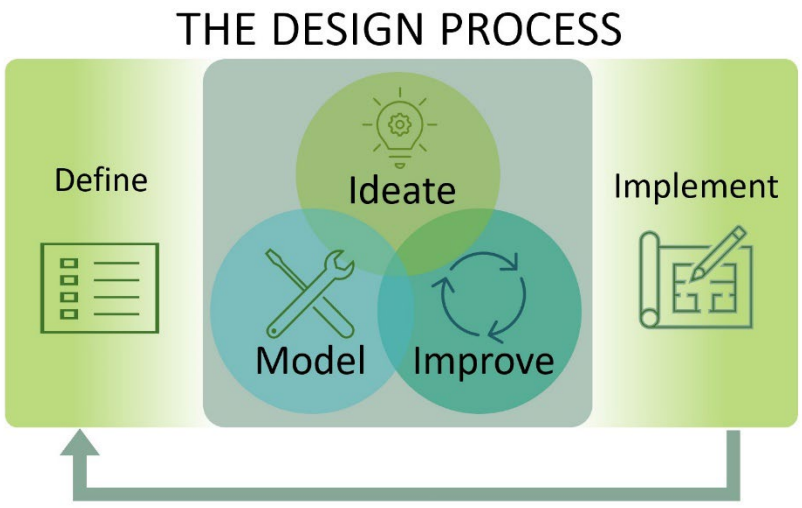

Figure 3 – Basic design process to be used as standard across the ME curriculum.

While some design practitioners now focus on characteristics of designers rather than discrete, sequential process steps, it was determined that having general steps organized in a sequential manner would be beneficial to student learning, as well as to faculty instruction. For each of the general steps shown in Figure 3, there are more detailed activities that would be done during that phase of the process. These activities are shown in Table 5. This process and the specific activities will serve as the standard for design instruction across the curriculum of the ME program at UVU.

In the current program curriculum, there are 3 classes that are being used to evaluate design as part of the ABET evaluation (ABET Student Outcome 2). These classes occur in the third and fourth years of the ME program. While these three courses offer the best opportunity to evaluate students' performance related to ABET Outcome 2, it doesn't allow the faculty to see how students' understanding of the engineering design process improves and evolves over the course of their studies. It is proposed to offer formal coverage of at least a portion of the standard engineering design process in courses occurring in each semester during the 2nd and 3rd year of study. These courses would include: ENGR 2010 Statics and ENGR 2160 Material Science (Fall 2nd year), ENGR 2450 Computational Methods and ENGR 2030 Dynamics (Spring 2nd year), ME 3010 Linear Systems and ME 3140 Machine Design (Fall 3rd year), and ME 3210 Manufacturing Processes and ME 3335 Thermal Fluid Experimentation (Spring 3rd year). ME 4410 Computer-Aided Engineering would also be included as it is in the process of being moved from the fourth year to third year in the recommended course flowchart.

Conclusion and Next Steps

In this study, two surveys were conducted, one given to students, one given to faculty, in order to better understand how students were learning the engineering design process throughout their mechanical engineering studies, as well as how faculty incorporated the design process in their courses. The student survey results indicated that students best understood the design process in their first and fourth years of study, but believed the engineering design process was being taught in courses in each year of study. Interestingly, nearly half of fourth-year students believed they

were being taught a different design process than what they had seen in previous courses at UVU, despite the same process being taught in the capstone courses as is taught in the introduction to engineering course. Additionally, students were best at identifying the steps of the design process in the first and fourth years but were only able to identify the correct order of steps to within +/- one spot. The faculty survey illustrated a strong interest from faculty in improving how the design process is taught by utilizing a standardized design process that is incorporated in courses throughout the program.

Future work will focus on the implementation and evaluation of the proposed curricular changes. The data set of student design surveys will be expanded by further delivering the survey to mechanical engineering students in all four years of the program. It is anticipated that the survey questions will allow for comparison of student learning and understanding of the design process before and after the curricular changes.

Table 5 - Characteristics of phases of proposed design process

Process Phase	Typical Activities & Characteristics
Define	• Identify the Problem • Ask, Research, Empathize • Discover Customer Needs, Design Requirements, Constraints
Ideate	• Brainstorm • Encourage Creativity • Select Concept
Model	• Prototype • Analyze • Experiment
Improve	• Refine • Optimize • Iterate
Implement	• Set Final Specifications • Communicate • Reflect

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Appendix A – Student Survey

Engineering Design Survey
Help us better understand your experience with learning the engineering design process at UVU.

1. What is your major?
    a. Mechanical Engineering
    b. Civil Engineering
    c. Other (Can fill in)
2. Which year of the ME program are you currently in?
    a. 1st year (ENGR 1000 Introduction to Engineering)
    b. 2nd Year (ENGR 2010 Statics)
    c. 3rd Year (ME 3010 Linear Systems)
    d. 4th Year (ME 4810 Capstone 1)
3. Which of the following classes have you completed at UVU?
    a. ENGR 1000 - Introduction to Engineering
    b. ENGR 2010 - Statics
    c. ME 3010 – Linear Systems
4. Had you learned the engineering design process prior to taking classes at UVU? If yes, type where you learned it next to "Other..."
    a. Yes
    b. No
    c. Other…
5. Below in the left column are possible steps of the design process. Identify which are actual steps and what their proper order is in the design process. (For the first step of the process, click the bubble under column 1, for the fourth step the bubble under 4 etc. If a term is not part of the design process, leave it blank.)
    a. Manufacturing & Assembly
    b. Identify the problem
    c. Experiment to test hypothesis
    d. Generate Ideas
    e. Define design criteria
    f. Analyze Solutions & Test Models
    g. State hypothesis
    h. Select a solution
    i. Research/Gather Data
    j. Implement solution
    k. Product Maintenance
6. For the following questions, assume the formal engineering design process has 10 steps: 1) Identify the Problem, 2) Define Design Criteria/Goals, 3) Research/Gather Data, 4) Brainstorm/Generate Ideas, 5) Analyze Solutions, 6) Test Models, 7) Decide on a Solution, 8) Communicate, 9) Implement, 10) Post-Implementation Review

    For the course you are currently in, how much do you agree with the following? (Likert)

a. The steps of the entire design process were taught in this class.
b. If the design process was taught in your class, it was presented in a way you had seen in at least one other class you took at UVU.
c. You applied the at least part of the design process on at least one assignment or project for this course .
d. Your instructor explained the design process in a new way you had not seen before.
e. If the design process was presented in a new way, the new process was helpful.
f. This class was focused on only a portion of the entire design process (i.e., analyze solutions and communicate your answers)
g. This class improved your understanding of the design process.
h. You are still confused about the steps of the design process.

7. Based on what you expected in this course, how would you describe the amount of time spent covering the engineering design process in your current course?
    a. Not enough time
    b. Appropriate amount of time
    c. Too much time
8. I am better at utilizing the engineering design process after having taken this course?
    a. True
    b. False

Appendix B – Faculty Survey

Please complete this survey to help us better understand how the design process is currently being taught in the ME program at UVU.

1. Do you currently teach the design process in any of your classes?
    a. If yes, what is the course number(s) of the class(es) in which you teach the design process?
    b. Approximately how many lectures do you dedicate to teaching the design process?
        i. Select on scale 0 to 10 or more.
2. What are the steps of the design process you teach in your classes?
3. Do you currently have a design project or activity in any of the classes you teach?
    a. If yes, what is the course number(s) of the class(es) which include a design project or activity?
4. If you have a design activity or project, how heavily weighted is the design project or activity (%of final grade)?
    a. 5% or less
    b. 10%
    c. 15%
    d. 20%
    e. 25% or more
5. Which courses in the ME program should include an emphasis on the design process?

6. Do you think the UVU ME program should teach a standard design process?
7. Would you be willing to incorporate the teaching of one or more steps of the design process in a class you teach that does not currently include instruction on the design process?