EXPERIMENT DESIGN IN ENGINEERING DESIGN AND DEVELOPMENT

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ABSTRACT

At one time, US industry was the world leader in quality and productivity. However, in many markets, this situation no longer exists. American industry has systematically lost its competitive advantage to off shore competition. In particular, the ability to engineer quality into basic product and process design, and then to translate this into a manufacturing system that operates effectively is a characteristic of our competitors that has been partially responsible for this loss of competitiveness. This paper discusses the role of experimental design methods in product and product development, and discusses how to more effectively educate engineers with proper experimental design methods.

INTRODUCTION

The purpose of this paper is to describe the use of statistical experimental design methods in engineering design and development. We will also discuss some guidelines for using experimental design methods as part of a logical and organized strategy for process and product development that can assure continuing and ongoing improvement in quality and productivity.

The need to focus attention on the engineering design and development process can be easily demonstrated. For example, it is well-known that the cost of failure associated with defects and product performance is an increasing function of the stage of the product development cycle at which these defects are discovered. This argues for the introduction of quality and productivity improvement technology as early as possible in the overall product development cycle. The early stages of this cycle would include engineering design and development for products and processes.

In the process design and development arena, engineers typically focus on issues such as material selection, basic product and process configuration, component tolerance determination, determination of operational levels for process variables, and determination of operational tolerances for process variables. The traditional engineering approach to resolving these issues in product and process design consists of working from first scientific principles to develop prototype or pilot designs. These prototype or pilot designs are use to verify the underlying principles, usually through experimentation, then to develop the product or process to the point were it can be transitioned to the factory floor.

This development procedure usually involves considerable testing and empirical analysis, and it is in this area that designed experiments can be of enormous benefits. Specifically, the use of statistically designed experiments enables the engineer to achieve the development objectives while using far fewer resources than traditional methods. The experimentation required to develop a product or process may drop by as much as an order of magnitude when effective experimental design techniques are employed. It is not unusual for development cycle time and associated costs to be reduced by 30 to 50%, because experimentation and test is such a significant portion of the overall development cycle. Furthermore, because product quality and process design are being addressed at the earliest point in the product cycle, many decisions that effect product field life, reliability, performance, and manufacturer ability can be made early.

EXPERIMENTAL DESIGN STRATEGY

We may define a designed experiment as systematic manipulation of the input variables to a process or system to provide output information which can be analyzed to identify the important input factors and the effect they have on the system response. In general, we may view a system or process as a "black box" in which a series of controllable input variables are manipulated, and a series of uncontrollable inputs also interact with the system or process to produce an output response characteristic. This output response characteristic is viewed as a random variable, with a nominal value and perhaps upper and lower specification limits which are dependent upon customer requirements. The purpose of the designed experiment is to identify the set of input variables that are most influential on the output, and then to determine what levels of the active input variables optimize the output performance. A subset of this problem, called robust design, involves determining the best set of levels for the controllable input variables so that variation in the output characteristic is minimized regardless of the levels taken on by the uncontrollable inputs. The concept of robust design is not new to engineering professionals; however, the use of statistically designed experiments to achieve robust product and process design is not familiar to most engineers. Instead, robustness is often achieved by other, less efficient and less effective methods.

Experimental design methods play a major role in process development. Developing a new process requires three distinct steps. The first of these is *characterization*, in which the key influential variables in the process are identified. The second step is *control* in which provision for monitoring these variables and the output, and for reducing variability in the output of the system over time is made. The third stage is *optimization*, in which the key variables are set at levels that result in minimum cost, minimum variability, maximum yield, or other desirable functional properties in the product or process. Experimental design methods are of direct benefit to development engineering at the characterization and optimization phase. Statistical process controls and engineering process control technology is useful at the control stage. Characterization and control may take place concurrently in some systems.

There has been a long history of the use of statistical methods in engineering and development. The primary techniques that have been used includes statistical process control in manufacturing, acceptance sampling in manufacturing and production, and statistically designed experiments. Statistically designed experiments are a major off-line quality engineering tool, because they are most effective in the early stages of manufacturing and development, rather that as a routine on-line or in-process control procedure.

The traditional approach to experimentation in engineering design and development include the best guess method, which is often very successful because of the training which engineering professionals receive in physical sciences, and the one-factor-at-a-time method. The one-factor-at-a-time method is widely taught and reinforced through engineering laboratory courses in universities. It is rare for factorial design methods to be taught to engineers at the undergraduate level. Some engineers are exposed to these methods as part of a graduate level experience.

Factorial experimental designs are a powerful experimental strategy. Education for engineers and designed experiments should include the two-level series of factorial designs and the useful fractions of those designs. Two-level fractional factorial designs are a powerful tool for engineering development because they allow a large number of factors to be investigated in a relatively small number of runs. The two-level series of designs is particularly useful, because of the projection property of the designs and the ease in which they can be sequentially assembled into either larger fractions or response surface designs. With the addition of center points to these designs, they can provide reasonable protection against curvature. These designs should be taught widely to engineers from all disciplines.

PRACTICAL GUIDELINES FOR USING EXPERIMENTAL DESIGN

We now present some practical guidelines for using experimental design methods. It is necessary for everyone involved in the experiment to have a clear idea in advance of exactly what is to be studied, how the data are to be collected, and everyone must have at least a qualitative understanding of how these data are to be analyze. An outline of the recommended procedure for the successful use of experimental design methods is as follows.

1. Recognition of and Statement of the Problem.

This may seem to be a rather obvious point, but, in practice it is often not realized that a problem requiring formal experimentation exists, nor is it simple in many cases to develop a clear and generally accepted statement of the problem. However, a good statement of the problem often contributes substantially to a better understanding of the phenomena, and to the final problem solution. Without careful attention at this phase, it is likely that we will comment a type III error, or put another way, it is likely that we will solve the wrong problem.

2. Choice of factors and levels.

The engineer must select the independent variables or factors to be investigated in the experiment. The factors are either qualitative or quantitative. If the factors are quantitative, thought should be given as to how these factors are to be controlled at the desired levels, and how they are to be measured. We must also select the ranges over which these factors are to be varied and the number of levels at which runs are to be made. At the early stages of experimentation, we suggest using relatively few levels across the many factors that are likely to be present. As discussed above, two level designs are often best at this phase. Generally, experience with the phenomena under study and engineering knowledge is essential in choosing the factors, levels, and ranges. Also, we usually do not have the answer to all of these questions at the beginning of the project-instead we learn the answers as we go along. This argues in favor of an itierative or sequential approach to experimentation. That is, as the experiment progresses some of the initial factors may be eliminated, other factors introduced, the range over which some factors are varied will change, and in some instances, new response variables will be defined. There are situations were comprehensive experiments are appropriate, but the vast majority of experiments in the design and development world should be sequential. We usually do not recommend investing more than 25 or 30 percent of the total resources for experimentation in the initial designed experiment. Often, these first experiments are just learning experiences and some resources must be available to accomplish the final objectives of the project.

3. Selection of a Response Variable.

In choosing a response or dependent variable the experimenter must be certain that the response to be measured really provides information about the problem under study. Thought must also be given as to how the response will be measured, the capability of the gage used to make these measurements, and how the gaging system will be maintained and calibrated over the course of the experiment.

4. Choice of Experimental Design.

The engineer must determine the difference in the true response that he wishes to detect, and the risk he is willing to tolerate so that an appropriate sample size may be chosen. He must also determine the order of data collection and the method of randomization to be employed. In selecting the design, it is important to keep experimental objectives in mind. In many engineering experiments we already know at the outset that some of the factor levels produce different responses. Consequently, we are interested in indentifying which factors cause this difference, and in estimating the magnitude of response change. In other situations we may be more interested in verifying uniformity, or in finding factor levels that make the product or process robust to uncontrolled changes in other factor levels.

5. Conducting the Experiments.

This is the actual experimental trial and data collection activity. The engineer should carefully monitor the progress of the experiment to insure that it is proceeding according to the design. Particular attention should be paid to randomization, measurement accuracy, and the maintenance of uniform experimental conditions. The logistical aspects of conducting a designed experiment should not be underestimated. This is often one of the most time-consuming aspect of the process, from the engineer's viewpoint.

6. Data Analysis.

Statistical methods should be employed in the analyzing the data from a designed experiment, because statistical methods lend objectivity to the analysis. In general, if steps 1 through 5 have been performed successfully, the type of statistical methods that are required are very simple and easily automated. The widespread availability of excellent software for analyzing data from designed experiments will usually make this aspect of the experimental process simple. An important part of the data analysis process is model adequacy checking; that is, a critical examination of the underlying statistical model and the associated assumptions. Once again, the computer is highly useful in this regard.

7. Conclusion and Recommendations.

Once the data has been analyzed, the experimenter must draw conclusion or inferences about the results. The statistical inferences must be interpreted and the practical significances evaluated. The recommendations may include a further set of experiments, since experimentation is usually sequential. In presenting the results and conclusions, engineers should be careful to minimize the use of unnecessary jargon and to phrase conclusions and results as simply as possible. The use of graphical methods is an effective way to present important experimental results to nonstatistically trained management.

CONCLUSION

Experimental design methods have wide potential application in the engineering design and development environment. Potential applications include the analysis of basic design configuration, material selection, selection of component and system tolerances, process selection, process troubleshooting, and process optimization.

There is substantial evidence that our off-shore competition has made wide use of experimental design methods for at least the past 15 years, and that these methods have played a major role in the competitive advantage that they enjoy in many industries. The use of statistical experimental design methods early in the product cycle for characterization, control, and optimization can significantly reduce engineering development lead time, improve product performance, lower overall cost, and improve customer satisfaction with the product. Consequently, a working knowledge of statistically designed experiments should be part of every engineers tool kit.

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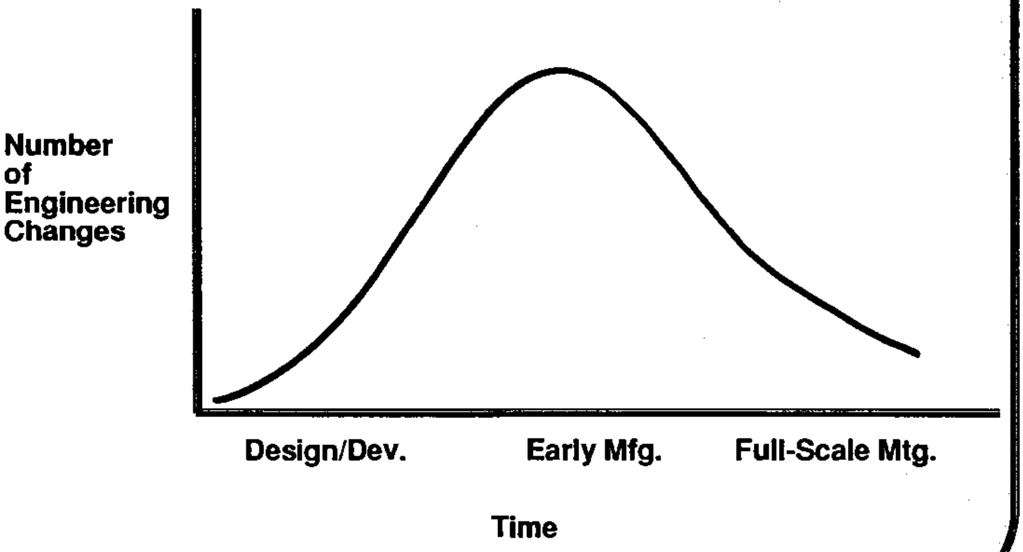
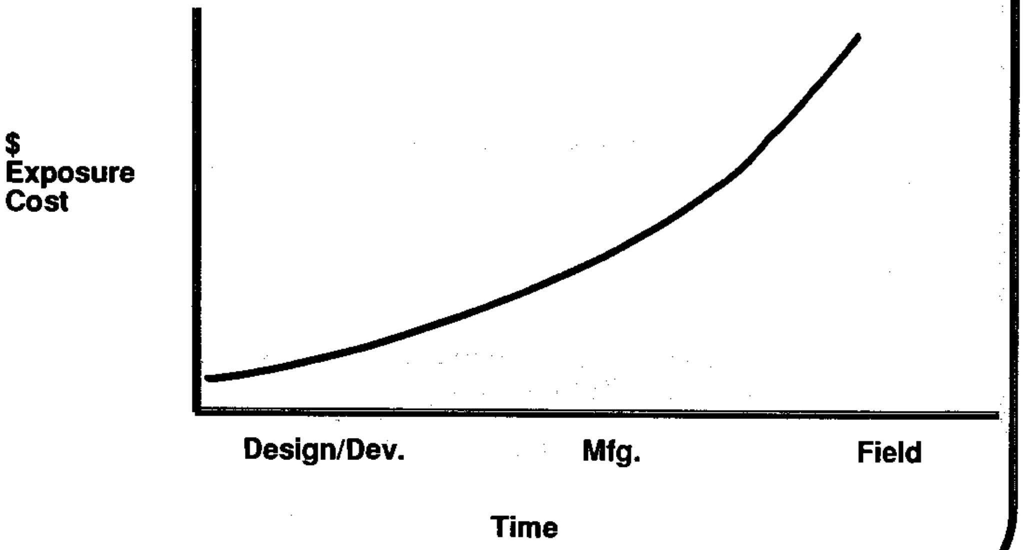




Experimental design is a critically important tool in the engineering world for improving the performance of a manufacturing process. It also has extensive application in the development of new processes. The application of experimental design techniques early in process development can result in

1. Improved process yields.
2. Reduced variability and closer conformance to nominal or target requirements.
3. Reduced development time.
4. Reduced overall costs.

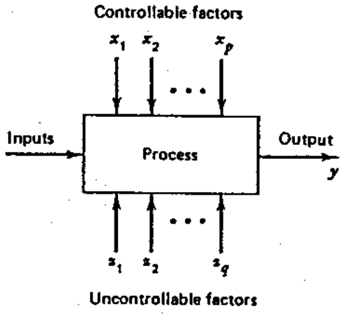
Experimental design methods also play a major role in *engineering design* activities, where new products are developed and existing ones improved. Some applications of experimental design in engineering design include

1. Evaluation and comparison of basic design configurations.
2. Evaluation of material alterations.
3. Selection of design parameters so that the product will work well under a wide variety of field conditions, that is, so that the product is *robust*.
4. Determination of key product design parameters that impact product performance.

CHARACTERIZATION

CONTROL

OPTIMIZATION



Example 1-1

Characterizing a Process

A flow solder machine is used in the manufacturing process for printed circuit boards. The machine cleans the boards in a flux, preheats the boards, and then moves them along a conveyor through a wave of molten solder. This solder process makes the electrical and mechanical connections for the leaded components on the board.

The process currently operates around the 1 percent defective level. That is, about 1 percent of the solder joints on a board are defective and require manual retouching. However, since the average printed circuit board contains over 2000 solder joints, even a 1 percent defective level results in far too many solder joints requiring rework. The process engineer responsible for this area would like to use a designed experiment to determine which machine parameters are influential in the occurrence of solder defects and which adjustments should be made to those variables to reduce solder defects.

The flow solder machine has several variables that can be controlled. They include:

1. Solder temperature.
2. Preheat temperature.
3. Conveyor speed.
4. Flux type.
5. Flux specific gravity.
6. Solder wave depth.
7. Conveyor angle.

In addition to these controllable factors, there are several other factors that cannot be easily controlled during routine manufacturing, although they could be controlled for the purposes of a test. They are

1. Thickness of the printed circuit board.
2. Types of components used on the board.
3. Layout of the components on the board.
4. Operator.
5. Production rate.

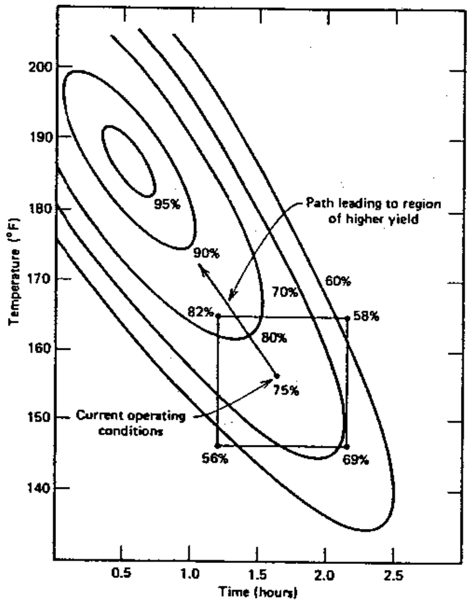
Example 1-2

Optimizing a Process

In a characterization experiment, we are usually interested in determining which process variables affect the response. A logical next step is to optimize, that is, to determine the region in the important factors that leads to the best possible response. For example, if the response is yield, we would look for a region of maximum yield, whereas if the response is variability in a critical product dimension, we would seek a region of minimum variability.

Suppose that we are interested in improving the yield of a chemical process. We know from the results of a characterization experiment that the two most important process variables that influence the yield are operating temperature and reaction time. The process currently runs at 155°F and 1.7 hours of reaction time, producing yields of around 75 percent. Figure 1-2 shows a view of the time–temperature region from above. In this graph, the lines of constant yield are connected to form response *contours*, and we have shown the contour lines for yields of 60 percent, 70 percent, 80 percent, 90 percent, and 95 percent. These contours are projections on the time–temperature region of cross sections of the yield surface corresponding to the aforementioned percent yields. This surface is sometimes called a *response surface*. The true response surface in Figure 1-2 is unknown to the process personnel, so experimental methods will be required to optimize the yield with respect to time and temperature.

To locate the optimum, it is necessary to perform an experiment that varies time and temperature together. This type of experiment is called a *factorial experiment*, and an example of the results of a factorial experiment with both time and temperature run at two levels is shown in Figure 1-2. The responses observed at the four corners of the square indicate that we should move in the general direction of increased temperature and decreased reaction time to increase yield. A few additional runs could be performed in this direction, and this additional experimentation would be sufficient to locate the region of maximum yield.



Example 1-3

A Product Design Example

Experimental design methods can often be applied in the product design process. To illustrate, suppose that a group of engineers are designing a door hinge for an automobile. The quality characteristic of interest is the check effort, or the holding ability of the door latch that prevents the door from swinging closed when the vehicle is parked on a hill. The check mechanism consists of a leaf spring and a roller. When the door is opened, the roller travels through an arc causing the leaf spring to be compressed. To close the door, the spring must be forced aside, and this creates the check effort. The engineering team thinks that check effort is a function of the following factors:

1. Roller travel distance.
2. Spring height from pivot to base.
3. Horizontal distance from pivot to spring.
4. Free height of the reinforcement spring.
5. Free height of the main spring.

The engineers can build a prototype hinge mechanism in which all of these factors can be varied over certain ranges. Once appropriate levels for these five factors have been identified, an experiment can be designed consisting of various combinations of the factor levels, and the prototype hinge can be tested at these combinations. This will produce information concerning which factors are most influential on the latch check effort, and through analysis of this information, the latch design can be improved.

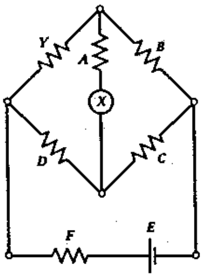
Example 1-4

Determining System and Component Tolerances

The Wheatstone bridge shown in Figure 1-3 is a device used for measuring an unknown resistance, Y. The adjustable resistor B is manipulated until a particular current flow is obtained through the ammeter (usually $X = 0$), and then the unknown resistance is calculated as

$$Y = \frac{BD}{C} - \frac{X^2}{C^2E}[A(D + C) + D(B + C)][B(C + D) + F(B + C)] \quad (1\text{-}1)$$

The engineer wants to design the circuit so that overall gage capability is good; that is, he would like for the standard deviation of the measurement error to be small.



GUIDELINES

1. RECOGNITION OF AND STATEMENT OF PROBLEM
2. CHOICE OF FACTORS AND LEVELS
3. SELECTION OF RESPONSE(S)
4. CHOICE OF EXPERIMENTAL DESIGN
5. CONDUCTING THE EXPERIMENT
6. DATA ANALYSIS
7. CONCLUSIONS AND RECOMMENDATIONS