AC 2009-1520: THE ENGINEERING DESIGN PROCESS: AN ASSESSMENT OF STUDENT PERCEPTIONS AND LEARNING AT THE FRESHMAN LEVEL

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The Engineering Design Process: An Assessment of Student Perceptions and Learning at the Freshmen Level

Abstract

An investigation into the impact of a simple team design experience in teaching the engineering design process is described. The design experience occurred early in an Introduction to Engineering course after a single lecture on the engineering design process. The design activity, necessarily simple at this stage, consisted of designing, building, and testing a drag racer, constructed from LEGO® MINDSTORMS® NXT parts and powered by a single rubber band. Assessment of the value of the experience focused not only on gains in student perceptions of knowledge of and confidence in applying the engineering design process, but also on actual gains in knowledge, as judged by written responses, and on the use of the engineering design process, as judged by student design step logs.

Student learning was assessed through questionnaires at the beginning and end of the laboratory period. The questionnaires addressed both student knowledge and student confidence levels. In addition to assigning numerical values (on a scale from 1 to 5) to their perception of knowledge about and confidence in applying the design process, students responded to the knowledge questions with short, written statements. These statements were then scored by the investigation team and the resultant scores compared with the students' perceptions of knowledge. The assessment data showed a significant overall increase of both student perception of knowledge (from an overall average of 2.28 to 3.06) and confidence scores (from an overall average of 3.09 to 3.66) as well as significant individual incremental increases. The assessment of student knowledge as evaluated by the investigation team showed a somewhat smaller, but still significant, increase (from an overall average of 2.35 to 2.74).

Assessment of the student design logs indicated good general adherence to the design process with interesting exceptions. Detailed analysis of the assessment data revealed strengths in student preparation for the experiment as well as certain course topics, which will require more in-depth coverage in subsequent offerings of the course. An unexpected result was the finding that there is a requirement to define commonly used terminology when introducing students to the engineering design process.

Introduction

The engineering design process is fundamental concept in engineering education. One good definition of the engineering design process was provided by the conventional ABET criteria[1] (pre 2000):

> "*Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.*"

Guidelines and recommendations for the inclusion of the engineering design process into an engineering curriculum were further provided in the conventional ABET criteria:

> *"The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, production processes, concurrent engineering design, and detailed system descriptions. Further, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact."*

Engineering design is often described in textbooks by two widely divergent processes: one quite structured the other unstructured. Some textbooks (e.g. Oakes, Leone, and Gunn[2]) present the engineering design process as a linear series of steps: others extend the linear steps with the inclusion of iteration (Wickert[3]; Dym and Little[4]; Moaveni[5]). A less structured approach to engineering design is based on the work of Schön[6]: In this approach all steps of the engineering design interconnect. Examples of completely unstructured engineering design processes are presented by Hyman[7] as well as Ford and Coulston[8]. A summary of typical design processes, highlighting commonalities and differences between the various phases, has been collected and explored by Howard[9].

The primary objectives of this study are the assessment of student learning of the engineering design process and student confidence in applying the concepts of engineering design, and a qualitative observation of an early usage of the design process by freshman students enrolled in an introduction to engineering class. In the following discussion, the introduction to engineering course, the engineering design lecture coverage, and the initial associated laboratory activity are described. The assessment of the laboratory activity is then presented and discussed. Finally, an analysis of the design process structure, as used by the students, is provided.

Introduction to Engineering Course

The engineering design lecture material and associated laboratory activity assessed here are part of a Fall 2008 freshman-level Introduction to Engineering course (ENGR 101) at the University of San Diego (USD). The course meets each week for two one-hour lectures and one two-hour laboratory. This course is part of USD's Preceptorial Program and combines aspects of a freshman seminar and academic advising with a regular class. Preceptorial courses are typically taught by experienced full-time, tenure-track faculty members, course enrollment is limited to 16-18 students, and the faculty member teaching the course is the initial academic advisor for incoming freshmen. The Preceptorial Program has the following goals[10]:

1. *To fulfill a general education requirement by instruction in an essential academic discipline [typically for students who do not know what area they want to major in] or to prepare the student for a future major or minor [for those who do have a proposed major];*
2. *To provide early and continuing communication between the student and the advisor;*
3. *To assist the student in planning a cohesive and productive educational program;*
4. *To introduce the student to the intellectual resources of the University; and*

5. *To help the student develop the inquiring habit of mind that is fundamental to higher education.*

For this study of the design process, the Introduction to Engineering course was chosen to ensure that all students had limited or no previous exposure to the engineering design process.

Lecture Coverage of the Engineering Design Process

The engineering design process is covered in the first two lectures of the Introduction to Engineering course. The first class starts with a welcome and student/instructor introduction and continues with a discussion of the course syllabus. The remaining third of the first class is used for a "*Building Castles in the Air*"[11] assignment. Groups of 3-4 students are formed and the students are handed a deck of cards. The students are then challenged to build the highest possible free-standing card castle within four minutes. After the time is up, the height of the card castles is measured and basic observations are discussed. The students then have three minutes to plan how they can achieve a better result in a second round. This discussion period is followed by another four minutes of construction time. Finally, the height is measured and the solutions are discussed in more detail. The students learn through this hands-on activity how improved planning, communication, delegation, and learning from their success and failure leads to a better outcome.

The second lecture of the Introduction to Engineering class is completely devoted to the engineering design process. The lecture introduces the design process and discusses specifications, objectives, and concerns. The design process lecture is based on a ten-step process from the textbook (Oakes, Leone, and Gunn[2]) used in the course:

1. Identify the problem / product innovation
2. Define the working criteria / goals
3. Research and gather data
4. Brainstorm / generate creative ideas
5. Analyze potential solutions
6. Develop and test models
7. Make the decision
8. Communicate and specify
9. Implement and commercialize
10. Perform post-implementation review and assessment

The design process is discussed by considering an example, such as the design of an automobile, a power tool, a child's toy, or inline skates (the textbook example). In order to facilitate the discussion, students are asked to identify the three most important steps and find reasons to support their choices.

Laboratory Activity to Reinforce the Design Process

All laboratory assignments for this class are based on the LEGO® MINDSTORMS® NXT system[12]. Over the course of a semester, students work on a total of seven project assignments in small teams of 2-4 students. Project assignments include a drag racer, a shuttle race, a line follower, and a final competition involving the retrieval of colored tokens. The assignments' lengths vary from a single week to four weeks.

The first laboratory assignment, the vehicle for this study, is the design and construction of a drag racer. The drag racer is constructed from LEGO® MINDSTORMS® NXT parts and powered solely by a rubber band. The student groups compete against each other for the drag racer covering the greatest distance. The purpose of this assignment is twofold:

1) the assignment reinforces the engineering design process covered previously in the lectures, and
2) the students are familiarized with the mechanical components of the LEGO® MINDSTORMS® NXT system, including structural components, connectors, axles, gears, and tires.

The controller, sensors, motors, and programming interface are introduced in the following week.

The assignment is broken down into three phases. In the first phase, students have 20 minutes to design, build and test a rubber-band powered vehicle. A first competition is held at the end of this time (30% of the grade). In the second phase, students have 15 minutes to redesign and test their vehicles. A second competition is performed, but no points are awarded. In the third phase, the students have another 15 minutes to redesign their vehicles. The final drag racers are peer-evaluated for design features and esthetics (30% of the grade) and a final competition follows (40% of the grade).

Assessment and Analysis

The investigation team, consisting of the authors, gathered data during the concerning:

- gains in student knowledge of the design process as a result of a simple design exercise (the LEGO® drag racer),
- gains in student confidence in the ability to use the design process, and
- how students apply the design process to the design problem.

A two-pronged approach was utilized:

1) questionnaires, focused on knowledge and confidence, were completed by the students at the beginning and end of the laboratory period, and
2) students completed a log indicating the order of the design steps they used during the design exercise along with a short description of their activity during each step.

Assessment Student Knowledge

Short questionnaires were designed to provide insight into the student level of knowledge concerning the design process and their confidence in applying that material. At the beginning of the lab period, students were asked to score (on a scale from 1 to 5) their prior knowledge of the design process. In response to an insightful question[13] about whether student-assigned knowledge scores were a measure of knowledge or a rather a measure of student *perception of knowledge*, students were also asked to respond with a short answer to the knowledge questions. To provide further insight into actual student knowledge level, these short answers were later scored by each of the three investigators. After the lab period, the questionnaires were again completed by the students and the post-exercise written responses scored by the investigators to measure changes in knowledge level. In order to track individual student incremental changes, the two questionnaires were printed on opposite sides of the same page, thereby preserving student confidentiality without the need for secret identification marks on the questionnaires. A total of forty-seven survey pairs were completed by the students in four separate sections of the course. Four students completed only one of the surveys and those results were not considered in this study. The use of student-assigned scores to assess gains in student knowledge and confidence has been successfully used by the investigator team in a previous study (Schubert, Jacobitz, and Kim[14, 15]).

The following five questions concerning knowledge of the design process were asked before and after the lab exercise:

- What are the important components of the engineering design process?
- What procedures or techniques do you know to search for and generate possible solutions?
- Why is the design process iterative?
- What methods for the evaluation of possible solutions do you know?
- Why do you document the design process?

Students assigned knowledge scores based on the following scale:

1 = No clue, this concept is new to me
2 = Low, I have only heard about the concept
3 = Moderate, I know about the concept, but have not applied it
4 = High, I know the concept and have tried it
5 = Superb, I know the concept and have successfully applied it

The distribution of the overall student knowledge of the design process before and after the exercise is shown in Table I. Students reported the highest average levels of knowledge concerning components of the design process and the importance of documentation both before and after the exercise (2.59→3.31[*] and 2.69→3.35, respectively) and lowest level of knowledge concerning iteration (1.73→2.65). Faculty assessment of the student written responses concurred with the students: highest levels of knowledge concerning components of the design process and documentation both before and after (2.80→3.02 and 2.84→3.07, respectively) and lowest concerning iteration (1.73→2.31).

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[*] The construct A→B is used here to indicate the average score before (A) and after (B) the design exercise.

Table I Student knowledge distribution

Knowledge Level		Student Perception		Faculty Perception	
		Before	After	Before	After
1 = No clue		42	15	179	97
2 = Low		71	20	193	186
3 = Moderate		93	85	187	258
4 = High		26	88	104	125
5 - Superb		3	26	6	36
Statistics	$\overline{X}$	2.28	3.06	2.35	2.74
	σ	1.13	1.35	1.06	1.06

A summary of the individual student incremental change in knowledge scores is shown in Table II. On individual knowledge questions, most students reported either no change (42.4%) or a positive increment of one (34.1%): smaller fractions indicated positive knowledge increments of two (17.3%) or three (3.1%). Faculty scoring of the short written statements indicated similar knowledge increments with no change being dominant (46.7%) followed by positive one (27.3%), positive two (9.8%), and negative one (9.5%).

Table II Individual student incremental change in knowledge

Change in Knowledge	Individual Incremental Change									Statistics	
	-4	-3	-2	-1	0	1	2	3	4	$\overline{X}$	σ
Student Perception				6	108	87	44	8	2	0.75	0.90
Faculty Perception			17	61	301	176	63	25	1	0.44	1.01

Students reported the strongest incremental changes in questions concerning generation of solutions, iteration, and evaluating solutions (average incremental change ranging from +0.82 to +0.86) with the smallest average incremental change concerning documentation (+0.67). The faculty assessment of knowledge agreed with the students concerning strong change in iteration and evaluation of solutions (average incremental change ranging from +0.60 to +0.64) and the smallest change concerning documentation (+0.25), but also found small incremental change in knowledge concerning the basic components of the design process (+0.27).

Of particular concern was the considerable number of students who seemed to be unfamiliar with the term "iterative" as expressed in the third knowledge question. Prior to the lab exercise, 47.8% of the students reported the lowest level of knowledge, "*No clue, this concept is new to me*," on that question: faculty concurred with the students' lack of knowledge concerning iteration giving 57.6% of the students that low rating. Student comments included:

- "I don't know what iterative is."
- "Unsure of meaning, will be prepared next lab."
- "Excuse me?"

Iteration is a critical component of the engineering design process and should be fully understood for meaningful discussions of the engineering design process. Although some students did not understand the word "iterative" and the textbook presented a strictly linear design process, analysis of the student design logs shows that most students performed iterative design in their LEGO® Drag Racer design assignment. The design process lecture component will be adjusted to address that concern.

Assessment of Student Confidence

The second portion of the questionnaire was designed to assess student confidence in applying the concepts of the design process. The following seven questions were asked before and after the design exercise was performed in order to assess student confidence:

- I can recognize the needs to be addressed by a problem and formulate those needs in clear and explicit terms.
- I can establish criteria for evaluating a solution.
- I can apply procedures or techniques to search for and generate solutions.
- I can select a solution that best satisfies the problem objectives.
- I can build and evaluate a prototype or final solution.
- I can recognize when changes to a solution may be necessary through iteration in the design process.
- I can document the design process.

Students were asked to respond to the questions concerning their confidence in applying the concepts using the five-level scale:

1 = No Clue, I have no idea if I can apply the concept
2 = Low, I have heard of the concept, but have little confidence that I can apply it
3 = Moderate, I think I understand the concept, but am unsure about applying it.
4 = High, I am fairly sure I understand the concept and am fairly sure I can apply it.
5 = Superb, I am very confident that I understand the concept and can apply it to a new problem

The distribution of the overall student confidence in applying the concepts of the design process before and after the exercise is shown in Table III. Average student confidence was remarkably uniform across the questions both before (ranging from 2.89 to 3.19) and after (3.54 to 3.78) the design exercise.

Table III Overall student confidence distribution

Student		Before	After
1 = No clue		104	32
2 = Low		203	54
3 = Moderate		336	290
4 = High		141	326
5 - Superb		16	90
Statistics	$\overline{X}$	3.09	3.66
	σ	0.94	0.78

Once again, individual student incremental change was tracked: the overall change in student confidence level is shown in Table IV. On individual confidence questions, most students reported either no change (48.3%) or a positive increment of one (36.5%), with a smaller fraction indicated positive knowledge increments of two (8.3%).

Table IV Individual student incremental change in confidence

Change in Confidence	Individual Incremental Change									Statistics	
	-4	-3	-2	-1	0	1	2	3	4	$\overline{X}$	σ
Student Perception				15	152	115	26	6	1	0.55	0.81

The strongest incremental change in confidence related to building/evaluating a prototype (+0.84), and the least incremental confidence changes related to applying techniques to generate solutions and in selecting the best solution (+0.38 and +0.42 respectively). The remaining incremental confidence changes were clustered around an average incremental change of +0.52 with documentation showing a slightly higher confidence increment of +0.64.

Investigating the Design Process with Design Logs

Forty-seven students completed a log of their application of the design process to the design exercise. Students were given a listing of the design steps as identified in their course textbook, but artificially randomized by alphabetizing the steps (textbook design step order is indicated by the numbers in braces {#}):

A.	Analyze potential solutions	{5}
B.	Brainstorm / generate creative ideas	{4}
C.	Communicate and specify	{8}
D.	Define the working criteria / goals	{2}
E.	Develop and test models	{6}
F.	Identify the problem / product innovation	{1}
G.	Implement and commercialize	{9}
H.	Make the decision	{7}

I. Perform post-implementation review & assessment {10}
J. Research and gather data {3}

Students were informed that the steps could be in random order and asked to indicate the design process steps that they took to generate a solution to the given engineering design problem. In addition to logging their design steps taken, students were asked to briefly describe each of their actions and decisions.

Overall student-reported design step usage is tabulated in Table V. Of the forty-seven design logs completed, only four students (8.5%) fell into the alphabetical-order trap. Most groups started by either identifying the problem (44.7%) or by analyzing potential solutions (29.8%). Defining goals, generating ideas, and identifying the problem were steps used by more than 80% of the students: the research and implementation steps were least used with only about half the students reporting using those steps. Students most often repeated the steps concerning developing/testing models and generating ideas with some students using those steps as many as five times. The final step taken was most often review and assessment (36.2%) with all other steps taken as the final step by less than 15% of the student designers each. The significance of the "research and gather data" step (Step 3) as a reported ending point is most likely significantly skewed since it fell last alphabetically, and more than half of those using it as a final step were those who fell into the "alphabetical-order trap." Similarly, the significance of "analyze potential solutions" (Step 5) as a starting step is somewhat reduced with about 30% of those using it first being led astray by alphabetical-order.

Table V Overall design step usage

Step Usage	Step									
	1/F Identify	2/D Define	3/J Research	4/B Brainstorm	5/A Analyze	6/E Test	7/H Decide	8/C Communicate	9/G Implement	10/I Assess
% students using step	81	60	53	85	72	89	66	72	49	60
% students repeating step	6	0	2	13	6	19	0	4	0	2
Maximum # of usages by same student	4		2	5	2	5		4		2

The student designer path to a final solution was analyzed by tallying the next step taken after each step (Table VI).

Table VI Tabulation of design paths

Frequency		Next step									
		1/F	2/D	3/J	4/B	5/A	6/E	7/H	8/C	9/G	10/I
Current Step	1/F Identify	2	6	2	12	3	2	2	1	6	3
	2/D Define	2	0	6	3	1	9	2	1	0	0
	3/J Research	0	2	0	3	4	1	2	3	2	1
	4/B Brainstorm	1	3	4	2	5	12	2	18	0	1
	5/A Analyze	0	2	0	13	1	10	6	3	0	0
	6/E Test	14	1	3	2	3	7	10	6	4	5
	7/H Decide	0	1	3	0	1	7	0	3	4	7
	8/C Communicate	2	8	1	3	4	10	1	2	6	1
	9/G Implement	0	1	1	0	0	0	6	0	0	11
	10/I Assess	1	1	6	2	1	0	0	1	1	0

In order to gain insight into the design path data of Table VI, graphical representations were created. The first representation (Figure 1a) is a chart showing all paths with at least 1/3 of the maximum number of travelers: that is, paths with a value of 6 or more in Table VI. Here, line width is an indicator of the number of travelers, the two most common starting steps are indicated by green squares, and the two most likely stopping steps are indicated by red octagons. Unfortunately, in this representation, exits to step 3 (the second most likely stopping point) and entrances to step 5 (the second most likely starting point) do not meet the display criterion. The second representation (Figure 1b) attempts to remedy that omission by showing only the most likely path into or out of a step. Paths within 10% of the most likely path were also included. These paths are created from the data by choosing the path indicated with the largest number in either a row or column of Table VI: other paths in that row or column with a number at least 90% of the largest number are also indicated. Again, line width is the indicator of the number of travelers.

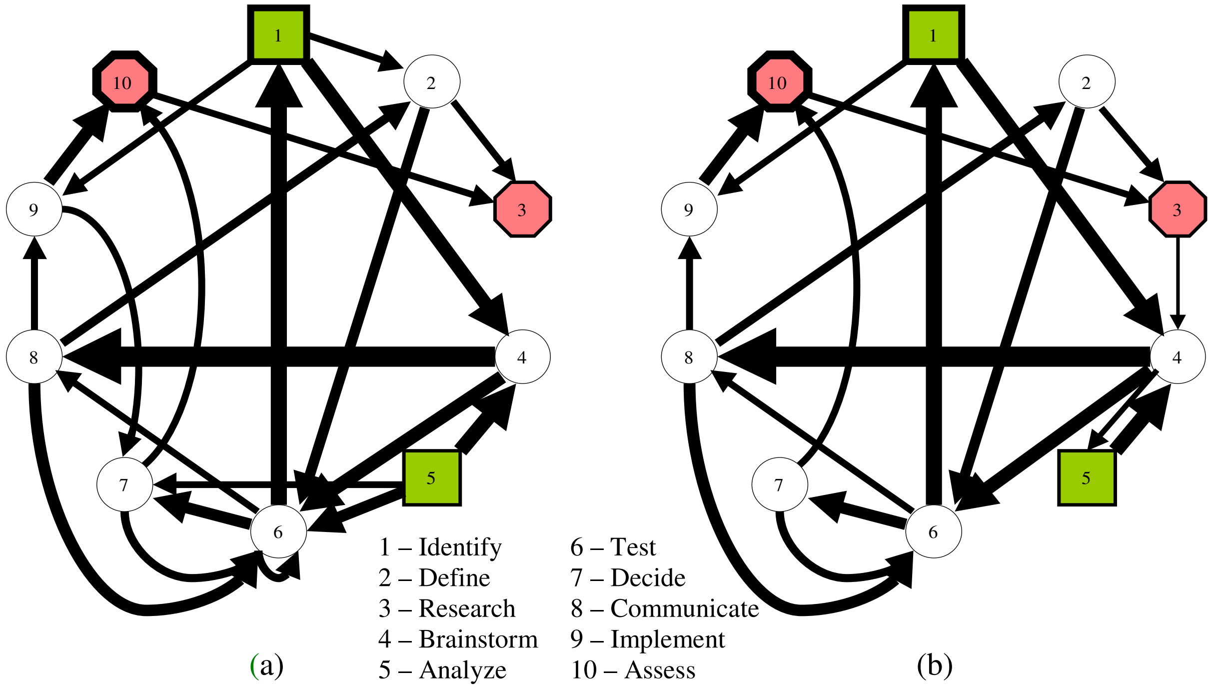

Figure 1 Two graphical representaitons of student design paths

a) Overall most likely paths (indicated by a 6 or more in Table VI)
b) Most likely entrance or exit path to a step (indicated by the largest number in a row or column in Table VI and those at least 90% of that value)

Interpretation of Student Design Paths

Analysis of the student design paths indicates that after *identify the problem* (step 1), most proceed to *brainstorm/generate creative ideas* (step 4). This may be an indication that steps 1-3 (1. *identifying the problem*; 2. *defining work criteria/goals*; 3. *research and gather data*) can be interpreted and grouped as the single activity of defining the design problem. This grouping is particularly appropriate for design problems that are limited in scope.

Upon completion of *brainstorming potential solutions*, most proceeded to either *develop and test models* (step 6) or *communicate and specify findings* (step 8). *Analysis of potential solutions* (step 5) was rarely taken by students as a separate step in the design process. It appears from the design logs that step 5 was incorporated in the brainstorming step of the given design process. Therefore, steps 4 (*brainstorming*) and step 5 (*analysis*) could be combined as a single design activity in the process.

There were also a significant number of students proceeding from step 4 (*brainstorming*) directly to step 8 (*communicate and specify*) bypassing all intermediate steps. This jump could again be indicative of the grouping together of steps by students as evidenced in their design logs. This path also seems to be indicative of the student interpretation of the word "problem" to mean difficulty or dilemma as opposed to the intended meaning as the device to be designed.

The charts, along with the data of Table VI also indicate significant iteration, or looping, in the following steps:

- 1-4-6 (repetitive loop*) identify the problem*, *generate creative ideas*, and *develop and test models*.
- 6-7-6 (single loop) *develop and test models* and *make the decision*.
- 6-8 (repetitive loop) *develop and test models* and *communicate and specify*.
- 4-5 (repetitive loop) *generate creative ideas* and *analyze potential solutions*

It should be noted that the lab assignment required the students to go through two improvement cycles. We cannot conclude that all the iteration was independent of these instructions.

These results imply that a more compact and concise design process that encapsulates several of the steps provided in this assessment must be developed

Assessment of the Design Log

While the student design logs showed good adherence to the design process provided to students in the lecture portion of the course, several observations were made. The most prominent observations were:

- The design process discussed in the lecture portion had too many steps
- The vocabulary used in the textbook and the lecture was not understood by all students
- The terminology used in the design process used in the textbook and lecture could be misinterpreted by students

The ten step design process appeared to be overly comprehensive and did not allow for a broad interpretation of the design process. For example, steps 1 and 2 (*identify the problem / product innovation* and *define the working criteria/goals*) could conceivably be grouped as one step in the design process. This step compression is could be particularly descriptive in the case of simple, short design tasks. It was also found in the student design logs that not all design steps were used. Only 28% of the students used all the design steps and the average number of unutilized steps was 3.9 (standard deviation of 3.35). This statistic further indicates that a simplification of the process may be in order.

The terminology used in some of the design process steps lead to misinterpretation of the action required in that step. For example, in step 1, *identify the problem / product innovation*, some students appeared to interpret the word “problem” as some issue causing failure or obstruction instead of as the challenge. The faculty assessment has concluded that the design process as defined to students should be modified to clarify each step in the process to eliminate misinterpretation and terminology should be carefully defined to allow students to apply the design process appropriately.

Summary

Student knowledge and confidence increased upon completion of the design exercise as evidenced in the assessment study. Average student confidence before and after the design exercise were 3.09 (with standard deviation of 0.94) and 3.66 (standard deviation of 0.78), respectively. At the same time, average student knowledge before and after the design exercise were 2.28 (with standard deviation of 1.13) and 3.06 (standard deviation of 1.35), respectively. Equally important, faculty perception of student knowledge also increased from 2.35 to 2.74.

There was also evidence that students had different levels of understanding of the design process, even within a single project group. Evidence of these different levels of understanding was found in their design log narratives and the interpretation of the design process as evidenced by different design paths taken to the solution.

Assessment data and student design logs indicated that the discussions of the design process indicated that modifications could be made to improve student comprehension of the design process. In particular, the number of steps in the design process could be reduced to eliminate misinterpretation of the steps and vocabulary used in the process can be clearly defined.

The faculty assessment team plans to follow this cohort of students throughout their curriculum through graduation with future design exercises to assess their level of understanding and confidence in implementing projects using the engineering design process.

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