Teaching Experimental Design in a Fluid Mechanics Course

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Abstract

In this paper we discuss the development and implementation of a new Design of Experiment (DoE) experience in the junior-level Thermal-Fluid Systems course. The goal of the DoE is to teach students about dynamic similarity, uncertainty quantification, and technical communications through a hands-on experience with direct connections to real-world applications. In the newly-designed DoE, students must determine whether they can accurately predict pressure drop in real-world pipe systems---including an oil pipeline, a ventilation duct, a natural gas line, and a water supply line---using the equipment we provide. Although the equipment is prescribed, the procedure is not, which has the benefit of minimizing material requirements while allowing students the freedom to pursue a unique approach. The experience is divided into stages with a mixture of individual and group efforts. Students begin by deriving the relevant equations and crafting an experimental procedure as an individual. They then come together in groups of three or four to conduct the experiment and analyze the data, which includes uncertainty quantification. An instructor provides feedback on the data analysis portion before students communicate their results in a short lab report with extensive appendices. Throughout the experience students are required to communicate the limitations of their experiment by quantifying uncertainty and questioning the validity of their assumptions. Overall, the DoE is an exercise in critical thinking, data gathering, analysis, and interpretation of results. We present details of the DoE assignment, assessment of student learning, student feedback from course evaluations, and recommendations for instructors seeking to implement similar projects in their courses.

Introduction

In recent years, inquiry and problem-based learning within engineering education has gained momentum and has proliferated across many engineering programs. A literature review revealed numerous examples of development and implantation of these techniques into classrooms [2, 4-6]. Kolb [7] has written extensively on the model of experiential learning and how this technique enhances learning and mastery of engineering concepts. Experiential or laboratory based learning fits within the active learning dimension within their index of learning styles (ILS) described by Felder and Silverman [7-8]. The basis of ILS is that students have preferences for one category within the ILS model: sensing, visual, active, or sequential [7].

A consideration of all mechanical engineering curriculums, the ABET Criterion 3b, states that a student outcome is “an ability to design and conduct experiments, as well as to analyze and interpret data [1].” Many university programs have restructured their courses in order to introduce and evaluate design of experiments in their engineering curriculum. There have been multiple papers discussing and evaluating a design of experiment into an engineering course including Pape [2], Anagnos et al. [3], Sawyers and Marquart [4], and Satish et al. [5]. Each paper describes their own methodology of introducing and then evaluating an open-ended laboratory or design of experiment. Pape's [2] methodology was to introduce six cookbook labs, then move to two-week open ended labs building upon skills, and culminated with a four week experimental design laboratory where students formulate their own problems, elect and manipulate the equipment, execute the experiment, and then write a technical lab report. Anagnos et al [3] refined a general process developed from Du et al. [9] on how a student should design an experiment starting with defining goals and objectives, conducting background research, selecting variables, describing the experiment protocol, selecting proper ranges for independent variables, and determining the proper number of data points. Sawyers and Marquart's [4] methodology begins with the students completing a detailed step by step cookbook style lab and then allowing students in groups of two develop lab plans based on the following topics: objective, data to be collected, equipment, procedure, equations required for data reduction, how data is to be presented, and then references.

In summary, these papers introduce a traditional step-by-step lab procedure often referred to as "cookbook" style labs and then move to more open-ended labs increasing in complexity and reporting requirements where the students formulate a problem, select and manipulate the equipment, execute the experiment, and then write a technical lab report. Attempting to build on this crawl-walk-run style of executing laboratories, the methodology used in Thermal-Fluid Systems II (MC312) has students design an experiment using an idea (internal flow) and an apparatus (pipe friction demonstrator) that were introduced in the previous course, Thermal-Fluid Systems I (MC311). Previous courses in the mechanical engineering and foundational physics and chemistry courses have conducted the well-scoped, step-by-step laboratory experiments discussed earlier.

A design of experiment (DoE) has been a part of the MC312 course since its inception in academic year 2006. The learning objectives of the previous iteration of the DoE were to reinforce dimensional analysis principles, designing and conducting an experiment with uncertainty, and reporting findings in a technical report. The DoE required the students to use a plastic paratrooper to design and conduct an experiment that models an actual paratrooper and attempt to match similarity. Unfortunately, the provided model was not realistically sized for similarity to be achieved. Better students appreciated the difference, but many students learned unintended lessons about the feasibility of modeling and reached for conclusions or made the math work to show similarity. Generally the student feedback on the experiment was neutral, occasionally students would call out the use of a toy paratrooper to demonstrate a complex topic. The DoE in its previous form survived for the better part of 10 years largely due to the ability to introduce dimensional analysis, modeling and similarity, and experimental methods reasonably well.

However, upon further review of the course, the new team of instructors decided to search for another platform to introduce the desired concepts. Looking at the various laboratories and demonstrators across the program, the little used pipe friction demonstrator was settled upon. It would allow for the introduction of the dimensional analysis, modeling and similarity, and experimental methods leveraging the previously introduced topic of internal flow and provide easy comparison to theoretical results through the Moody diagram. Additionally, the course was selected to modify and implement several assignments that would emphasize Technical Communication (TECOM). These changes were implemented beginning in Academic Year 17-1 and have been continuously refined in the subsequent semesters. The DoE was selected to be the platform to evaluate technical writing and the final individual report serves as the "signature writing event" for both the Chemical and Mechanical Engineering Division's Writing-in-the-Major requirement.

In the new version of the Design of Experiment (DoE), the problem statement is:

> "You have been tasked to design an experiment to predict pressure drop in fully developed pipe flow for a variety of full-scale prototypes. Table 2 [not shown] contains the parameters for each of the following four prototypes: water in a residential water service line, crude oil in a pipeline, air in an HVAC duct, and compressed natural gas in a supply line. The equipment available to you is the pipe friction demo (PFD), which you may recall from MC311. A description of the PFD is given in Section 1.4. The equipment will be provided but you must develop the experimental procedure. You will determine whether it is possible to reliably and accurately use the PFD (the model) to predict the pressure drop in real piping systems (the prototypes). First you should determine whether you can achieve full similarity between the model and prototype(s). Then you should assess the accuracy of your experiment by comparing it with the known solution described in Section 1.3.
>
> The variable of interest in this experiment is the pressure gradient, ∇P, which depends on properties of the flow (density, ρ, dynamic viscosity, μ, and mean velocity, V) and pipe geometry (diameter, d, and mean roughness height, ϵ). Using dimensional analysis, we can write the relationship as
>
> $$\frac{\nabla P d}{\rho V^2} = F\left(\frac{\rho V d}{\mu}, \frac{\epsilon}{d}\right) \tag{1}$$
>
> which reduces the number of terms requiring investigation from five (ρ, μ, V, d, ϵ) to two ($\rho Vd/\mu$ and ϵ/d). The first term on the right-hand side of Equation 1 is the Reynolds number based on diameter, Re_d, a common dimensionless parameter in fluid dynamics."

The DoE mixes individual and group work. The pre-lab is an individual assigning and consists of derivations of Equation 1, isolating the friction factor within the Mechanical Energy Equation, and developing the step-by-step experimental procedure for the lab. The group comes together at a previous coordinated time and has an hour with the apparatus. An instructor is present, but only provides a quick overview of the operation of the lab and emphasizes the potential trouble spots (i.e. closing the lever too quickly may cause it to seize). Figures 1 and 2 below are directly from the DoE assignment prompt. The blue valve controls the flow of mineral oil and the mass flow rate is determined using the scale shown in Figure 2. The students use the hour to first orient themselves to the apparatus and then execute their agreed upon plan.

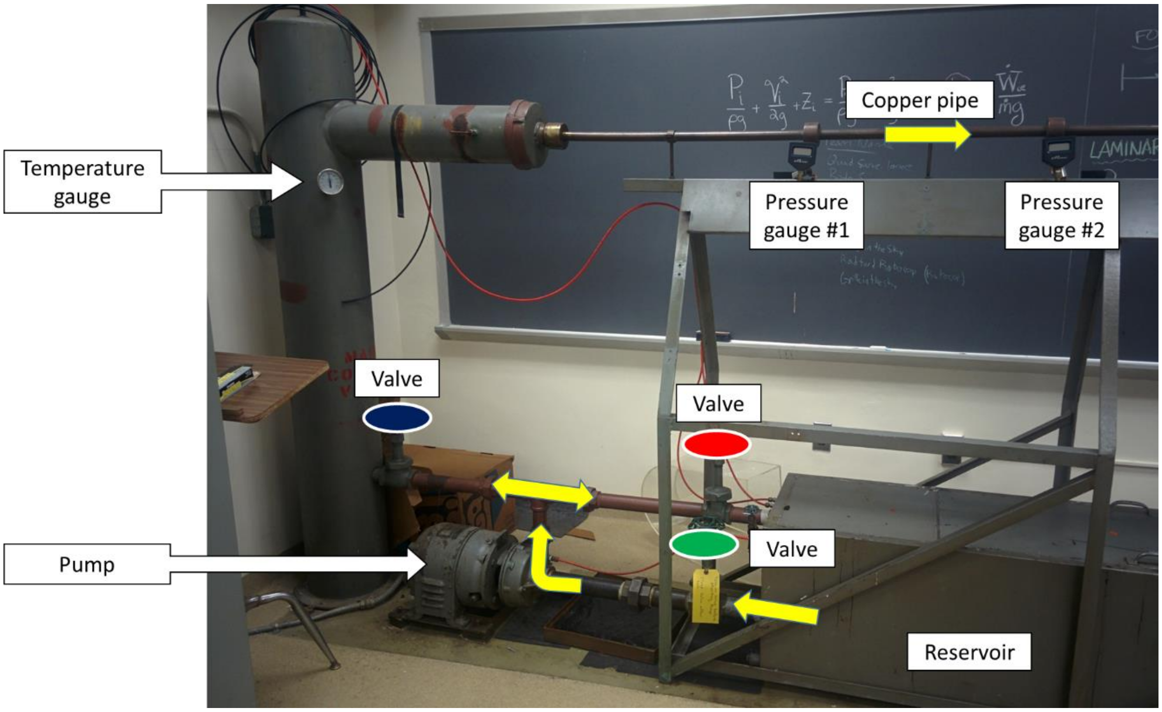

Figure 1: The left-hand side of the demo includes the pump and three valves to control how much mineral oil flows through the copper pipe, located at the top of the picture. Six pressure gauges are located along the length of the pipe. Yellow arrows indicate the flow direction.

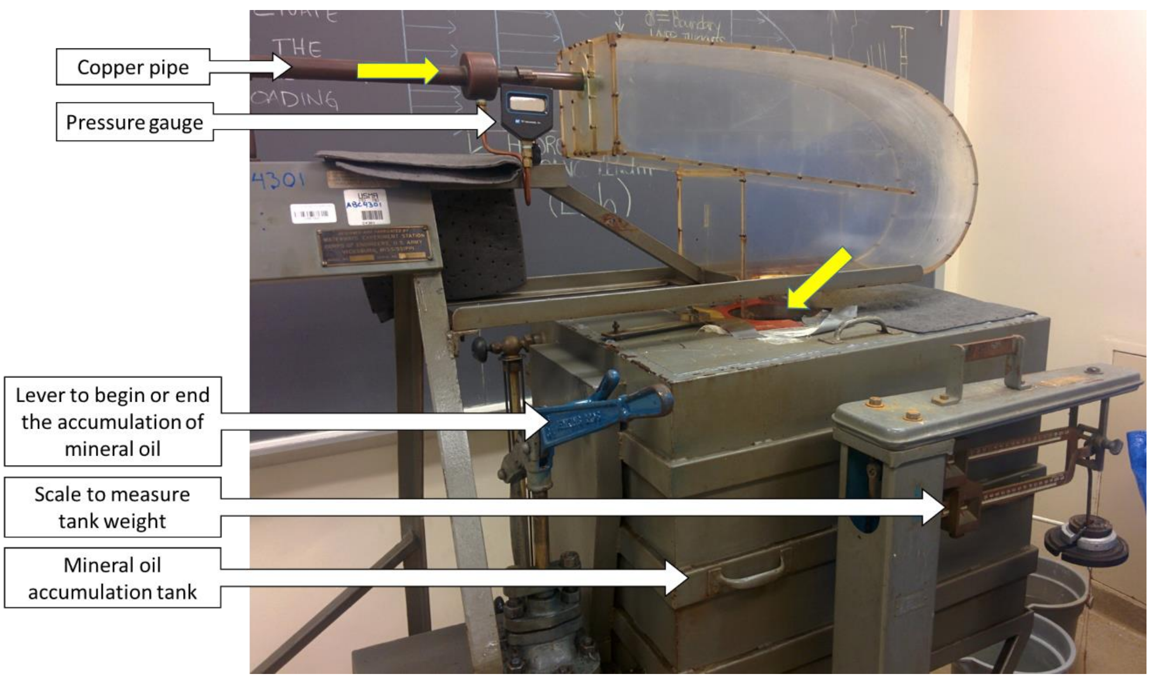

Figure 2: The right-hand side of the demo contains a tank that can accumulate oil when the lever is depressed. The scale is used to measure the weight of the tank and collected mineral oil. Yellow arrows indicate the flow diagram.

Following the lab, the next assignment is a group submission of the analysis which includes production of a plot that presents friction factor vs. Reynolds number for each flow rate comparing the experimental to the approved solution from the Moody diagram or equations with uncertainty. From these calculations, the group is asked if the model can achieve full similarity with the four prototypes discussed in the assignment prompt. Finally, the previous portions of the report and corrected and assembled into an individual final report in a standard publication style format with appendices.

Results and Discussion

Two sources were used to obtain student feedback on both the course and the design of experiment. The first survey asks the population to compare their experience in the course to that of other course in the Mechanical Engineering program, the department (CME), and the university and has been captured over four semesters; Academic Year (AY) 16-2 (the baseline) which preceded the new TECOM initiatives and AY17-1, 17-2, and 18-1 that followed (Figures 3 – 7). Additionally, the course data from AY17-2 was compared to both the mechanical engineering (ME) program and the Civil and Mechanical Department (CME) for that term in Figure 5. The second survey was an internally produced questionnaire that asked for more specific feedback on the DoE (Figures 8 – 11).

The first set of university-wide questions asked about the effectiveness of instructor techniques for both in and out-of-class assignments and the motivation to learn. Figure 3 shows the increase from the pre-TECOM initiative (AY16-2) to the three semesters following. The nearly 10% (0.5 on a 5 point scale) increase in motivation to learn and continue learning (A6) is particularly rewarding.

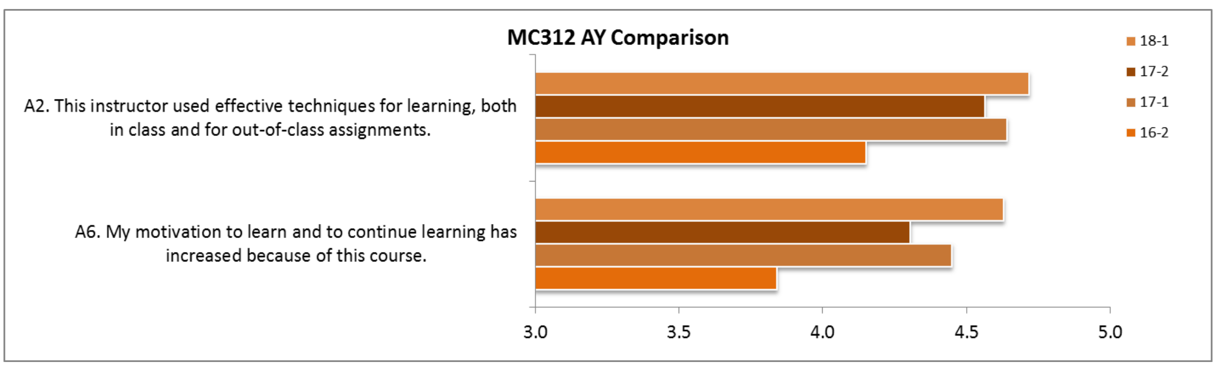

Figure 3. Responses from four academic terms of MC312 regarding instructor effectiveness and motivation to learn. AY16-2 shows the results prior to the Technical Communication initiative.

Figure 4 shows that the course was reasonably effective prior to the TECOM initiative from the high marks in instructor plan (C4) and enhancing learning (C10) for AY16-2. However, the student responses in the effectiveness of laboratory exercises contributing to learning (C8) show a notable increase from AY 16-2 to AY 18-1. Figure 5 highlights the overall effectiveness of the instruction in the department and program, but also the notable increase in effectiveness of the laboratory exercises. A 0.25 average increase is observed compared to the ME division, and a 0.5 increase compared to the department.

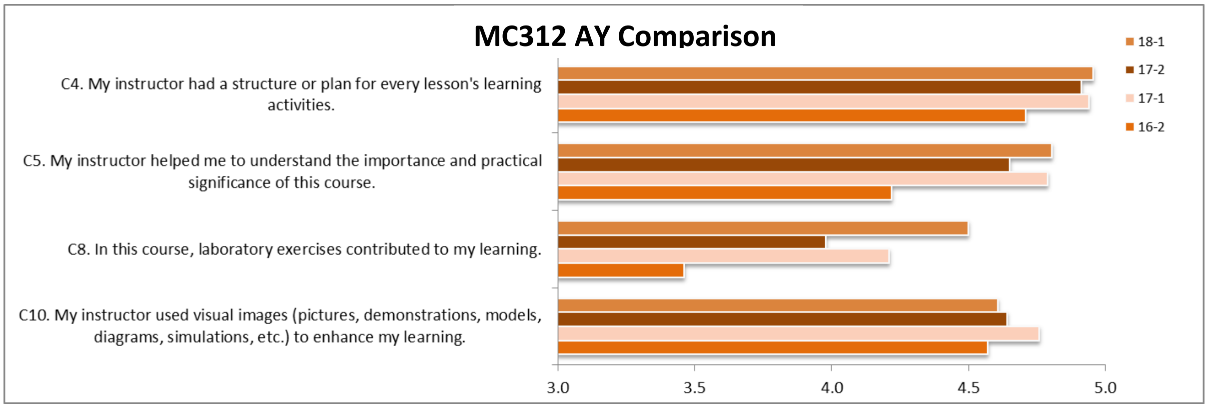

Figure 4. Responses from four academic terms of MC312 regarding instructor organization and emphasis as well as effectiveness of laboratory exercises. AY16-2 shows the results prior to the Technical Communication initiative.

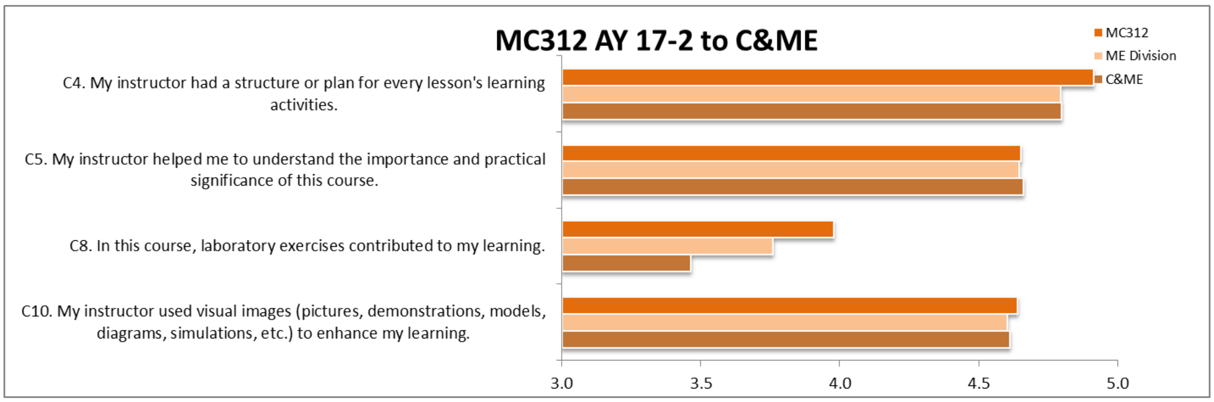

Figure 5. Responses to the questions included in Figure 4 comparing the AY17-2 offering of MC312 to the C&ME Department and ME Division in the same academic term.

When questioned about the courses impact on the students' ability to apply knowledge to engineering, over a 0.5 average increase is observed from AY 16-2 to subsequent terms in Figure 6 (question D1). Data also support perceived improvement to the ability of the population to design and conduct experiments (D2). The significant increase in agreement to whether this course improved ability to design and conduct experiments (D2) and student ability to communicate effectively (D7) validates not only the renewed emphasis on the Design of Experiment but also the entire technical communication initiative embarked upon for the course.

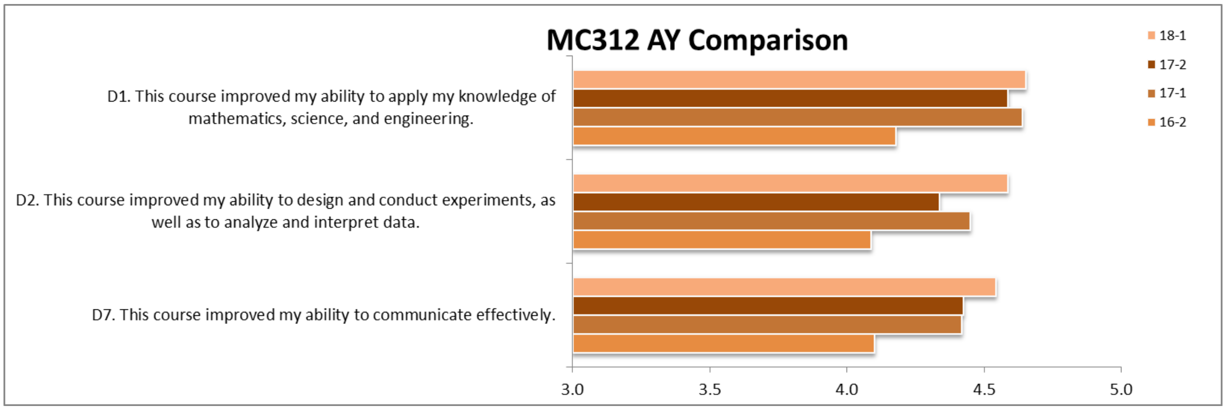

Figure 6. Responses from four academic terms to MC312 compared to ME Division. AY16-2 shows the results prior to the Technical Communication initiative.

Specific responses to the DoE are displayed in Figure 7. The population shows moderate to high confidence in the ability to design and experiment (E1), implement uncertainty calculations (E2) and provide an opportunity to think creatively (E16). This illustrates the need for such a DoE in the course and in the major as well as confirms the effectiveness of the new version of the DoE.

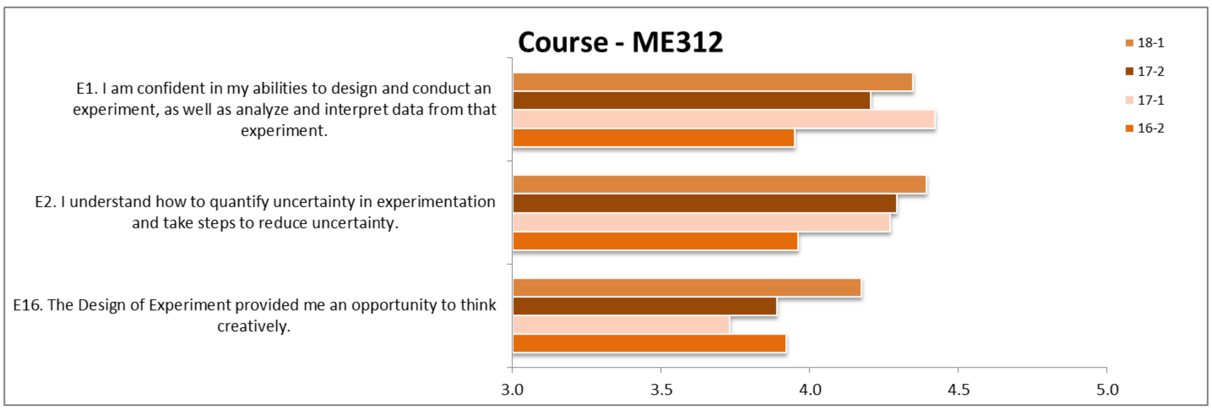

Figure 7. Responses from four terms of MC312 regarding the DOE. AY16-2 shows the results prior to the Technical Communication initiative.

The responses shown in Figures 3 – 7 strongly support both the new version of the design of experiment (Figure 6 and 7) as well as the overall TECOM initiative and its' positive effect on the course (Figure 3 – 6). The second survey asked more specific questions on each of the TECOM initiatives implemented over last the three academic terms. However, only those pertaining to the Design of Experiment are discussed in this report. For this second survey, the total sample size, n, equaled 171 students from various academic majors including mechanical, nuclear, and chemical engineering. The three separate but consecutive terms consisted of 33 students in Academic Year 2017, Term 1 (AY 17-1), 89 students in AY 17-2, and 49 students in AY 18-1. Standard deviations were calculated for each question in each academic term for the respective sample size ($n_{AY\ 17\text{-}1} = 33$, $n_{AY\ 17\text{-}2} = 89$, $n_{AY\ 18\text{-}1} = 49$) and compared to the standard deviation for the total sample size ($n_{TOTAL}=171$).

When questioned on how well other engineering courses prepared them to design an experiment, just over half (55.5%) of students responded "very well" or "extremely well." The standard deviation σ for each academic term was $\sigma_{AY\ 17\text{-}1} = 0.820$, $\sigma_{AY\ 17\text{-}2} = 0.850$, $\sigma_{AY\ 18\text{-}1} = 0.587$ with standard deviation of the entire sampled population of $\sigma_{TOTAL} = 0.796$.

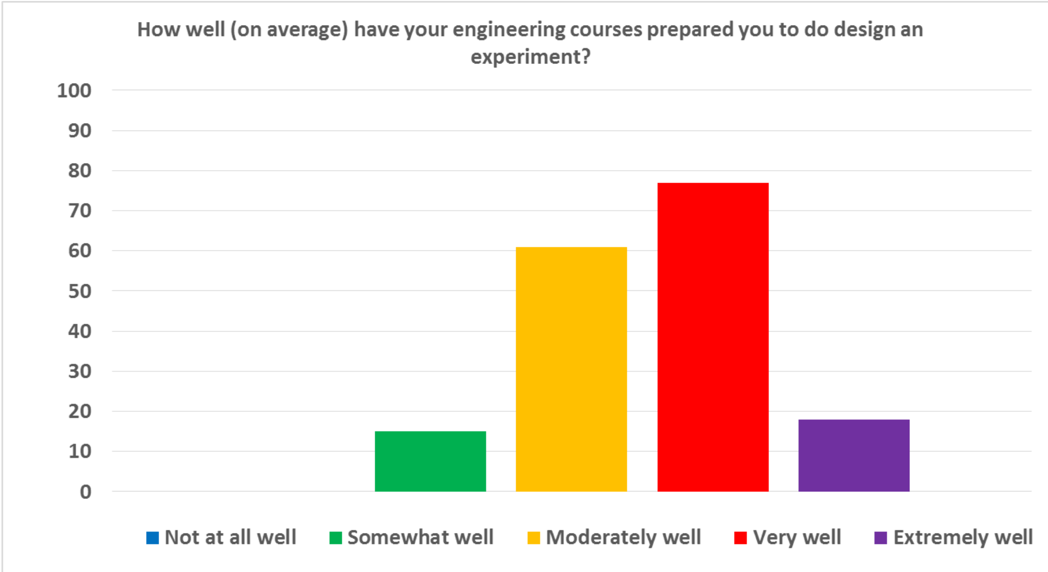

Figure 8. Student self-assessment responses of how previous engineering courses prepared them to design an experiment.

After conducting six laboratory exercises (including one design of experiment) during MC312, students were asked, with hindsight, how well MC312 specifically prepared them to design an experiment. Compared to their response to how well other engineering courses have prepared them to design an experiment (Figure 8), two-thirds of the respondents (66.7%) stated that they felt “very well” or “extremely well” prepared having taken MC312 as shown in Figure 9. The vertical axis for both figures represents the total number of students over three semesters replying to the survey. The standard deviation σ for each academic term was $\sigma_{AY\ 17\text{-}1} = 0.761$, $\sigma_{AY\ 17\text{-}2} = 0.973$, $\sigma_{AY\ 18\text{-}1} = 0.520$ with standard deviation of the entire sampled population $\sigma_{TOTAL} = 0.837$.

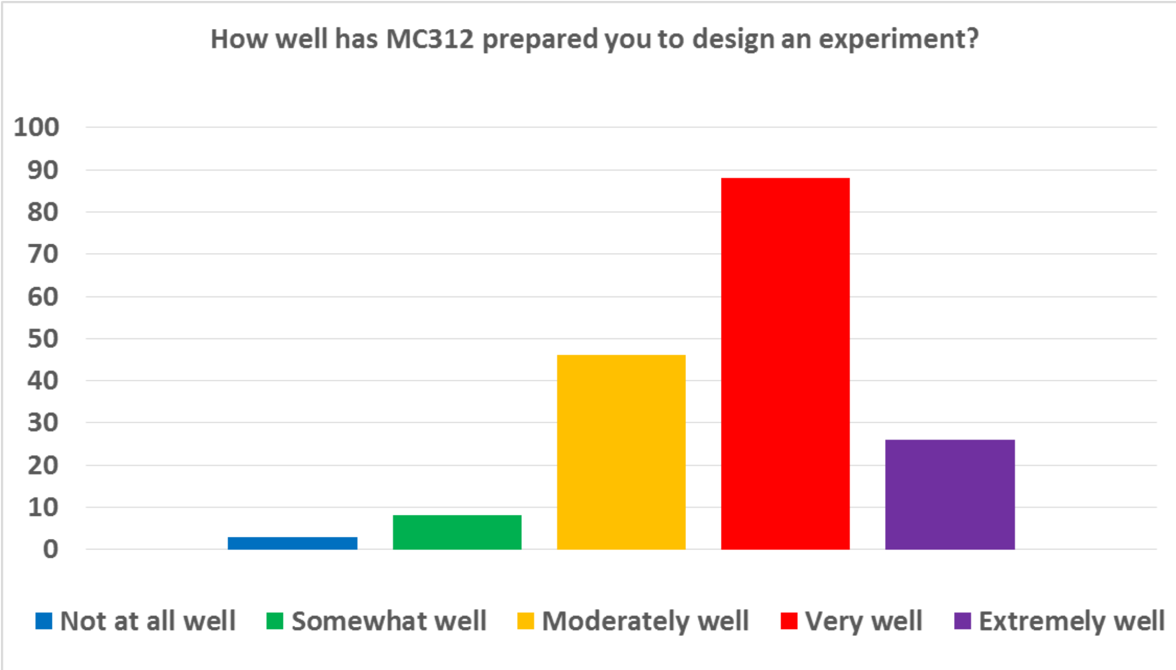

Figure 9. Student self-assessment responses of how well MC312 prepared them to design an experiment.

The student population was subsequently asked a series of questions specific to the Design of Experiment laboratory exercise. Responses to the 11 questions are provided in Figures 10 and 11, with standard deviations reported in Table 1. As with Figures 8 and 9, the vertical axis for Figures 10 and 11 represent the total number of students responding to the survey over the three semesters.

When asked about preference between creating a self-developed lab procedure versus being provided a step-by-step checklist (Question 2), 45.6% responded “disagree” or “strongly disagree,” while 37.4% responded “neutral,” and 17.0% responded with “agree” or “strongly agree.” When asked if there was one correct method to desiging and exectuing the lab (Question 3), 59.0% stated “strongly disagree” or “disagree”, while 21.0% responded “neutral,” and 20.0% responded “agree” or “strongly agree.” The strongest agreements, thus the smallest standard deviations, among the surveyed population are observed in Questions 5, 6, and 7. A 73.7% majority believed the design of experiment was an effective use of class time (Question 8) while 70.2% believed it should be included in future offerings of MC312 (Question 11).

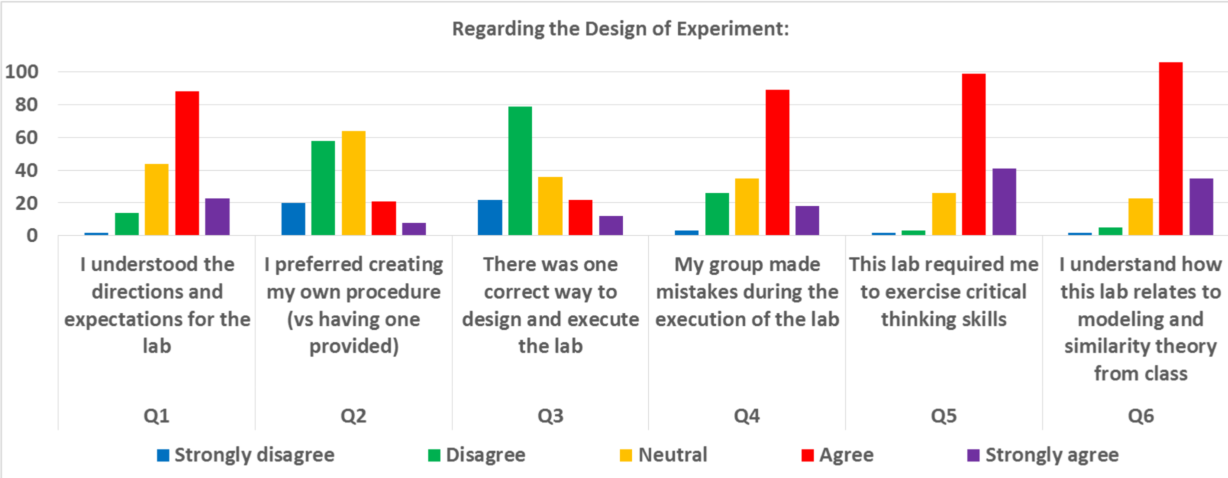

Figure 10. Student responses to questions 1-6 of MC312 Design of Experiment Survey.

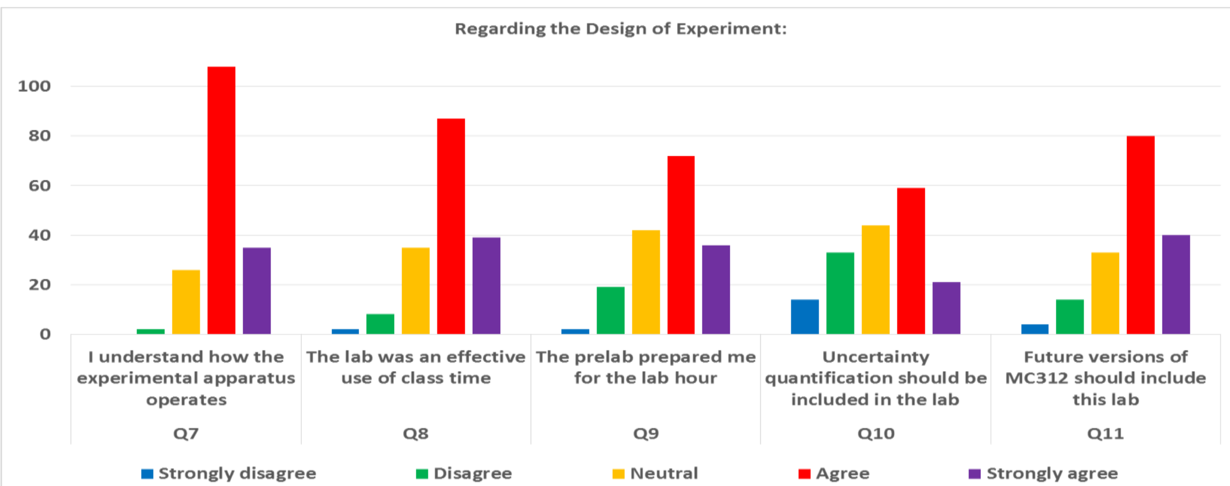

Figure 11. Student responses to questions 7-11 of MC312 Design of Experiment Survey.

A clear requirement was identified for students to design an experiment with 44.5% of respondents stating that other engineering courses prepared them only “moderately well,” “somewhat well,” or “not at all.” This is substantiated by the 11.2% increase in the same responses after conducting the DOE in MC312. This exercise also supports the ABET 3b student outcome of conducting and designing an experiment.

When asked about preference between creating a self-developed lab procedure versus being provided a step-by-step checklist (Question 2), students generally favored the latter. This is expected because up to this point, most laboratory exercises in other courses are well-scoped, with clear procedures and expectations outlined in detail. Of note, however, responses to Question 3 indicate that the majority believe there is more than one way to conduct the experiment. The existing DoE permits and encourages creativity in the execution of the experiment, leaving room for multiple avenues to achieve the same outcomes.

In Question 4, 62.6% of the population “agree” or “strongly agree” to making mistakes during the DoE. While making mistakes is not the intent of the DoE, it serves as a learning exercise with respect to approaching and solving a new problem. This is complemented in Question 5 by the 82.4% majority responding “agree” or “strongly agree” to the DoE requiring the use of critical thinking skills.

Table 1. Standard Deviation for total population and respective academic terms.

	Standard Deviation			
	AY 17-1, n=33	AY 17-2, n=89	AY 18-1, n=49	Total n = 171
Q1	0.816	0.931	0.612	0.853
Q2	0.854	1.034	1.014	0.998
Q3	1.141	1.167	0.866	1.091
Q4	0.781	1.024	0.842	0.934
Q5	0.635	0.837	0.659	0.755
Q6	0.678	0.823	0.661	0.751
Q7	0.659	0.682	0.526	0.636
Q8	0.659	0.939	0.638	0.848
Q9	0.893	1.087	0.702	0.962
Q10	1.237	1.160	0.977	1.144
Q11	0.902	1.047	0.685	0.964

Several indications point to sustaining the DoE in its current form in future MC312 offerings. Almost three-quarters of the course (73.7%) responded “agree” or “strongly agree” to the DoE being an effective use of class time (Question 8), with a total standard deviation of $\sigma_{TOTAL} = 0.848$. Furthermore, 70.2% stated they would “agree” or “strongly agree” with providing the DOE in future versions of MC312 (Question 11) with a total standard deviation of $\sigma_{TOTAL} = 0.964$.

Some negative responses to the DoE were observed. Three students (1.75%), all from AY 17-2, stated that MC312 did not prepare them at all for designing an experiment. Four students (2.34%), also all from AY 17-2, responded “strongly disagree” when asked if the DOE should be included in future offerings of MC312. Because the survey is taken anonymously, further investigation into the individual reasons for this response is required.

Conclusions and Future Considerations

Based on the desire to increase the technical rigor of the assignment, the need to satisfy the new writing-in-the-major requirement, and the positive feedback from the students, the new version of the DoE is an overwhelming success. As always, however, there are improvements to be made. The requirement of an instructor to proctor the one group of students’ use of the pipe friction demonstrator adds a sizeable time demand to the laboratory. Additional options that still allow for reliable matching of similarity between the model and prototype are being considered. One includes the construction of a parachute to model the delivery of air-dropped supplies.

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