AC 2009-1258: BLACK BOX DESIGN OF EXPERIMENTS

Christopher Pung, Grand Valley State University

Dr. Pung joined the faculty of Grand Valley State University in August 2007. He has 14 years of experience in the automotive industry and brief stints at a nuclear plant and office furniture manufacturer. His areas of interest are product design, manufacturing and composite materials. B.S. & M.S. from Michigan State University and Doctorate from Lawrence Technological University.

Black Box Design of Experiments

Abstract

The faculty at Grand Valley State University, a primarily undergraduate engineering school, use black boxes to teach basic design of experiments techniques. The black boxes are literally wooden cubes painted black with four knobs projecting from the surface for the adjustable variables. One of the knobs was a dummy and did not affect the response. The measured response is the height of a metal rod projecting from the top of the box. Anecdotal evidence suggests that the black boxes were an effective teaching aid.

I Introduction

Design of Experiments (DOE) is a useful tool for practicing engineers[1,2,3]. It can be applied to both processes and products. DOE is a very efficient methodology for generating a great deal of useful data with a minimum of expended time and resources. Teaching DOE fits the coupled lecture and lab model for covering material. The lecture portion of a class is useful for conveying the necessary knowledge regarding statistics, orthogonal arrays, variable selection and a variety of other items. Typical labs using DOE range from optimizing injection molding processes to paper airplane flight time. Injection molding is a mature technology and has been the subject of a great deal of research. A design of experiments intended to characterize a new product or machine type can be very efficient. Past experience may be used to make decisions about which interactions and main effects are important. Similarly for the paper airplane example. The students can use their intuition to guide them when selecting variables and levels. These examples address the situation where a great deal is already known about the product or process and fine tuning is required. Situations where very little is known about the variables influencing the process or product variables and their possible interactions. This second area is the focus for using the black boxes for DOE. The black boxes are simple mechanisms to simulate an unknown or unfamiliar process.

II Apparatus

Two black boxes were constructed and are shown in Figures 1 and 2. Each box has four color coded knobs for the inputs and the length of the steel rod projecting from the box is the response variable. The blue and green knobs (top left and top right) were connected to the horizontal rubber band. The pink knob (bottom left) was connected to the vertical rubber band. Both rubber bands were connected to the vertical rob to create a response. The yellow knob (bottom right) was a dummy knob and was not connected to the rubber band/metal rod assembly. The boxes were inexpensive and were constructed from plywood, rubber bands and common fasteners.

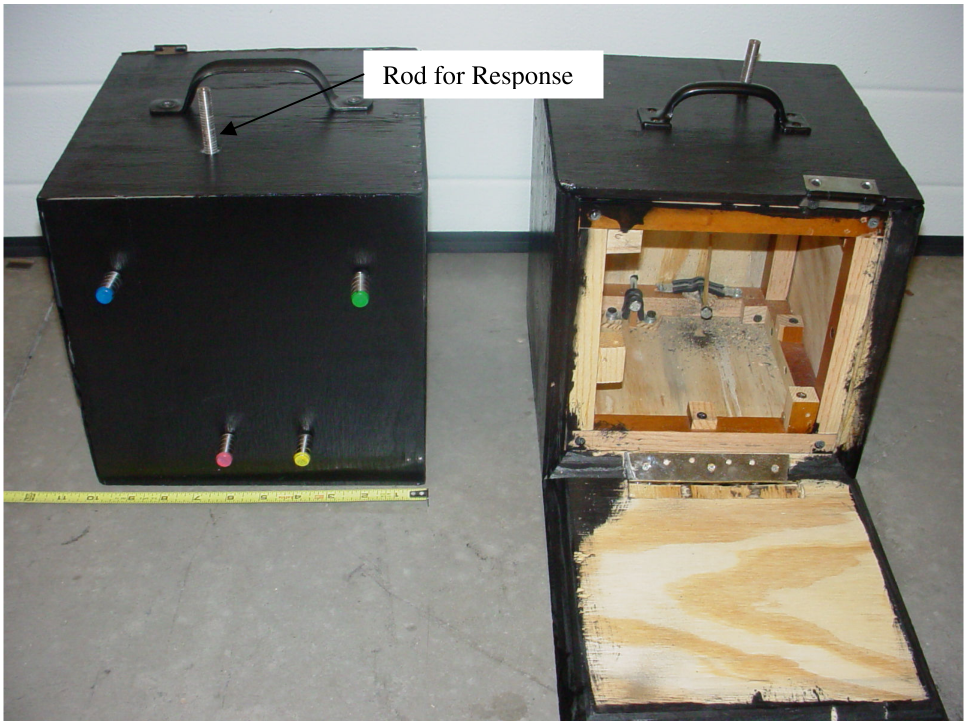

Figure 1. Black boxes open and closed.

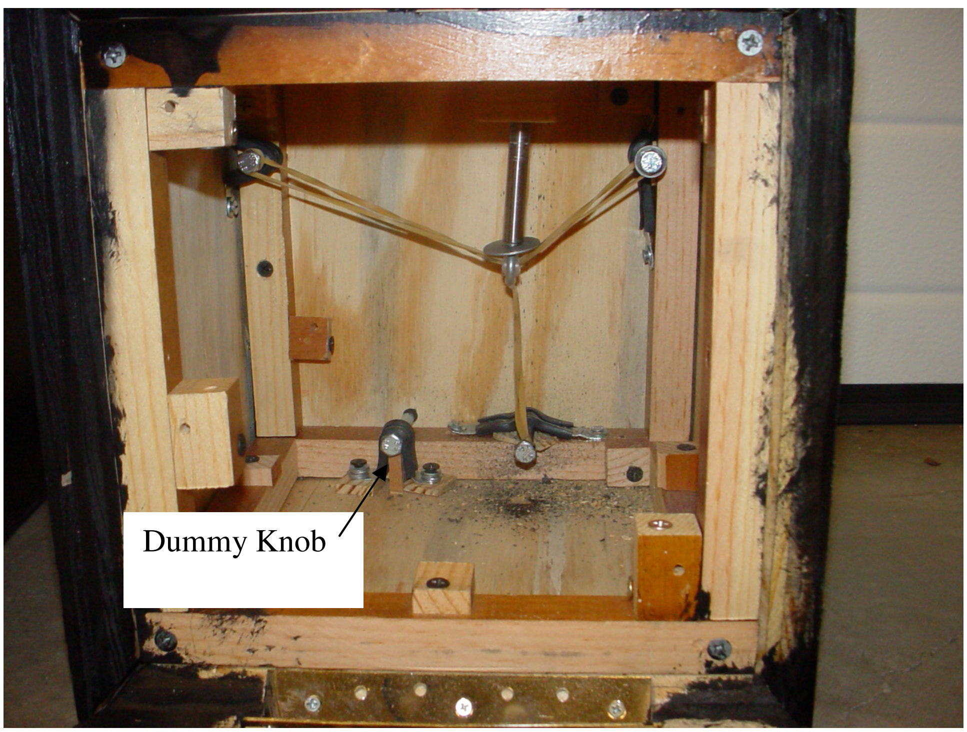

Figure 2. Black box internal close-up.

Each of the knobs was secured using metal strapping with rubber strips to provide friction. This provided the illusion of feedback for the dummy knob. The boxes are easily reconfigurable to provide different interactions and main effects. For example the green and blue knobs could be attached to the rod using a single rubber band as shown or individual bands. The yellow knob, instead of being a dummy knob, could have a rubber band attached to it as well.

III Lab Format:

Senior level students in a product design and development class were presented with the two closed black boxes. The class was broken into teams of two and three students. Each team was instructed to perform a two level full factorial design of experiments on each box. Levels were given for each knob. The levels varied between two and six revolutions. Initially the knobs were set to a relative zero. The zero setting was midway between the upper and lower levels. The four knobs were treated as continuous variables and the two black boxes were treated as a discrete variable. This resulted in a total of 32 (2^5) trials per team. The class was required to pool their data for comparison. Table I lists the variables and levels for each run. The combinations were created using the standard Yates order. The 16 trials were performed using each of the two boxes.

Table 1. Combinations

Run Order	Standard Order	Yellow	Pink	Blue	Green
*	1	-1	-1	-1	-1
*	2	1	-1	-1	-1
*	3	-1	1	-1	-1
*	4	1	1	-1	-1
*	5	-1	-1	1	-1
*	6	1	-1	1	-1
*	7	-1	1	1	-1
*	8	1	1	1	-1
*	9	-1	-1	-1	1
*	10	1	-1	-1	1
*	11	-1	1	-1	1
*	12	1	1	-1	1
*	13	-1	-1	1	1
*	14	1	-1	1	1
*	15	-1	1	1	1
*	16	1	1	1	1

*The run order was random and was different for each team.

After recording the readings the assignment was to evaluate the effect of each variable and all of the interactions. After this evaluation the students were required to speculate on the mechanism inside the box. The next lab period each team had a representative present their suggestion for the internals. The black boxes were then opened and the results discussed.

A significant question and additional homework assignment was whether a fractional factorial experiment would have yielded the same or very similar results when compared to the full factorial experiment. A fractional factorial for a two level experiment allows the number of runs to be cut down significantly. For example a ½ fraction allows ½ the number of runs, similarly for a ¼, 1/8, …$1/2^n$. There is a tradeoff for running fewer runs. A full factorial allows all of the main effects and interactions to be quantified. A fractional factorial confounds effects. This may be main effects with interactions or interactions with other interactions.

The student's predictions varied. All teams concluded that the yellow knob did not have a significant effect on the response. Several speculated that a torsion spring of some sort was used and others predicted an arrangement of linear springs. After being allowed to view the inside of the boxes the students were pleased and somewhat surprised.

The question of whether a fractional factorial design could have been used was a unanimous 'yes'. A one half or even one quarter design would have yielded very similar results.

This opinion was validated by comparing the main effect plots for the full factorial and ½ fractions DOE's. The main effects for the full factorial and ½ fraction are shown below in figures 3 and 4.

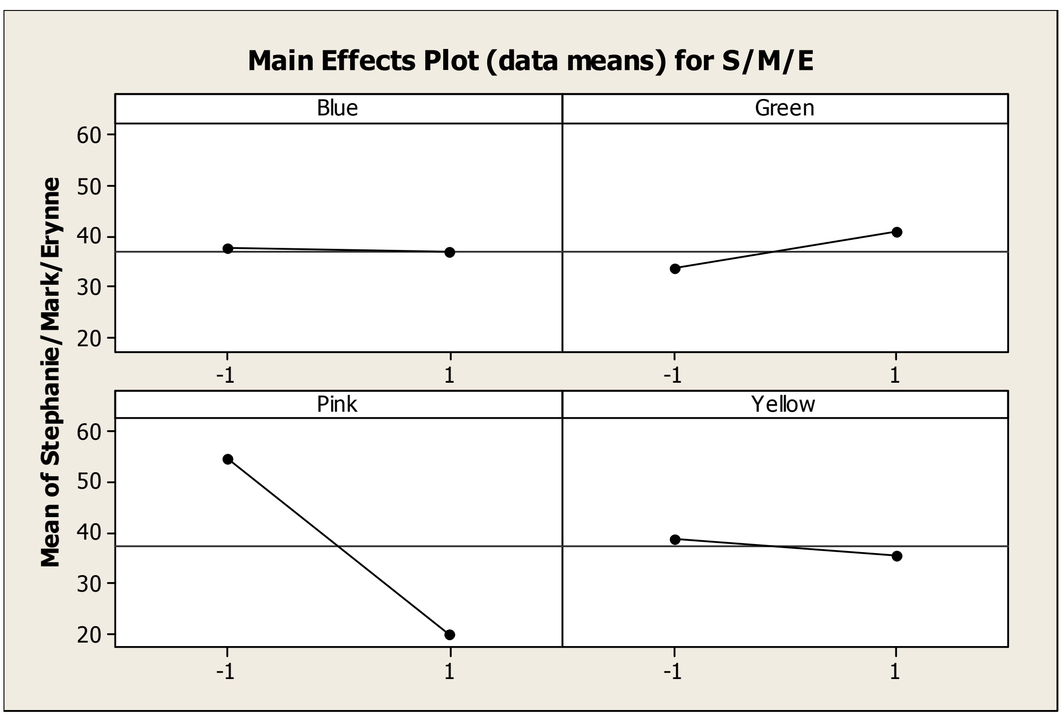

Figure 3. Main Effects Plot for the full factorial DOE for a single box.

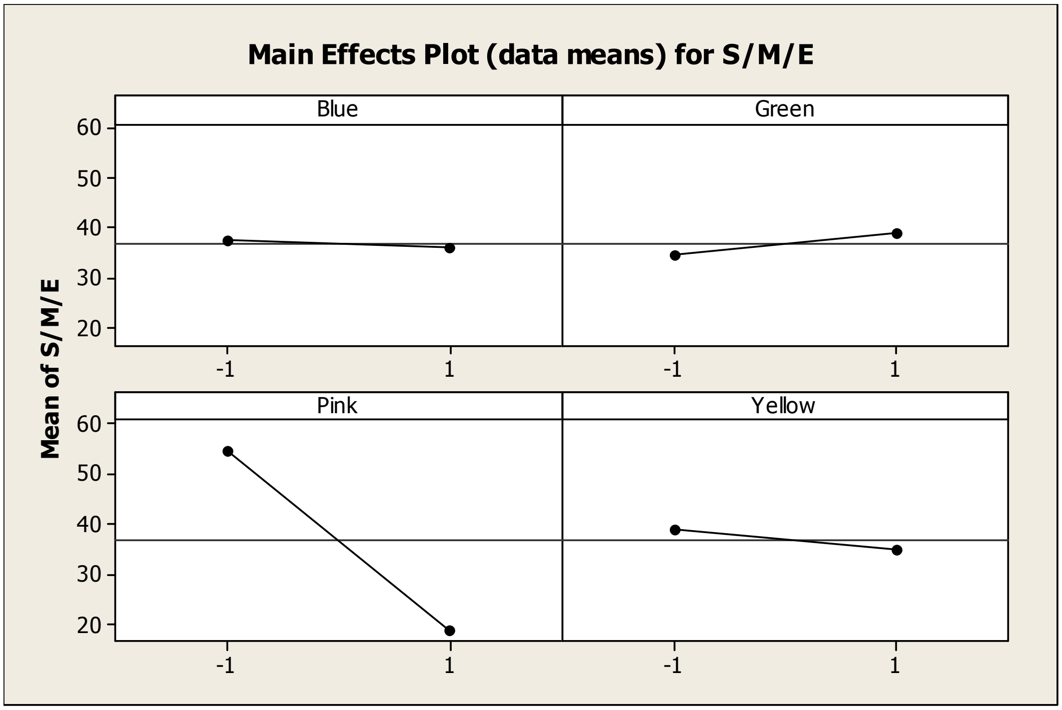

Figure 4. Main Effects plot for hypothetical ½ fraction DOE for a single box.

From inspection the main effects that would have been estimated with the ½ fraction design (8 trials) are very similar to those from the full factorial design (16 trials).

IV Results:

A short group discussion and several individual conversations on the topic of the black boxes as learning aides were held.

Positive:

"I learned a lot, the testing levels (now) make more sense to me."

"Making the predictions was kind of fun and it was nice to see that they mostly matched the boxes."

"It helped clear up what you meant by interactions."

Negative:

"It seems like we could have done something different with an actual process."

"I didn't like having to compare our data to the other teams."

The requirement to pool the data caused some minor confusion because of the lack of structure for the experiments. Several teams used English units, some metric, two teams measured from the table top to the tip of the metal rod while the remaining teams measured from the top of the box to the tip of the rod. This was expected and reinforced the importance of communication.

V Conclusions & Future Work

Based on the student feedback the black boxes were an effective teaching aid for DOE. Opening up the black boxes and comparing the internals to the students predictions I believe heightened the importance of gathering data and modeling. For future classes I plan on changing the levels so that one variable does not dominate the response and perhaps adding an additional variable or perhaps two. The data collection by the students took about half of an hour. Adding another variable should double this time and still leave a large portion of the lab period available for analysis and discussion.

References:

1 Balachandran, S., "Teaching Design of Experiments at the Graduate Level Using Prometheus", ASEE 2002.

2 Das, P., Ravine, J., Pung C., "Enhancing the Surface Finish of LFT Compression Molded Parts via Application of Surface Film", Composites Research Journal, V2, I4, 2009.

3 Enemuoh, E., "Integrating Design of Experiments and Writing into a Manufacturing Processes Course", ASEE 2003.