AC 2011-37: ENHANCING THE STUDENTS' ABILITIES IN EXPERIMENTAL DESIGNS THROUGH DESIGN-EXPERT

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Enhancing the Students' Abilities in Experimental Designs through Design-Expert

Mechanical engineering students at the University of Kentucky are required to take a sequence of experimentation courses: Engineering Experimentation I (ME310) and Engineering Experimentation II (ME311). Engineering Experimentation II is an advanced laboratory course with the specific goal to enhance the students' abilities in experimental design and analysis to partially satisfy the ABET's learning outcome. Experimental design relies on principles of combinatorial mathematics such as combination, permutation, factorial, blocking, Latin square, etc. The analysis of experiments uses theories from statistics such as hypothesis, t-test, ANOVA, etc.

It is often hard for the students to manually design experimental layouts if they do not have sufficient combinatorial mathematics background. The theories of statistical analysis are relatively easy for students to grasp, but the calculations can be time-consuming. These issues could potentially shift the course focus away from experimentation and thus jeopardize the students' interests in this important subject. A Design-Expert software has been integrated into the experimentation course to help students learn the principles of the DOE. Students have used the software for designing the experiments and analyzing the results. This paper presents example lecture and experiment to demonstrate the effectiveness of the software. The impact on students' abilities in experimental designs is also discussed.

Introduction

Laboratory courses are an important component of engineering education. "Engineering without labs is a different discipline. If we cut out labs we might as well rename our degrees Applied Mathematics".[1] Laboratory courses are also important in accreditation and in ASEE Quality in Engineering Education Project.[2,3] The Accreditation Board for Engineering and Technology (ABET) requires that engineering programs demonstrate that their students attain eleven outcomes, including one that most specifically addresses laboratory courses:[2]

Outcome (b): Our students will have an ability to design and conduct experiments as well as to analyze and interpret data.

At the University of Kentucky, all mechanical engineering students are required to take a sequence of experimentation courses: ME310-Engineering Experimentation I and ME311-Engineering Experimentation II. While ME310 focuses on fundamentals of measurement techniques, instrumentation, interfaces, etc, ME311 focuses more on the overall experimentation process including the design and analysis of experiments, known as the DOE. One of the major learning outcomes, Outcome (1), as specified in the course syllabus is for students to develop:

1. *an ability to design, conduct and analyze experiments. Specifically, graduates will have*

    a. *a thorough understanding of the experimental design and analysis process;*
    b. *the ability to design, conduct and analyze experiments using modern principles and computer software;*
    c. *knowledge of basic probability necessary for modeling variability in data;*
    d. *knowledge of statistical tests for analyzing and interpreting experimental data;*
    e. *hands-on experience in conducting laboratory experiments and field surveys to collect data.*

Modern design of experiments relies on principles of combinatorial mathematics such as combination, permutation, factorial, blocking, Latin square, etc. and statistics such as hypothesis, t-test, F-test, ANOVA, etc. [4,5,6] It is often hard for students to manually design an experimental layout if they don't have sufficient combinatorial background. The theories of statistical analysis are generally easy for students to grasp, but the calculations are often tedious and can consume a significant amount of class time.

As a laboratory oriented course, ME311 consists of 4-hour lab and 1-hour lecture each week. With limited lecture hours, it has been a challenge to cover all the contents involved in the DOE. Since the fall of 2006, we have integrated the Design-Expert software into the ME311 course. This software is developed by Design-Ease, Inc. for experimental design and analysis.[7] It comes with the textbook Design and Analysis of Experiments, by D. C. Montgomery, published by Wiley.[4] The Design-Expert is a Windows-based program with many powerful DOE tools, such as two-level factorial screening, general factorial design, response surface methods, mixture design and Taguchi design, etc.[4,7] With the use of this software, the lecture contents have been presented more effectively. Students have used this software for designing and analyzing their experiments. As a result, the overall quality of the lab experiments has been significantly improved.

Overview of Design of Experiments: Design and Analysis of One-Factor Experiment

"Experimentation is a vital part of the scientific (or engineering) method".[1] Most problems in science and engineering requires experimentation to elucidate information about why and how the physical phenomena works. To better achieve the goals of the experiments, modern experimental strategy uses the method of factorial design and statistical analysis. The ME 311 lectures cover the theories of design and analysis of experiment (DOE). The lecture contents include: basic statistical analysis, blocking design, comparative experimental design, one-factor experimental design, factorial experimental design, fractional factorial design, and Taguchi's factorial design. All those topics have been discussed in class with the help of a computer program – Design-Expert.[7] The goal is to illustrate the complicate subjects more effectively within limited lecture hours. The following example lecture is used to illustrate briefly the principle of design of experiment and the use of Design-Expert software.

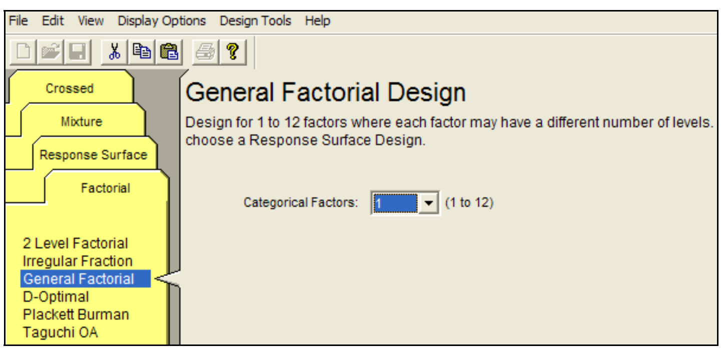
Example problem: A hardness machine is used to measure the hardness of a material. There are four indenter tips available and we wish to determine whether or not the four different indenter tips produce different hardness readings. Since the surface quality of test coupon can greatly affect the experimental results, the test coupon has to be considered as a block.

Step 1: Design of experiments

A factorial experiment can be designed based on the information stated in the problem:

Factor: indenter tip
Level: 4 different tips
Block: specimen
Replication: 4
Randomization: Yes
Response: Hardness

In Design-Expert, the general factorial is first selected. The number of factor is chosen as "one" since there is only one factor involved: the indenter tip. Since the replication of the experiment is desired, the number of replicates is entered. In addition, the "blocking" box is checked to eliminate the nuisance factor occurred at the experiments. Blocking is an important technique in designing an experiment. It is intended for minimizing or eliminating the effect of "nuisance factors" or "noise factors" that occur in the experiments, such as variations from raw materials, specimens, operators, environment, etc. Different statistical analyses will be used for experiments with and without blocking. Finally, the information for "response" is entered. The overall design process with Design-Expert is illustrated in Figure 1.



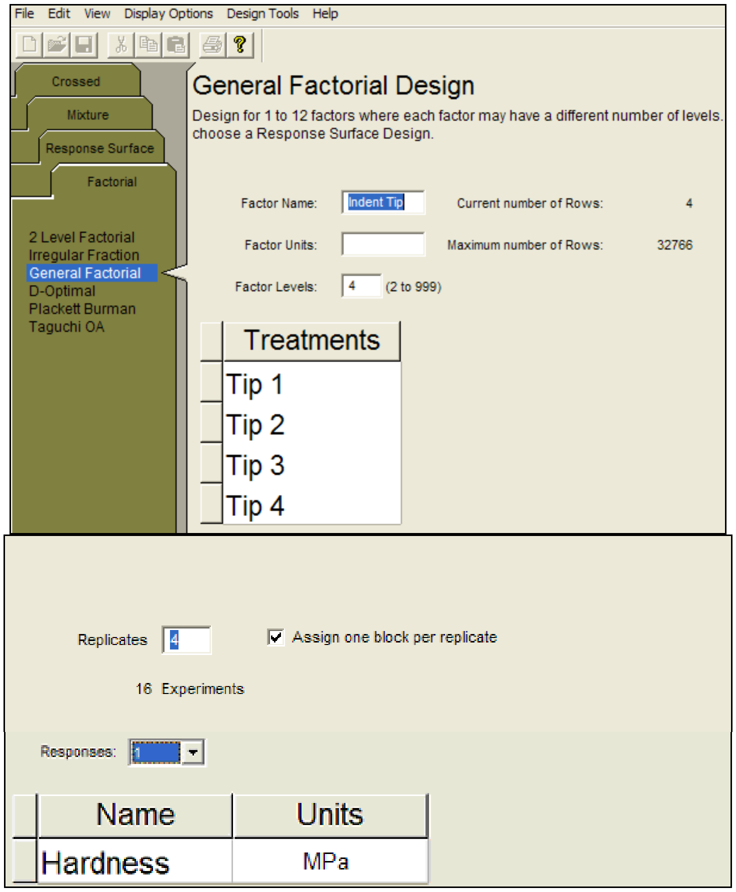


Figure 1. Design of One-Factor Hardness Experiment with Design-Expert.

Once all information are provided, the software will generate a “standard” design layout. If we want to further eliminate additional errors that may come from other sources such as the variation in equipment and/or operator, we can randomize the test sequence by conducting “randomize by run order”. Since there are four (4) tips and each tip needs to be replicated four (4) times, there are a total of 4x4=16 tests. Within each block, there are 4!=24 possible arrangements. For the four (4) blocks, the total number of ways of arranging the experiments is: 24x4=96. So it is highly likely that each student will obtain a different design layout. Figure 2 shows one of the experimental layouts after randomization.

<u>Execution of experiments</u>

Once the experimental design is completed, the students shall follow the design layout to carry out the experiments in the lab. After completing the experiments, the students can enter the results under the “Response” in the design layout, as seen in Figure 3.

Run	Block	Factor 1 A:Indent Tip	Response 1 Hardness
1	Specimen 1	Tip 4	
2	Specimen 1	Tip 1	
3	Specimen 1	Tip 3	
4	Specimen 1	Tip 2	
5	Specimen 2	Tip 4	
6	Specimen 2	Tip 1	
7	Specimen 2	Tip 2	
8	Specimen 2	Tip 3	
9	Specimen 3	Tip 3	
10	Specimen 3	Tip 2	
11	Specimen 3	Tip 1	
12	Specimen 3	Tip 4	
13	Specimen 4	Tip 2	
14	Specimen 4	Tip 1	
15	Specimen 4	Tip 4	
16	Specimen 4	Tip 3	

Figure 2. One Possible Design Layout for One-factor Hardness Experiments from Design-Expert.

Block	Factor 1 A:Indent Tip	Response 1 Hardness
Specimen 1	Tip 1	9.3
Specimen 2	Tip 1	9.4
Specimen 3	Tip 1	9.2
Specimen 4	Tip 1	9.7
Specimen 1	Tip 2	9.4
Specimen 2	Tip 2	9.3
Specimen 3	Tip 2	9.4
Specimen 4	Tip 2	9.6
Specimen 1	Tip 3	9.6
Specimen 2	Tip 3	9.8
Specimen 3	Tip 3	9.5
Specimen 4	Tip 3	10
Specimen 1	Tip 4	10
Specimen 2	Tip 4	9.9
Specimen 3	Tip 4	9.7
Specimen 4	Tip 4	10.2

Figure 3. Experiment Results in the Hardness Experiments.

Analysis of experiments

For experiments involved multiple factors, the analysis of variance (ANOVA) is required. Procedure for conducting an ANOVA consists of three steps:

(1) Set up hypotheses: Null hypothesis $H_0 : \mu_1 = \mu_2 = ... = \mu_a$
Alternative hypothesis $H_1 : \mu_i \neq \mu_j$

(2) Perform statistic test: $F_0 = \frac{MS_{Treatment}}{MS_E}$

(3) Draw conclusions:

- compare F_0 to $F_{a, a-1, (a-1)(b-1)}$, the critical value in F-distribution
- if $|F_0| > F_{a, a-1, (a-1)(b-1)}$, the null hypothesis is rejected and the alternative hypothesis is accepted.

For this experiment, the hypothesis may be stated as follows

- Null hypothesis: all tips produce the same hardness number
- Alternative hypothesis: one tip produces different hardness number from the other tips

The statistical test is then performed in the ANOVA analysis as summarized in Table 1.

Table 1. The ANOVA Table for One-factor Experiment

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0
Treatments	$SS_{Treatment}$	a-1	$SS_{Treatment}$ /(a-1)	$MS_{Ereatment}/MS_E$
Blocks	SS_{Blocks}	b-1	SS_{Blocks} /b-1	
Error	SS_E	(a-1)(b-1)	SS_E/(a-1)(b-1)	
Total	SS_T	N-1		

The variables in Table 1 are defined by the following equations[4]

$$y_{..} = \sum_{i=1}^{a}(\sum_{j=1}^{n} y_{ij})$$

$$\bar{y}_{..} = y_{..} / N$$

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n} y_{ij}^2 - \frac{y_{..}^2}{N}$$

$$SS_{Blocks} = \frac{1}{a}\sum_{j=1}^{b} y_{i.}^2 - \frac{y_{..}^2}{N}$$

$$SS_{Treatment} = \frac{1}{n}\sum_{i=1}^{a} y_{i.}^2 - \frac{y_{..}^2}{N}$$

$$SS_E = SS_T - SS_{Treatment}$$

Once the analysis is completed, one can draw a conclusion on if the hypothesis is accepted or rejected. If rejected, it means that one tip performs differently from the others. Next, one would like to know if any pair of tips performs the same or differently. That requires that the Fisher's LSD (Least Significant Difference) test be performed, which is essentially the multiple paired t-tests.[4]

$$\mathrm{LSD} = t_{\alpha/2,\ (a-1)(b-1)}\sqrt{\frac{2MS_E}{n}}$$

where $t_{a/2, (a-1)(b-1)}$ is the critical value from t-distribution and MS_E is the mean square of error shown in Table 1.

If $|\bar{y}_{i.} - \bar{y}_{j.}| > \mathrm{LSD}$, we conclude that the means μ_i and μ_j differ.

Statistical analysis has been covered to some extent in the first experimentation course (ME310). But, to actually carry out the entire statistical analysis by hand can be time consuming and inaccurate. With Design-Expert, the ANOVA can be calculated easily and accurately. Once the experimental results are entered, as shown in Figure 3, all statistical analyses, diagnostics, plots, etc. are generated immediately. Table 2 shows the ANOVA table for the present hardness experiments by using Design-Expert. Overall format of Table 2 is the same as Table 1. The conclusion on the hypothesis test is also given as indicated by "significant" or "insignificant".

Table 2. The ANOVA Table for One-Factor Hardness Experiments from Design-Expert.

Response:	**Hardness**					
ANOVA for Selected Factorial Model						
Analysis of variance table [Partial sum of squares]						
	Sum of		**Mean**	**F**		
Source	**Squares**	**DF**	**Square**	**Value**	**Prob > F**	
Block	0.82	3	0.27			
Model	0.38	3	0.13	14.44	0.0009	significant
A	*0.38*	*3*	*0.13*	*14.44*	*0.0009*	
Residual	0.080	9	8.889E-003			
Cor Total	1.29	15				

Table 3 below summarizes the Fisher's LSD calculations from Design-Expert. It is basically six paired t-tests. Based on this, we can conclude that tips 1 and 2, 1 and 3, 2 and 3 are essentially the same, while tips 1 and 4, 2 and 4, 3 and 4 are different. The effect of indenter tip on hardness can also be graphed as seen in Figure 4. The validity of the analysis can verified by plotting out the normal probability of the residuals (Figure 5).

Table 3. The Fisher's LSD for One-Factor Hardness Experiment from Design-Expert.

Treatment	Mean Difference	DF	Standard Error	t for H_0 Coeff=0	Prob > |t|
1 vs 2	-0.025	1	0.067	-0.38	0.7163
1 vs 3	0.13	1	0.067	1.87	0.0935
1 vs 4	-0.30	1	0.067	-4.50	0.0015
2 vs 3	0.15	1	0.067	2.25	0.0510
2 vs 4	-0.27	1	0.067	-4.12	0.0026
3 vs 4	-0.43	1	0.067	-6.37	0.0001

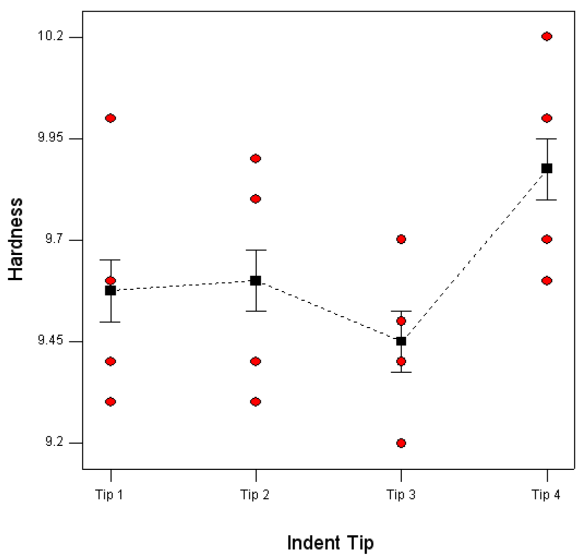


Figure 4. The Hardness Number vs. Indenter Tip.

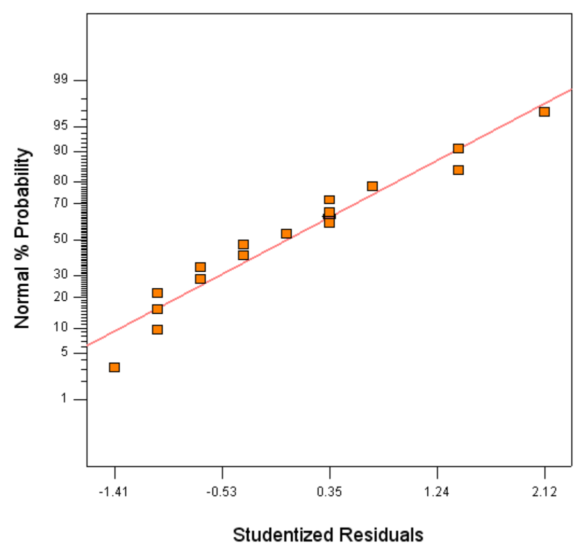


Figure 5. The Normality Plot of Hardness Experiments.

Example Lab with Design-Expert: Dynamic Optimization of a Square Plate

ME311 typically consists of four experiments, covering different mechanical engineering subjects such as fluid mechanics, heat transfer, dynamics, and thermal science. All experiments are open-ended in nature, so the students have the complete freedom to design their experiment based upon the assignment given by the instructors. Students are encouraged to use Design-Expert for all their experimental activities. The following is an experiment assigned to the students:

Dynamic Experiment: Optimal design of a structural plate for vibration attenuation

The objective of this experiment is to seek an optimal design solution of a structural plate (1/8" thick steel) used for vibration attenuation. Your task is to find out the factors that will affect the structure's model frequencies and then alter those factors to maximize the modal frequencies (first three modal frequencies) while keeping the cost at a minimum.

The students first had the brain-storm meeting and came up with the possible factors that may affect the dynamic response of the plate. After taking into account of various constraints such as timing and materials, most students have chosen to conduct either a two-factor or three-factor factorial experiment. One example design is to consider the factors of: (A) reinforcing rib size and (B) reinforcing rib position on the plate. Each factor has been varied at two levels. That results in a 2^2 factorial experiments, and the design layout is shown in Table 4. The actual fabricated plates are seen in Figure 6.

Figure 6. Specimens Used in the 2^2 Factorial Experiments. From Left to Right: Smooth plate, Small-rib-parallel plate, Small-rib-cross plate, Big-rib-parallel plate, Big-rib-cross plate.

To execute the experiments, the plates of various configurations (Figure 6) were stroked with an impact hammer and the frequency responses of the plates were measured with the accelerometers. With the Fast Fourier Transform (FFT), the frequency spectrum of each plate was constructed, from which the first three modal frequencies were identified.

Once the frequencies were obtained for each plate, as seen in Table 4, the students then went on the "analysis" step with Design-Expert. The ANOVA result for the 1st modal frequency is seen in Table 4. It shows that both factors, (A) reinforcing rib size and (B) reinforcing rib position, have significant effects on the first mode of the plate. Figure 7 depicts the effects graphically. The same analysis is then repeated for the 2nd and 3rd modal frequencies, and similar results have been obtained. Students have greatly appreciated the use of the software since it has improved the quality of the experiments and saved the amount of time that would otherwise be spent on experimental design and analysis.

Table 4. Design Layout and Results for the 2^2 Factorial Vibration Experiments.

Run	Factor 1 A:Rib Size	Factor 2 B:Rib Position	Response 1 1st Modal Freq. Hz	Response 2 2nd Modal Freq. Hz	Response 3 3rd Modal Freq. Hz
1	Big	Parallel	781.0	1422.	1747.
2	Small	Parallel	722.0	1288.	1981.
3	Big	Cross	865.0	1281.	2431.
4	Small	Cross	772.0	1194.	2191.

Table 5 – ANOVA Results for the 1st Modal Frequency

Response: 1st Modal Frequency						
ANOVA for Selected Factorial Model						
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
A	5.8E+003	1	5.8E+003	20.	0.14	(significant)
B	4.5E+003	1	4.5E+003	16.	0.16	(significant)

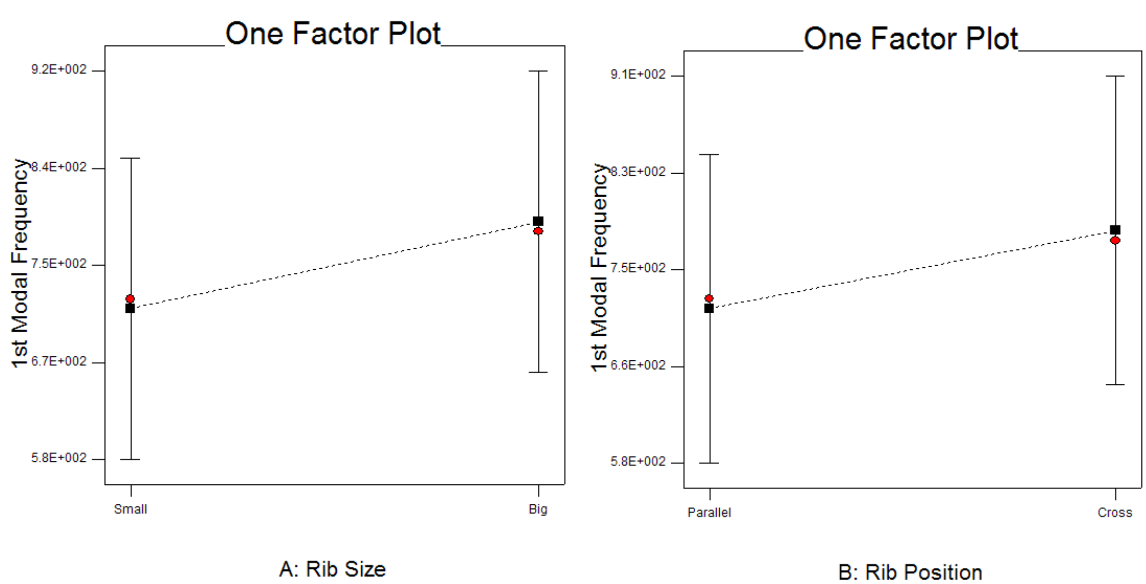


Figure 7. Effects of Rib Size and Rib Position on 1st Modal Frequency of the Plate.

Assessment and Evaluations

The student performance in this lab course has been evaluated through several venues: including the assessments from the instructors and from the students themselves.

Instructor assessments: There are four opportunities in which Outcome (1) assessments can be performed: 1) homework, exercises, and exam on the DOE theory, 2) the group presentations on their experimental design plans, 3) their group presentations on their experimental results, and 4) their final lab reports. These areas should very adequately cover the major components of Outcome (1). The first two areas address their ability to design and conduct experiments while the latter two areas address the ability to analyze and interpret data.

A synopsis of the assessment results for the Fall 2009 ME 311 course is shown in Table 6. The first line assesses their overall performance on the DOE theory component. Since the design of the experiments, their execution, and the analysis of data are evaluated separately, the scores for each lab experiment have been weighted to produce a single assessment score. The weighting factors that were used were:

Experimental design presentation - *15%*
Experimental result & analysis presentation - *15%*
Lab reports - *70%*

Table 6. Summary of the Scores from Assessing Outcome (1) in ME 311 (Fall 2009).

Source	**Description**	**Possible Score**	**Ave.**	**Min.**	**Max.**
DOE Lecture components	Theory of Design and Analysis of Experiments (DOE) • DOE Homework • DOE Tutorials • Exams	100	84	70	92
Lab 1	Dynamic Experiments • Oral presentation on experimental design. • Conducting the experiment. • Oral presentation on experiment results. • Submitting individual lab report.	100	87	82	92
Lab 2	Heat Transfer Experiment • Oral presentation on experimental design. • Conducting the experiment. • Oral presentation on experiment results. • Submitting individual lab report.	100	82	77	86

Lab 3	<u>Fluid Experiments</u> • Oral presentation on experimental design. • Conducting the experiment. • Oral presentation on experiment results. • Submitting individual lab report.	100	80	67	88
Average			84%		

As with any design problem, there is no single correct way to design an experiment, so the grading criteria are based on correct application of DOE principles and statistical analysis that should yield valid results. Based on these measures with the average assessment score of 84%, we conclude that our students have acceptable abilities outlined in Outcome (1).

<u>Student assessments:</u> At the end of the semester, the students are required to complete the course evaluation. One set of the questions is about the students' own assessments on their learning outcomes. Results from the last seven years (before and after the use of Design-Expert software) are shown in Table 7.

Course Evaluation Questions:

1. Understand the principles of engineering methods and apply the principles when solving problems.
2. Design and conduct experiments
3. Analyze experimental data including procedures to handle uncertainties and errors which occurred during the measurements.
4. Communicate experimental results effectively in writing and presentation.
5. Opportunity to perform experiments in dincrent technical areas such as thermodynamics, fluid mechanics, heat transfer, mechanics, power systems such as rotating machinery and engines, and instrumentation and data acquisition.
6. Articulate the principles of teamwork.
7. Work with a team to complete a project involving multiple roles and apply skills of effective teamwork.
8. Have an ability to use the technical skills, and modem engineering tools necessary for engineering practice (i.e., Data Acquisition).

Questions 1-3 particularly access the students' ability in designing and analyzing engineering experiments. It is seen that, since adopting the Design-Expert software, the scores for these questions have been noticeably improved.

Table 7. Summary of the Scores from Course Evaluations in ME 311.

Question	Before Using Design-Expert			After Using Design-Expert			
	2003	2004	2005	2006	2007	2008	2009
1	3.5	3.4	4.1	4	4.2	4.4	4
2	3.5	3.3	3.9	4.7	4.4	4.5	4
3	3.4	3.2	4.1	3.5	4	4.2	4.1
4	3.4	3.6	4	3.8	4	4.3	4.1
5	3.3	3.7	4	4.3	4.3	4.5	4
6	3.4	3.6	4	4	4.1	4.4	3.9
7	3.4	3.7	4.1	4.3	4.2	4.5	4.3
8	3.5	3.3	4	3.7	4.3	4.5	4.1

0 = Not Applicable 1 = Unacceptable 2 = Poor 3 = Acceptable 4 = Good 5 = Outstanding

Conclusions

Design-Expert software has been integrated into an advanced engineering experimentation course that deals with design, execution and analysis of experiments known as DOE. Design-Expert has been found to be an effective tool for illustrating the DOE principles and performing the statistical analysis. The amount of time spent on "abstract" combinatorical design and statistical analysis can be greatly minimized. Students have used this software for designing and analyzing their experiments. The quality of the experiments has been improved and the learning outcomes are better achieved.

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