AC 2010-180: INTRODUCING FRESHMAN ENGINEERING STUDENTS TO EXPERIMENTAL DESIGN: COFFEE BREWING

Stephanie Farrell, Rowan University

Stephanie Farrell is an Associate Professor of Chemical Engineering at Rowan University. Her educational interests include the incorporation of experiential learning throughout the ChE curriculum and the development of academe-industry-government collaboration. She is the recipient of the National Outstanding Teaching Award (2004) and the Robert G. Quinn Award (2006), and she currently serves on the ASEE Board of Directors as Zone I Chair.

Zenaida Otero Gephardt, Rowan University

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Abstract

At Rowan University, we have introduced experimental design throughout the Chemical Engineering Curriculum, in all levels of Engineering Clinics (freshman through senior) as well as the senior Unit Operations Laboratory. This paper describes a module used in our Freshman Clinic which introduces students to experimental design through a hands-on coffee brewing experiment and Statgraphics computer laboratory. Students perform a 2x2 experimental design to prepare coffee using a French press coffee maker, and the effects of water temperature and brewing time on the concentration of the coffee are determined. Hand calculations are performed to identify the effect of each variable and develop a predictive model for coffee concentration. In a follow-up computer laboratory, Statgraphics computer software is used to perform the same analysis and the results are compared with the hand calculations. Assessment results indicate that 85% of students successfully achieved learning objectives related experimental design.

Introduction

Experimental design is a statistics-based tool that uses experiments conducted at selected conditions to determine the effect of particular variables. Experimental design offers several advantages over the one-factor-at-a-time approach: the number of experiments is minimized, the information obtained is maximized, and local operational optima can be identified. Using critical and abstract reasoning to make the design and analyze results, meaningful conclusions can be made with a minimum number of experiments.

At Rowan University, all freshmen are required to take an introductory engineering course called Freshman [course]. This 2-credit, multidisciplinary course comprises a one-hour lecture and a 3-hour laboratory each week. Students learn engineering skills in a hands-on, project-based format. The technical learning objectives of the course include introducing students to measurements of physical quantities; units and conversions; collection, analysis and interpretation of data; and the formation of meaningful conclusions from experimental results. Additionally, students learn teamwork skills and oral and written communications by working in teams throughout the semester, preparing frequent technical progress reports, and delivering oral presentations based on the project.

The introduction of statistical experimental design through laboratory experiences in upper level engineering courses has been addressed previously [1, 2, 3, 4]. Ludlow et al.[2] address the importance of the application of statistics as a skill needed by undergraduate engineers and present a simple gas chromatography experiment which allows students to develop statistical skills without being bogged down by a complicated experiment. McCluskey et al. [5] describe a simple experiment that uses a factorial design to determine the best cup of coffee, but the quantification of experimental results posed a challenge. This paper describes the integration of experimental design into the Freshman Clinic, in a project-based format which involves many aspects of coffee brewing. Experimental design is one of several modules which also include one-factor-at-a-time (OFAAT) mass transfer analysis, heat transfer and energy efficiency, and product operation, dissection, and reverse engineering. After completion of the module, a student should meet the following learning objectives: To generate a factorial design for the investigation of a system or process; to use critical thought to specify appropriate ranges for the factors being investigated; to determine the effect and significance of the factors on the response of the system or process; to determine the effect and significance of curvature on the response of the system or process, and to determine whether interactions between factors are significant; to develop a process model and use it to predict the response of the system under specified operating conditions. Students should be able to perform the above tasks using hand calculations, and Excel spreadsheet, and Statgraphics computer software.

Experiment and Workshop

After performing a series of OFAAT experiments which investigated the effects of grinding time, temperature, and flow rate on the coffee concentration, students were introduced to experimental design. After a brief introductory presentation with examples, students spent the remainder of a class period working through detailed sample calculations for a 2x2 experimental design. One of the concepts that was emphasized was the importance of selecting meaningful and appropriate ranges for the factors being investigated.

Students were required to develop their own 2x2 experimental design for their next laboratory experiment. This experiment involved brewing coffee in a French press coffee maker (Figure 1). The factors investigated were water temperature and brewing time. The effect on coffee concentration was studied. Students specified a high, low and center point value for each factor (temperature and time), after considering what range of values would be most meaningful and appropriate for this process. Typically, students chose water temperatures in the range of 70 - 95 °C and times between 30 s and 6 min. Some teams chose wider ranges of temperature or time and would subsequently observe differences in the significance of the factors. Additionally, a separate set of experiments were conducted to determine the value of the standard deviation.

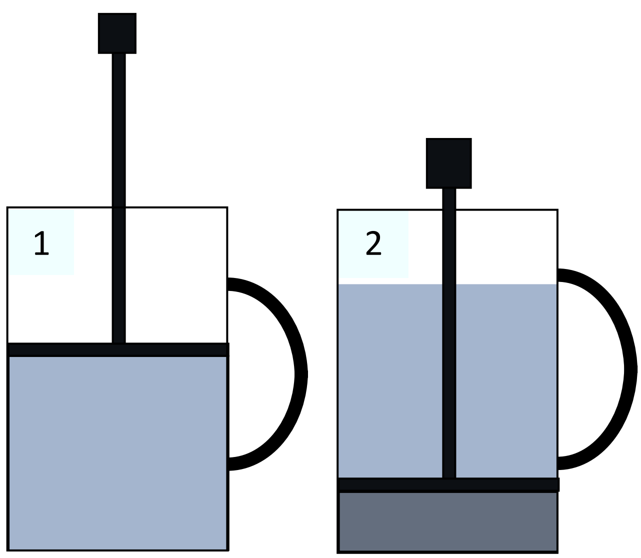

Figure 1. French Press Coffee Maker. First coffee grounds are brewed with hot water for a designated time (1). Then the plunger/filter is depressed, separating the coffee grounds from the coffee (2).

The experiment was performed according to the following procedure (which requires unit conversions): Coarse-ground coffee was measured out according to the manufacturer's instructions (1 rounded Tbsp per 4 oz of water). The coffee was weighed on an analytical balance, and this mass of coffee was used in subsequent experiments for accuracy. The recommended volume of water (237 ml) was measured in a graduated cylinder and introduced into the French press carafe; the carafe was marked at 237 ml, and then the water was removed from the carafe. Approximately 4 cups of water were boiled in an electric kettle. Some of this water was used to warm the glass of the French press carafe. The remaining water was adjusted to the desired temperature by mixing it with cold water, and then the carafe was filled with 237 ml water. The ground coffee was then introduced to the carafe, the time was monitored using a stopwatch, and the plunger was depressed at the desired brewing time. The coffee was poured into a cup and allowed to cool to 35 °C. The absorbance of the coffee was measured at a wavelength of 640 nm using a Spec 21 spectrophotometer.

Coffee concentration was correlated with absorbance using a calibration curve developed previously, as shown in Figure 2.

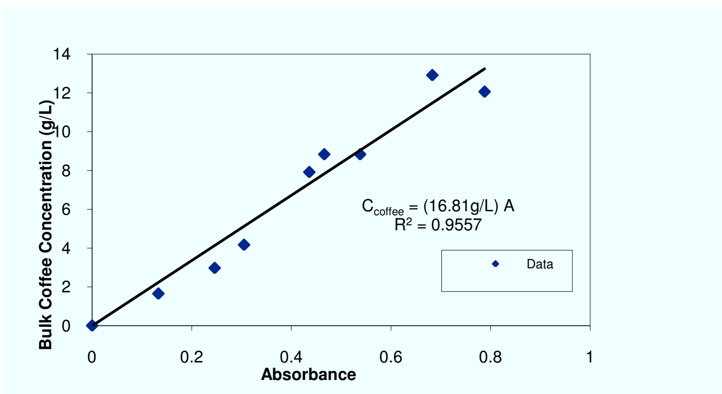

Figure 2. Calibration plot for SuperG Colombian Supremo at 640 nm

Data Analysis and Results

Experimental design analysis was performed using both tabular analysis and Statgraphics software. Using Excel, students determined the significant factors and developed a process model (regression equation). The process model was used to predict the concentration of coffee made at a specified temperature and brewing time.

Tabular analysis (Table 1) is used to determine the significance of each factor and curvature by comparison to the minimum significant factor and curvature effect values. Comparison of these values shows that the effect of brewing time is not significant (E=0.015 and MSFE = 0.0213), while the effect of temperature is significant (E=0.225 and MSFE = 0.0213). Curvature is not significant (Txt = 0.005 and MSCE – 0.0261). The data shown in Table 1 were obtained by students for the time and temperature ranges specified by the team.

Table 1. Sample analysis calculation table for coffee experiments.

Temperature Code and (^oC)	**Brew t Code and (min)**	**Brew t X T**	**Abs**
-1 (60)	**-1 (2)**	**+1**	**0.06**
+1 (93)	**-1 (2)**	**-1**	**0.28**
-1(60)	**+1(6)**	**-1**	**0.07**
+1(93)	**+1 (6)**	**+1**	**0.30**
S+ 0.58 S- 0.13 D 0.45 E 0.225	0.37 0.34 0.03 0.015	0.36 0.35 0.01 0.005	Sum of + values Sum of – values Difference betwn S+ and S- D/2
0 (170)	0 (4)		0.19
MSFE = $t \cdot s(2/mk)^{1/2}$=0.0213	MSCE = $t \cdot s \left(\frac{1}{mk} + \frac{1}{c} \right)^{½}$ 0.0261	s=0.011 t = 2.13	Curvature = 0.0125

Using Statgraphics software, students repeated the determination of significant factors and the development of a process model. The software was also used to generate a Pareto chart, main effects plot, interaction plot, and contours plot. Significant factors were evaluated using the Pareto chart and compared to the coefficients in the process model. The Pareto chart shown in Figure 3 shows that temperature has a significant positive effect on the coffee concentration, whereas the effects of time and curvature are not significant. The range of temperature used by this student team was from 60 - 93°F, and the range of time was from 2-6 minutes. It should be noted that these are not ideally chosen values if the goal is to represent realistic process conditions – a temperature of 60 °F is unrealistically low, and a time of 6 minutes is unrealistically long. This student team observed that time, in the range chose, was not a significant factor. When the teams compared results, it became apparent that time was a significant factor when shorter times were investigated, e.g., 3-s-2 min.

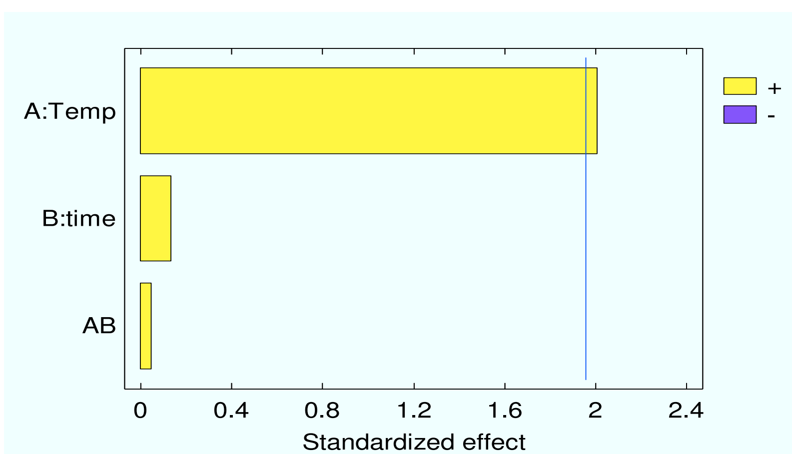

Figure 3. Standardized Pareto chart for absorbance.

An Interactions plot for the same experimental design is shown in Figure 4. This plot shows that there are no significant interactions present.

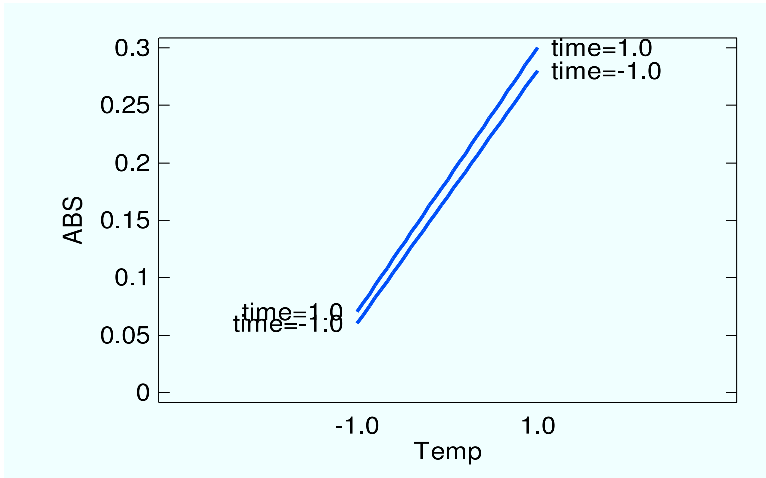

Figure 4. Interactions plot for absorbance

A contour plot showing the estimated response surface is shown in Figure 5. This plot allows selection of operating conditions to achieve a desired response, in this case coffee absorbance or concentration. For example, to achieve an absorbance in the range of 0.15-0.18, temperature and time could be chosen to in the range of values shown by the aqua region on the plot.

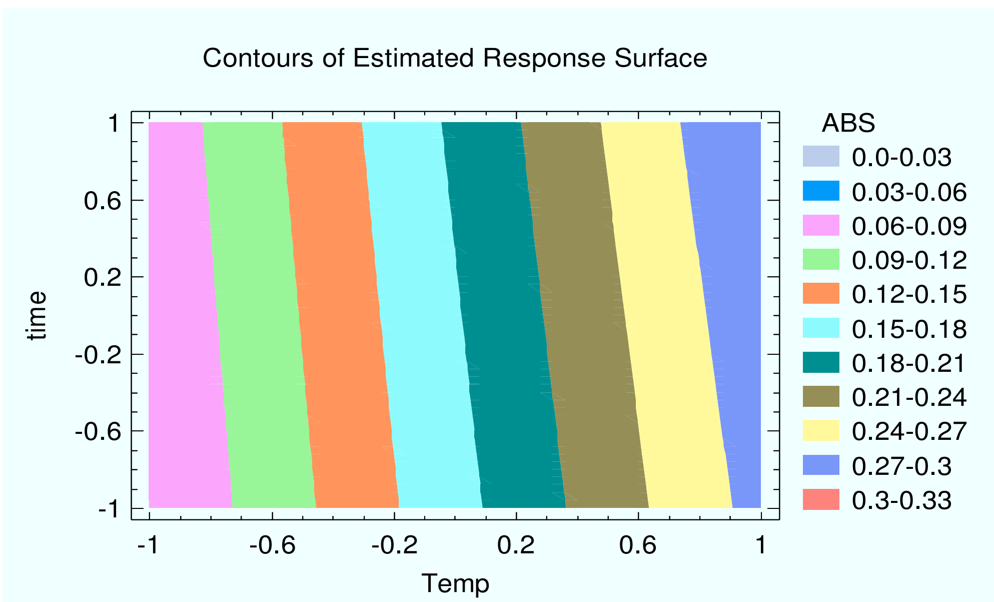

Figure 5. Contours of estimated response surface (absorbance).

The process model for this design is given by the following equation:

$$ABS = 0.17375 + 0.10875 * Temp + 0.006 * time + 0.00125 * Temp * time.$$

The small coefficients of the time and the Temp*time terms reflect the fact that these are not significant factors. This equation can be used to predict directly the response (absorbance) that will be achieved using specific operating conditions (temperature and time).

Assessment

This project and experimental design module has been run in three consecutive years of the Freshman Clinic. To evaluate student learning of concepts related to experimental design, three instruments were used: the final report, a final oral presentation, and the final exam. The cumulative results over the three year period are presented here. A total of 62 students were evaluated.

An assessment plan was developed to map student work directly to the individual learning outcomes of these freshmen. Levels of student performance were assigned values of 1-4 on an ordinal scale. A score of 4 represents an expert who has mastered the given objective; a score of 3 represents a skilled problem solver; a score of 2 represents a student who has some skills but lacks competence; a score of 1 represents a complete novice. This assessment was based on reasonable expectations for freshmen students who have had their first introductory exposure to engineering principles.

Four instruments were chosen for the evaluation: a team laboratory report, an individual computer workshop, an oral presentation, and a final exam. These were evaluated for three consecutive years. Using rubrics, levels of student performance are assigned values of 1-4 on an ordinal scale. A score of 4 represents an expert who has mastered the given objective; a score of 3 represents a skilled problem solver; a score of 2 represents a student who has some skills but lacks competence; a score of 1 represents a complete novice. Table 2 shows the stated objectives/outcomes that were evaluated on a four-point ordinal scale and results of student performance. The assessment scores were consistent and highly satisfactory; the percentage of students receiving a rating of 3 or 4 was above 85% for each objective.

Summary and Conclusions

Experimental design has been introduced in a project-based learning context in the freshman [course] at [ ] University. Students are familiarized with hand calculations (tabular analysis and calculation tables), Excel functions and calculations, and Statgraphics software. These tools were used to determine the effects of temperature, and time, on coffee concentration, to identify the interactions, and to evaluate curvature. A process model was developed that would allow the determination of optimum conditions to achieve a desired coffee concentration.

The student performance scores were consistent and highly satisfactory; the percentage of students receiving a rating of 3 or 4 was above 85% for each stated learning objective. We believe that the results indicate that successful completion of the learning objectives was achieved.

Table 2. Educational outcomes and student performance. Student performance is presented as a percentage of students achieving the denoted level of performance in the four instruments used for assessment.

Educational Outcome (Demonstrated Ability)	Student Performance (%)			
	4	**3**	**2**	**1**
To generate a factorial design for the investigation of a system or process	61	31	5	3
To use critical thought to specify appropriate ranges for the factors being investigated	64	25	6	5
To determine the effect and significance of the factors on the response of the system or process	60	32	3	5
To determine the effect and significance of curvature on the response of the system or process	56	36	3	5
To determine whether interactions between factors are significant	61	30	3	6
To develop a process model and use it to predict the response of the system under specified operating conditions	60	26	8	6

References

[1] Ludlow, D., Using Statistical Experimental Design to Optimize GC Operation, Proceedings of the Annual ASEE Conference, Session 3213 (1996).

[2] Ludlow, D., Schulz, K.H., and Erjavec, J, Teaching Statistical Experimental Design Using a Laboratory Experiment, J. Eng. Ed., 84(45) 351-359 (1995).

[3] Bulter, A., Moses, W.M., Introducing Experimental Design in Mechanical Engineering Laboratories, Proceedings of the Annual ASEE Conference (2005).

[4] Waitz, I.A., Barrett, E.C., Integrated Teaching of Experimental and Communication Skills to Undergraduate Aeorspace Engineering Students, Proceedings of the Annual ASEE Conference, Session 2302 (1996).

[5] McCluskey, R.J. and Harris, S.L., The coffee Pot Experiment: A Better Cup of Coffee Via Factorial Design, Chemical Engineering Education, Summer 1989, pp. 150-153.