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Loose Change and Dishwasher Optimization: Creative Applications of Engineering Statistics

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1. Introduction

The modern chemical engineering industry relies heavily on statistical process improvement methods to reduce the incidence of defects or otherwise poor output from a given process. Numerous Fortune 500 companies are known to use statistics-based process improvement methods such as Six Sigma[1], and an entire industry exists based on training and certification in these methods. The driver for the adoption of these process improvement methods by industry is the possibility of substantial savings, reliability and capability gains in the manufacture and sale of company products[2-4].

Though statistical analysis has important applications and is typically part of the operational culture many chemical engineers will encounter in the workplace, engineering statistics coursework is often considered to be "dry" or "boring" by undergraduate students. This viewpoint is often further aggravated by the teaching and testing associated with engineering statistics, which typically rely on lower-order thinking skills in Bloom's Taxonomy. For instance, a typical engineering statistics lecture would demonstrate to students how to complete a statistical analysis using provided data. The homework assignment associated with this lecture would simply provide similar data to the students while asking them to complete the required statistical analysis using the same rote problem-solution procedures specified in the lecture. This type of "plug-and-chug" approach only requires students to (1) remember the problem-solution procedure, (2) understand how to apply the problem-solution procedure, and (3) apply the procedure to the given data. While this approach can be used to evaluate students' application of statistical concepts to engineering data, due to its deficiencies students often struggle to understand the relationship between statistics and the real-life processes to which they will be applying statistics in their careers.

A particular concept in engineering statistics for which the rote problem-solution approach is especially poor is the subject of design of experiments (DOE). The DOE concept is a powerful statistical method which not only directs the planning and execution of an experiment, but also allows quantitative interpretation of the outcomes of the experiment. A key advantage of the DOE concept is that after choosing the dependent and independent variables of interest, the researcher then only needs to execute the experimental design suggested by DOE to provide data ready for analysis. However, many homework assignments related to the DOE concept do not lead students through the entire DOE process, instead presenting data from an already-completed study for students to evaluate. Based on this type of homework problem, it is difficult for an instructor to determine if students *understand* the application of DOE and the relationship between statistical design and real-life processes, since students do not actually "design" the experiment, execute the design, then draw conclusions based on statistical analysis – someone else has already designed the experiment and collected the data, leaving students only to crunch the numbers.

An alternative assignment for evaluating student understanding of statistical methods, namely the DOE concept, is presented in this study. In the assignment, students are asked to evaluate any process and factors they desire via the DOE method. Allowing students to apply the DOE concept to any process they choose is a strategy to enable students to relate the subject of engineering statistics to their everyday lives, increasing subject relevance. Critical thinking is encouraged in the assignment by tasking students to determine the appropriate dependent and independent variables which affect their process, as well as the values to be tested for each variable. Students are encouraged to be creative in choosing their tested process and variables, allowing them to investigate topics of interest that may not be suitable for evaluation in other engineering courses. The key goals of offering this assignment are to (1) increase subject relevance, (2) improve critical thinking skills, and (3) develop and strengthen creativity in order to encourage higher-order thinking skills of Bloom's Taxonomy such as analyzing, evaluating and creating.

Pedagogical research has found that writing assignments effectively facilitate learning by forcing students to explore connections and patterns in the studied material[5, 6]. These benefits of writing assignments are enhanced in fields such as engineering, since students are rarely assigned reflective writing tasks and thus have few opportunities to develop associated abilities[7, 8]. With these factors in mind, students are asked to summarize their DOE study and findings in a brief two-page report. Additional details about the assignment and student feedback are provided in the following sections.

2. Background

2.1. DOE Background

Often in research it is desired to determine the effect of various independent variables on a single measured dependent variable. This dependent variable can be catalyst productivity, income, blood pressure or any similar quantitative property. DOE (also known as experimental design) is a structured approach used to establish and quantify causality relationships between independent variables (factors), as well as their interaction effects, and the outcome of an experiment. The DOE approach can be applied broadly to many fields outside of engineering, including finance, health and social sciences[9].

To illustrate the DOE method, suppose that you are planning a series of experiments that investigate the effect of three independent variables (A, B and C) on a measured response (Y). A first impression may be to vary each of A, B and C one at a time while measuring Y, but analysis of data and inference of conclusions would not be straightforward. Not only would such an approach be inefficient, but the researcher could also overlook possible interaction effects among the various factors[9]. For instance, perhaps a study on mixing is performed where Factor A is the injection temperature of a solvent and Factor B is mixing speed – the interplay of temperature with viscosity (and resulting shear forces) may affect results greater than either variable alone.

A case study follows which illustrates the analysis of a 3-factor, 2-level experimental design. The term “3-factor” indicates that three independent variables will be examined in the study, while “2-level” refers to the two levels (high and low, denoted by +1 and -1 respectively) for testing each variable. A DOE example is examined here for a study regarding beverage chilling. In this experiment, the process of cooling a room temperature beverage is examined. The dependent variable, which in this case is final beverage temperature, is an objective, quantitative response which is measured with a thermometer or thermocouple. The three independent variables (factors) evaluated in this study are:

- Factor A: Cooling time
    - +1 value: 40 minutes
    - -1 value: 20 minutes
- Factor B: Cooling method
    - +1 value: freezer
    - -1 value: refrigerator
- Factor C: Container material
    - +1 value: bottle
    - -1 value: can

In order to execute this experimental design, students would complete the testing scheme described in Table 1. For instance, the first experiment to be completed would be to place a can of the tested beverage (at room temperature) into a refrigerator for 20 minutes. At the end of this 20 minute period, students would measure and record the temperature of the liquid in the can (Y_i). After completing all of the experimental trials specified in Table 1, the experimental design can be evaluated using a standard method.

Table 1. Standard run order for 3-factor, 2-level DOE scheme.

Trial #	Experimental Factors (Independent Variables)		
	Cooling Time (A)	Cooling Method (B)	Container Material (C)
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1

The DOE analysis procedure is briefly summarized here; additional DOE description and examples can be found elsewhere[10,11]. The first step in evaluating the DOE data is to determine the overall mean response (φ_{mean}), which establishes the baseline response among the tested variables and serves as the starting point for the predictive model which will be developed. Next, the effects of Factor A (φ_A), Factor B (φ_B), and Factor C (φ_C) are calculated. The absolute values of φ_A, φ_B, and φ_C reveal the relative influence of each variable on the final response. In this example study it is found that $|\varphi_B| > |\varphi_A| > |\varphi_C|$, so it can be said that the cooling method has the greatest effect on the final beverage temperature, while the length of time in the refrigerator / freezer has the second-greatest effect. Choice of container material is shown to be a comparatively less significant affecter. The sign of each of φ_A, φ_B, and φ_C indicate whether the positive or negative value for each factor raises or decreases the system response. For instance, the value of φ_B for this study is negative; this indicates that cooling with the freezer (+1) causes a reduction in the response (final beverage temperature). This relationship is incorporated into a predictive model later in the DOE analysis.

A key advantage of the DOE method is the ability to quantify the effect of interactions between tested factors on the response, which would be difficult to discern with a less powerful method. After determining the effects of individual factors, the interactions between Factors A & B (φ_{AB}), Factors A & C (φ_{AC}), and Factors B & C (φ_{BC}) are determined. For this example study, the values determined for φ_{AB}, φ_{AC}, and φ_{BC} are small in comparison with φ_A, φ_B, and φ_C, indicating that interactions between the tested factors are secondary to the effect of the factors themselves. Practical conclusions from DOE analysis of this case study include the knowledge that if it is needed to chill beverages from room temperature as quickly as possible (perhaps upon arrival of unexpected guests), then (1) the ideal choice is to place the beverages in the freezer, and (2) neither bottles nor cans offer a significant advantage. While the former conclusion may be obvious, the latter conclusion is not.

Another advantage of the DOE method is that the φ values calculated for each factor and interaction may be used as input for a mathematical model which can predict system response for untested values of each factor within the tested range. For this 3-factor, 2-level experimental design, the model equation predicting experimental response (Y_{model}) would be:

$$Y_{model} = \varphi_{mean} + \frac{\varphi_A}{2}(A) + \frac{\varphi_B}{2}(B) + \frac{\varphi_C}{2}(C) + \frac{\varphi_{AB}}{2}(A)(B) + \frac{\varphi_{AC}}{2}(A)(C) + \frac{\varphi_{BC}}{2}(B)(C) + \frac{\varphi_{ABC}}{2}(A)(B)(C) \quad (1)$$

Equation 1 uses inputs for each factor (A, B, C) based on the specified +1 to -1 scale. For instance, if it was desired to predict the final beverage temperature for a can of room-temperature beverage placed in the freezer for 30 minutes, then the inputs for Equation 1 would equate to the following factor values:

- A = 30 minutes = 0 (in other words, 30 minutes equates to a value of 0 considering that 20 minutes is set as -1 and 40 minutes is set as +1 in the experimental design)

- B = freezer = +1
- C = can = -1

Based on the DOE model in Equation 1, the predicted final temperature for this specified trial is 35.5°F. An additional trial testing these factor values returns a response of 35°F, which is in reasonable agreement with the model prediction. The accuracy of the model prediction can be verified and reasons for inaccuracy proposed as by students part of the assignment.

2.2. Description of Assignment

The problem statement for the alternative DOE assignment allows students to test any process and factors they choose as long as the process provides a quantitative, objective response. A number of example studies are suggested in the problem statement in order to show students ways to be creative with choices for their studies; in the event a student has difficulty coming up with their own study, it is suggested that they complete one of the example studies. Allowing students to choose their own study is intended to encourage creativity. However, since students must also determine three factors to test which are expected to influence their measured response (and the associated values to test as -1 and +1 factor values), critical thinking and understanding of the tested system is required as well.

Once the experiment is planned, students execute their experimental designs and present their findings and conclusions in a brief two page report. Anecdotally, some ChE students have the misguided notion that written communication is not valued in industry, which is encouraged by the fact that few written assignments are required in ChE coursework. Asking students to summarize their work in a brief report with specified page limits assists in developing skills related to effective, concise written presentation of technical information. Three questions are provided to students in the problem statement to help guide their reports; these questions and associated instructor goals in asking each question are summarized in Table 2.

3. Application

3.1. Sample student assignments

The alternative DOE assignment has been offered for four semesters, comprising approximately 200 student studies. A variety of experiments have been designed and executed by students, spanning topics ranging from their undergraduate chemical engineering research to more light-hearted applications inspired by their everyday lives. Since applications of the DOE method toward chemical engineering applications are well-documented[10, 11], various creative examples of student-developed studies are highlighted here:

1) "Factors affecting rate of dissolving Alka-Seltzer in a liquid medium"
    - Objective: determine how factors affect the length of time needed to dissolve an Alka-Seltzer tablet

- Response: time until tablet disappeared to the naked eye (measured by stopwatch)
- Factor A: liquid temperature (measured by thermometer)
  - +1 value: 90°F
  - -1 value: room temperature
- Factor B: tablet size
  - +1 value: whole tablet
  - -1 value: tablet broken into eighths
- Factor C: Liquid composition
  - +1 value: water
  - -1 value: soda water
- Findings: liquid temperature was dominant affecter, with higher temperatures reducing time to dissolve the tablet. Liquid composition played the second largest role, while tablet size had an unexpectedly negligible effect.

Table 2. Questions provided in problem statement for alternative DOE assignment and goals of each question.

Question	Goals
Question 1: Execute a 2^3 full factorial experimental design for your study and describe findings via a table. Determine the effect (θ) for each factor and any interactions. Which factors and interactions contribute most/least to system response? What are the practical implications?	• Encourage creativity by allowing students to choose study • Develop critical thinking during process of determining which factors and levels should be tested • Student evaluation of data using statistical concepts • Develop skills in written communication of technical findings • Develop critical thinking by analyzing how conclusions can be used for process improvements
Question 2: Develop a predictive model equation for the studied system. Using the model, determine a predicted response for untested values of one or more factors. Then, perform a trial using these previously-untested values and compare experimental response to model prediction. Did the model accurately predict system response? What limitations may have impacted the prediction?	• Student evaluation of data using statistical concepts • Develop critical thinking by determining and analyzing any limitations of study (equipment, reproducibility, etc.) that may have impacted results
Question 3: What did you learn about the studied system that you didn't know before?	• Increase subject relevance and importance by showing relationship between statistical findings to process improvements

2) "A Nickel-and-Dime Study"
   - Objective: determine how factors affect the time elapsed before someone picks up change in a busy campus library
   - Response: time until someone picks up change (measured by stopwatch)
   - Factor A: number of coins
     - +1 value: two coins
     - -1 value: one coin
   - Factor B: monetary value of highest-valued coin
     - +1 value: 10 cents (dime)
     - -1 value: 5 cents (nickel)
   - Factor C: location of change
     - +1 value: top of main stairwell
     - -1 value: bottom of main stairwell
   - Findings: time elapsed before picking up change was seemingly random. The student attributed unpredictable data to study limitations such as inconsistent density of foot traffic based on time of day.
3) "Dishwasher Optimization through DOE"
   - Objective: determine how factors affect the cleanliness of dishes in an old apartment dishwasher
   - Response: number of visible food or soap spots on plate
   - Factor A: temperature of water during wash and rinse cycles
     - +1 value: hot water
     - -1 value: cold water
   - Factor B: type of dishwasher soap
     - +1 value: solid
     - -1 value: liquid/gel
   - Factor C: brand of dishwasher soap
     - +1 value: name brand
     - -1 value: economy brand
   - Findings: type of soap was dominant affecter, with liquid/gel soap producing fewer spots. Brand of dishwasher soap and temperature of water rinse were found to be negligible, suggesting an opportunity for savings on soap and electricity without diminished performance.

In each of these studies, students applied statistical concepts to processes with which they were familiar, increasing the relevance of the subject matter for each student. The student who performed the study on dishwasher optimization stated they were "impressed that such a simple application of statistics" allowed them to determine ways to save on bills, and that they would use the DOE method in the future when posed with a similar problem. The student who examined Alka-Seltzer tablet dissolution commented that, "prior to the experiment I would never have expected tablet size would play an insignificant role in dissolution time." Critical thinking was also demonstrated by the students during completion of the assignment, as demonstrated by the student who inferred limitations of their study on picking up change: "many limitations to this study contributed to its inefficacy… traffic through the library was not constant, and though many people were observed to notice or glance at change, it seemed only younger people stooped to pick it up." In all of these cases, students were creative in applying engineering statistics to real-world processes and using resulting data to evaluate and analyze processes.

3.2. Student views on assignment

In order to probe student views on the alternative DOE assignment, two open-ended questions were asked as part of end-of-semester course evaluations for Fall 2012 (number of students in course = 23, number of respondents = 9). The question statements and selected student responses are given in Table 3. No significantly negative comments were received, though some respondents seemed to feel homework was never enjoyable. Based on student responses, it appears that students felt that the alternative DOE assignment successfully increased subject relevance, while also being enjoyable to complete. Additional student feedback on the assignment is planned to be collected in future semesters.

Table 3. Questions related to alternative DOE assignment and selected student responses from end-of-semester course evaluations.

Question	Selected Student Responses
The Design of Experiments (DOE) homework assignment was a bit different from typical engineering homework sets. Do you think that the DOE assignment demonstrated the relevance of DOE concepts in everyday life?	• "Yes. I learned how to use [DOE] better by actually trying it, and I feel confident using it in my career." • "Yes, it was a good assignment." • "I thought it was a really interesting way to learn the concepts."
Was the DOE assignment more enjoyable to complete than a typical homework assignment?	• "Yes! It was a fun assignment that challenged students' creativity." • "Yes! I liked it a lot." • "I'm not sure if enjoyable is the right word, but it is a great way to illustrate the concepts in DOE." • "I don't usually consider homework to ever be enjoyable, but it was less terrible than a typical homework assignment."

4. Conclusions

An alternative assignment for evaluating student understanding of statistical methods, namely the DOE concept, has been presented. In the alternative assignment, students evaluate any process and factors they desire via a 2-level 3-factor full factorial DOE method. This approach is in contrast to typical engineering statistics assignments which involve providing experimental data from an already-performed study to students, who then complete data analysis by following rote problem-solution procedures. It is proposed that the latter approach causes students to struggle to understand the relationship between statistical design and real-life processes since they do not actually "design" the experiment, execute the design, then draw conclusions based on statistical analysis. The alternative assignment requires students to summarize their DOE study and findings in a brief two-page report, which is meant to facilitate learning and improve technical writing skills. Student responses to the assignment and comments on end-of-semester course evaluations indicate that the assignment successfully (1) increased subject relevance, (2) improved student critical thinking skills, and (3) developed and strengthened creativity in order to encourage higher-order thinking skills of Bloom's Taxonomy such as analyzing, evaluating and creating.

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