Laboratory Experience to Support Experimental Design by Engineering Students

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Abstract
The Accreditation Board for Engineering and Technology, ABET, requires that all undergraduate engineering curricula include the application of statistics to engineering problems. Faculty in the Department of Industrial and Manufacturing Engineering at Tennessee Technological University are developing a computer-based simulation which enables students to practice experimental design techniques in a "real world" industrial environment so that the design process, as promulgated by ABET, is enhanced in the curriculum.

Introduction
ABET criteria requires that "students must demonstrate knowledge of the application of statistics to engineering problems." The increasing role of statistics in engineering education was discussed at the ASEE Centennial Conference by Nelson and Wallenius who suggested an integration of statistical thinking and methodology throughout the undergraduate engineering curriculum. The Department of Industrial and Manufacturing Engineering at Tennessee Technological University, like other ABET accredited industrial engineering programs, offers several courses which emphasize topics such as exploratory data analysis, probability models and confidence intervals, statistical process control, regression models, and the design of experiments. These topics are presented in the framework of the Total Quality Management, TQM, philosophy. Lecture concepts are reinforced by a laboratory experience that includes data generation and computerized statistical analysis. All of the aforementioned topics are important in an environment which has embraced a (TQM) philosophy; however, critical to the procedure for evaluating and enhancing industrial processes is a thorough understanding, by engineers, of the design of experiments. The following describes various aspects of systems design, development, and enhancements which are subject to experimental design methods:

> Experimental design methods are necessary for comprehensive system design.
>
> Experimental design methods are a powerful experimental tool for system evaluation.
>
> Experimental design methods are necessary for improved quality, since it is the language of quality engineering.

ABET also places minimum standards on engineering curricula which are based upon principles of mathematics, basic sciences, engineering sciences, and engineering design. Generally accepted elements of the design process are those enumerated in the ABET guidelines. They are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. ABET guidelines state that the design process should include at least some of the following features:

> "...development of student creativity, use of open ended problems, development and use of design methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations and detailed system descriptions."

The proliferation of low-cost microcomputers has modified and redefined the design techniques and methodologies used by practicing engineers. In fact, the computer has become an integral component in the engineering design process. Rather than deal with idealized systems, remote from reality and irrelevant to industry chosen because they are mathematically tractable, computers now enable engineering educators to bring quantitatively "real world" engineering systems, machines, and processes to the laboratory.

Simulation has becomes a tool of investigation, paralleling theory and experimentation. This paper examines the issue of variability in engineering design within the engineering education environment. Attention is placed on the means in which experience in variability of design can be enhanced through a well-integrated course in the design of experiments. Specifically, an industrial engineering course in the design of experiments is presented which enables industrial engineering educators to reinforce engineering design techniques by utilizing a computer-based simulation which models a “real” industrial process.

Industrial Engineering and Variability in Design

Integrating process design throughout the engineering curriculum is a persistent and challenging problem for the faculty. However, with an adequate background, students are able to apply the statistical techniques as needed to advanced design and analysis. Otherwise when performing engineering design, effects of problems associated with the variability in design may be ignored at the expense of "critical components of the design and design process." Therefore, academic exercises which incorporate the design of experiments provide an important opportunity to link statistical concepts with engineering design.

Industrial engineering topics whose theoretical underpinnings are based on the design of experiments include simulation, ergonomics, manufacturing and production systems, operations research, stochastic processes, and control theory. To prepare industrial engineering students for these and other discipline specific topics based on design of experiments analysis techniques, a three-semester credit hour course is required for all industrial engineering majors. Upon completion of this course, students can utilize design of experiments techniques as a tool of investigation, paralleling theory and experimentation. The necessary background for students to enroll in this course is presented in the following section. Briefly stated, a student must have completed the basic course in probability and statistics and the quality control course.

Understanding and learning the concepts associated with the design of experiments can be facilitated when a laboratory or other facility is available in which actual experiments can be designed, conducted, and analyzed. Unfortunately, in the university environment, the department teaching the design of experiments courses may not have the resources readily available to offer a “real world” design experience. To compound the problem, most textbooks focus on the analysis of data from designed experiments, with less discussion devoted to the design aspect.

To provide students with additional “real world” experience in the design of experiments, simulation software has been developed for the design of experiments course. The software models an industrial process which can be monitored by the students. Based on carefully designed experiments, students can infer performance characteristics of the processes and optimize the system output. The software was first used during the fall, 1995 semester. Preliminary results are positive; however, additional efforts are necessary to validate effectiveness of the software as a learning tool. The simulation model is based on the process description shown in the attachment.

Sample Project

Conceptually the experimental design problem can be expressed as a function

$$y = f\ (x_1, x_2, \ldots\ldots, x_n)$$

where y is the response variable and x_j are independent variables for j = 1, 2, ...,n. The objective is to find the x_j values that will either:

maximize y, minimize y, or result in y being equal to a target value.

Of course in reality, all the x_j's that affect y can almost never be enumerated. That is, n is often extremely large, and in fact, often unknown. To be realistic, then, a subset of the x's are chosen to experiment with, where those chosen are those thought to have the greatest effect on y. The combined effect of all the other x's is lumped into a catchall category, referred to as experimental error. The model can be re-expressed as

$$y = f\ (x_1, x_2, \ldots\ldots, x_n) + \hat{\imath},$$

Where î = experimental error. The experimental design consists of:

Selecting the variables to use in the experiment.
Determining which levels of each variable to use.
Determining which combinations of variable levels to use.
Determining how many replicates are to be used.
Determining the order of experimentation.

Often the term "factor" is used instead of the term "variable". Once the data has been obtained from the experiment, it can be analyzed by:

Plotting, charting, or graphing in a way that makes sense based on objectives of the experiment.
Analysis of variance.
Regression analysis.

As shown below and in the attachment, the model used in the recent design of experiments course involves six independent variables that influence two responses.

$$y_i = f_i\,(x_1,x_2,x_3,x_4,x_5,x_6) + \hat{\imath}_i \qquad (\ i = 1, 2\ )$$

where y_1 is the yield of a batch process (to be maximized); y_2 is a measure of batch quality referred to as texture (Specifications are 150 +/- 10); factors and their feasible ranges are:

Factor	Range
x_1: = amount of # 1	5 - 20
x_2: = amount of # 2	10 - 60
x_3: = amount of # 3	4 - 12
x_4 = time in reactor	1 - 2
x_5 = temperature	30 - 40
x_6 = pressure	12 - 24

Simulation Software

The software has an instructor and student interface. The instructor may specify the model, associated predictor equations, and parameters to generate the responses. Second order models with some interaction are recommended. Any of the parameters may be changed to suit the process being simulated, but it is felt that six independent variables are enough to illustrate all important concepts. Of course, two models are required, one for y_1 and one for y_2.

With the student interface, students are permitted to experiment by simulating the manufacture of, say, 50 batches. The value for any or all x values for a particular batch may be specified. Without a specified value, the software randomly selects an x value from the specified range. Students can be given some hints about which interactions may be assumed to be negligible. An ASCII file which identifies the desired experimental conditions is submitted to the software. It returns responses, y_i values, and their corresponding x values in an ASCII file. Students use responses from one stage of experimentation for analysis and the resulting analysis is used to determine what to do in subsequent stages. They can do screening fractional 2k experiments initially, and more elaborate experiments later, including experiments that would permit fitting second order regression models.

The software maintains an ASCII file which contains a "time stamped" historical record of experiments conducted by each student or group of students. With this information, the instructor may examine how efficiently the students designed their experiments.

Summary

Integrating meaningful design experiences throughout the industrial engineering curriculum is a persistent and challenging problem for the faculty. This paper has presented an a computer-based simulation which enables students to practice experimental design techniques in a "real world" industrial environment. The approach also enables students to perform a meaningful analysis of the variation in design issues and provides the necessary background for many industrial engineering topics with a statistical analysis underpinning.

Reference

1. Nelson, P.R. and Wallenius, K.T., "An Integrated Statistical Experience in Engineering," *1993 ASEE Conference Proceedings*, 1869-1871.

Biographical Information

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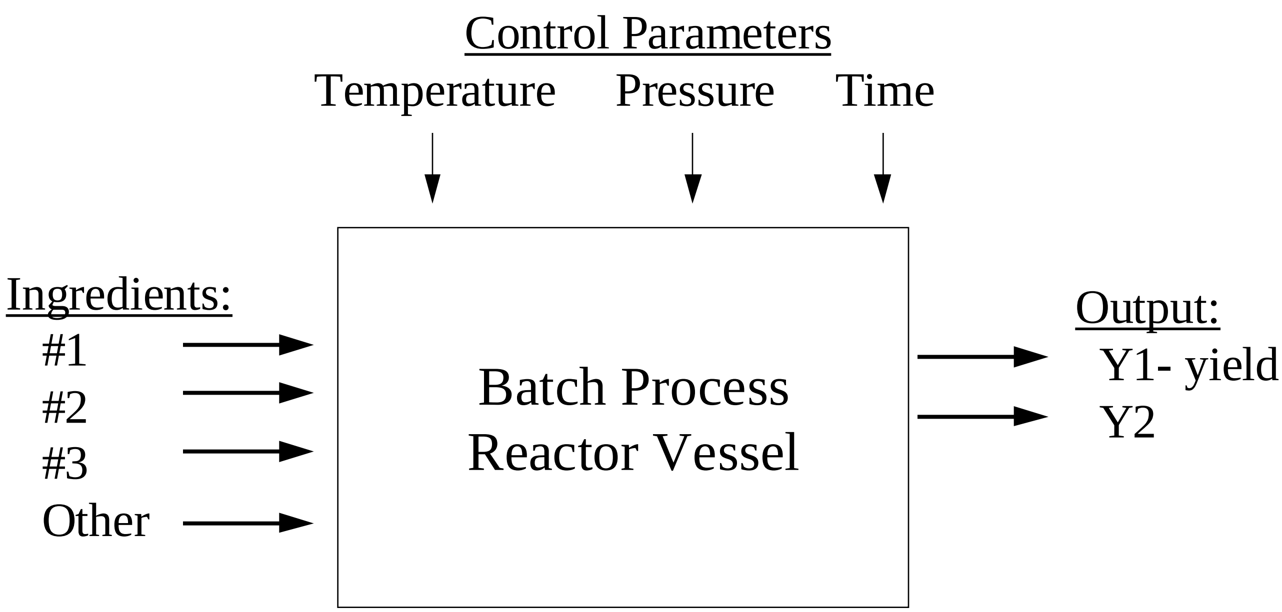
Sample Experimental Design Project



Objective: Maximize Y1 while keeping Y2 with specifications