Designing Quality into Products During the Design and Development Phase

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ABSTRACT

To be effective, quality needs to be built-in and planned already in the product design phase. In this article, we will provide an overview of how design engineers can use statistical experimental design to develop high quality, robust, low cost products. Specifically we will show how experimental design can be used to design, test and improve products, and how these tools can help reduce the cycle time from initial conception to market introduction. Our focus will be on general philosophy and ideas. Practical examples from industry will be used throughout to illustrate the concepts.

Designing Quality into Products During the Design and Developmental Phase

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To be effective, quality needs to be built-in and planned already in the product design phase. In this article, we will provide an overview of how design engineers can use statistical experimental design to develop high quality, robust, low cost products. Specifically we will show how experimental design can be used to design, test and improve products, and how these tools can help reduce the cycle time from initial conception to market introduction. Our focus will be on general philosophy and ideas. Practical examples from industry will be used throughout to illustrate the concepts.

Introduction

The foundation for high quality products is laid down in the product development phase. Moreover, it is increasingly recognized that product development is a vital strategic activity. It is an investment in the future, and of paramount importance for long term business survival. The future economic success of manufacturing companies depends in large measure on their ability to identify the needs of customers, and quickly translate these into products that can be produced at high quality and low costs to satisfy those needs. The increasing competitive pressures of the global economy lately, have drastically shortened the profitable life span of products. This means that product development costs must be amortized over ever shorter time horizons—a further reason for focusing on effective strategies so that there is less to amortize.

Studies by Page (1993) and many others, see e.g. Cooper (1993), Erhhorn and Stark (1994) Jurani (1988), Mørup (1993), Urban and Hauser (1993), Wesner et al. (1994), and Zangwill (1993), show that the physical development of products consumes most of the total product development cycle time. Few, however, seem to have recognized that a large portion of that time is spent experimenting (here we refer to any kind of experimentation). Focusing on improving the effectiveness of this large but overlooked portion of the effort can lead to significant overall improvements. Thus, a method for effective experimentation is key to improving product quality, reducing manufacturing costs, and shortening the total cycle time for the development of new products.

The literature on experimental design emphasizes technical and statistical aspects. Many potential users may therefore not fully appreciate what these tools can be used for, and what role they may play in the product development process.

We will instead provide a conceptual discussion on how these techniques can be applied to reduce product development time, and help build quality into products from the early design phases and all the way downstream. Examples will be used as illustrations of the concepts and ideas.

The Product Development Process

Before we enter into a discussion of the role of experimentation in the product development process, let us outline the process itself. Many authors including recent contributions from Wheelwright and Clark (1992), Pugh (1991), Cross (1989), and Pahl and Beitz (1984) have discussed the product development process. We prefer, however, a modified version first introduced by Bisgaard (1992a) shown in Figure 1. It can be seen that most of the steps are the same as those found in traditional text books, except we represent it not as a linear forward moving process with a beginning and an end, but envision it as an ongoing cyclic learning process. We believe that the cyclic model is a better synthesis of the product development process as it actually occurs. Moreover, by conceptualizing it as a continuous learning process, we believe that we present a normative model, true to modern principles of continuous never-ending quality improvement.

A key observation that led us to this modified model came from our field work where we observed that most new products, upon close examination to a varying degree, seem to be modifications of previous products. For example, a new car model is not a brand "new" car, but most likely a modification of a previous model. Although some new products really are "new," the overwhelming majority are better conceptualized as "new generations" rather than entirely new products. An important characteristic of our cyclic model is that learning and experience gained from the development and use of previous generations of a product is shown explicitly to be used to design and develop the next. The product development process can therefore be viewed as a Plan-Do-Check-Act (PDCA) cycle (see Deming, 1986).
Figure 1 only shows a macroscopic PDCA cycle. However, within the development process, we also envision microscopic PDCA cycles occurring repeatedly. For later reference, the examples presented below constitute parts of these microscopic PDCA cycles. By systematizing and institutionalizing learning, we increase the likelihood of providing the customers with progressively better products, and more likely prevent backsliding to lower levels of quality, sometimes manifested in costly recalls, reliability problems and high failure rates. Systematizing learning is also one of the key features of experimental design. This will be exemplified below, but first we will discuss the role of experimentation during product development.

The Role of Experimentation During the Development of New Products

Designing products that meet customers' expectations is a complex task. For a broad conceptual discussion, see Juran (1992). What makes the task particularly difficult is that often a multitude of variables influence the product's quality characteristics. These complex interrelationships are often poorly understood and seldom documented. This leads to uncertainties about future performance. Lack of knowledge has a by-product — bad decisions, and those may cause quality and reliability problems. The problem is further compounded by the very nature of product development; when developing a new product we are likely pushing the boundaries of our knowledge and understanding. Nevertheless, decisions need to be made and specifications written, frequently requiring knowledge we do not have. To avoid making decisions based on intuition or guesswork alone, we must conduct experiments often to provide the necessary decision-making support information.

It is a common misconception that experimentation only plays a role in the prototype testing phase. We have found
in our field work that product developers often use experiments in all phases of the development process. In Table 1 we provide a summary of some of the possible experimental objectives at different stages of the product development process.

**The Use of Experimental Design in Product Development**

We will now use some examples to explain what experimental design is and what role these tools may play in the product development process. A factorial or fractional factorial design (see e.g. Box et al, 1978) is a combined set of tests, for example 8 or 16, carefully laid out according to a plan. For example, if three factors are involved, and each can be varied at two levels, there will be \(2 \times 2 \times 2 = 2^3 = 8\) possible test combinations. To illustrate the concept we will use an example involving the development of a new design concept for a vital part of an outboard motor — a microscopic PDCA cycle within the larger cycle of developing next years motor model.

**Example: The Development of a Propeller-Shaft Assembly Mechanism**

An outboard motor manufacturer was contemplating a new design of the propeller-drive shaft assembly. Their current design attached the propeller to the drive shaft using a steel pin through the propeller and the drive shaft.

The pin’s primary function was to secure the transfer of the rotational force from the drive shaft to the propeller. However, an equally important function of the pin was to shear when overloaded. Simplicity has its virtues but this overload mechanism also had a serious drawback. When the pin breaks, the boat is without power. Since it is almost impossible to replace the pin on the water, this might cause navigational hazards. The customers had complained about this so the head of the design department formed a cross functional design team to look into alternative solutions.

After a few initial meetings the team suggested as one alternative that a rubber sleeve be placed between the drive shaft and the propeller. The idea was that the rubber sleeve would provide enough friction to establish a solid joint between the drive shaft and the propeller for normal operation, but would slip beyond a certain torque. The slip mechanism could therefore protect the motor’s vital parts from overloading.

To establish a “proof of principle,” the engineers needed to determine the parameters influencing the slip torque. The joint between the rubber sleeve and the propeller would need to be an interference fit, i.e. the outer diameter of the sleeve needed to be slightly bigger than the inside diameter of the hole in the propeller. However, the manufacturing engineers pointed out that such a design would be difficult to assemble. Instead they suggested that the hole in the propeller be tapered forming a funnel for easier assembly both on the assembly line and by customers in the field.

To get some ideas about the influence of the basic parameters, an experiment was proposed. The three factors were: \(A\) — the outer diameter (0.688 or 0.710 inches), \(B\) — the hardness of the rubber (55 or 60) also called the durometer, and \(C\) — tapered or straight hole. An eight run factorial design is shown graphically as a three-dimensional cube in Figure 2. The eight corners correspond to the eight factor combinations, and the numbers displayed are the outcomes of the tests.

A formal statistical analysis can be performed, but a simple visual inspection of the data will suffice. It is clear from Figure 2 that by increasing the diameter, the slip torque increased. Moreover, the harder the rubber, the the higher slip torque, and that a straight hole gave higher slip torque.

<table>
<thead>
<tr>
<th>Concept development</th>
<th>Prototype development</th>
<th>Preparing for manufacture and trial production</th>
<th>Ramp-up and production</th>
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<td>choice of materials</td>
<td>product manufacturability</td>
<td>process yield</td>
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<tr>
<td>establish new theories and concepts</td>
<td>product performance</td>
<td>simplicity</td>
<td>product and process quality</td>
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<tr>
<td>proof of principle</td>
<td>specifications</td>
<td>sensitivity to component</td>
<td>product and process reliability</td>
</tr>
<tr>
<td>what happens if....</td>
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<td>variation</td>
<td>process simplicity</td>
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<tr>
<td>generating new ideas</td>
<td>sensitivity to component variation</td>
<td>tolerancing</td>
<td>cost</td>
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<td>simplicity</td>
<td>reliability</td>
<td>trouble shooting</td>
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<td></td>
<td>trouble shooting</td>
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</table>

*Table 1. Examples of possible objectives of experiments at different phases of the product development process.*

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After looking over the results from this first experiment, the engineers decided that a slip torque of less than 150 probably would cause slippage problems during acceleration. A torque greater than 150 could only be achieved using a straight hole. However, this was an undesirable solution from a customer and manufacturing point of view. It was therefore decided to conduct a follow-up experiment. In this the outer diameter of the rubber sleeve was increased to 0.717 inches, but the other factors kept at the same levels as before. The follow-up experiment required only four more trials. The results of those are shown on the expanded cube plot in Figure 3.

From Figure 3 we see that with the larger interference fit provided by an outer diameter of 0.717, with the harder rubber of 60 and a tapered hole, a satisfactory compromise between slip torque and easy assembly was achieved. However, because of the large variation in the data, it was decided to replicate this combination. As it turned out the confirmatory trials were consistent providing the engineers enough confidence in the results to continue their design work using this combination in the next prototype model.

Simple as this example may be, it nevertheless shows what we have seen to be true in general; several technical issues are often solved quickly, systematically and cost effectively by performing factorial experiments in the early stages of the design process. Often well designed experiments will allow a project to go forward, rather than becoming bogged down in endless discussions. Good experiments at the early stages of the development of a product, as illustrated here, often shorten the development cycle time, reduce the risk of making design decision on a shaky foundation, and reduce the likelihood of quality problems emerging later when the product is manufactured, or worse, is on the market and in the customers' hands.

**Experimental Design for Different Purposes**

During the development of a product, there are many different reasons for performing experiments, and a wide variety of experimental designs are available specialized for these different needs. The initial full factorial experiment used for the propeller joint is a typical example, but for larger number of factors, the number of test combinations will increase and the experiments become prohibitively expensive. We may instead use a fractional factorial design. Such designs consist of a carefully selected fraction of all the combinations. This approach is particularly useful in screening situations, when the investigators are interested in finding out which out of a large number of potentially important factors have the biggest effects on certain quality characteristics.
Screening Experiments

To illustrate the usefulness of screening experiments, let us consider the following example from a company that develops ingredients for food products. The company was in the process of developing a new emulgor. To benchmark they wanted to compare the new product with another that was frequently used by their customers. From previous work, the development team knew that several factors might have an effect on the stability of the emulgor, and wanted to test it in as broad an environment as possible. The eight factors and their levels are shown in Table 2.

A full factorial experiment for eight factors would require 256 individual trials. That many tests were clearly out of the question. It was therefore decided to run only a 16th fraction of the full factorial requiring 16 trials. From it we will be able to estimate the effect of the eight factors and a number of interaction effects. The consequence of not executing all the possible combinations is, however, that we get confounding; several interaction effects will be mixed up and can only jointly be estimated as a group.

Without going into further details, this experiment showed that the stability seemed to increase with increasing fat concentration (C) and protein concentration (B). However, the key finding was that there did not seem to be any difference in stability between theirs and the competitor’s emulgor (H).

This experiment demonstrates the potential of using fractional factorial experiments to screen a large number of factors in few trials. In this specific case the screening experiment was used to evaluate eight different factors in only 16 trials and it was found that only two had a large effect. Moreover, it showed that the product appeared to be insensitive or robust to all the factors that did not have an effect. With such experiments, products can be tested and the most robust and reliable prototype design selected.

The insight gained from the experiment can often be used to suggest modifications of the product that go beyond any of the tested variants and hence provide genuine quality breakthroughs, see Juran (1964).

Frequently, experiments are used to optimize product characteristics. Experiments for that purpose are called optimization or response surface experiments.

Optimization Experiments

Response Surface Methodology (RSM) was introduced by Box and Wilson (1951) as a method for experimental optimization of industrial products and process; for a modern exposition see Box and Draper (1987). The basic concepts of RSM can be understood by looking at the six pictures in Figure 4. For simplicity, suppose two factors, pressure and temperature, are believed to have an impact on the yield of a chemical process, currently run at pressure $p_0$ and temperature $t_0$ as shown in Figure 4a. Suppose further that the yield is much lower than expected, but the challenge facing the experimenter is how to reach the "mountain top" in as few trials as possible without knowing where it is located.

RSM consists of essentially three phases: initial exploration, exploration along the direction of steepest ascent, and exploration of near optimal conditions. The initial phase involves the use of a relatively small inexpensive two-level factorial or fractional factorial designs. The four trials plus a center point shown in Figure 4c will allow the experimenter to estimate locally the direction of steepest ascent. The next phase of the RSM strategy involves trying out, step-by-step, factor combinations along the path of steepest ascent as indicated in Figure 4c. As long as this step-wise strategy yields increasing results, the experimenter will continue. However, when the yield no longer increases another two-level factorial experiment is performed around the current

<table>
<thead>
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<th>Factors</th>
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<tr>
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</tr>
<tr>
<td>B Protein type</td>
<td>1 2</td>
</tr>
<tr>
<td>C Fat concentration</td>
<td>40% 60%</td>
</tr>
<tr>
<td>D Fat type</td>
<td>1 2</td>
</tr>
<tr>
<td>E Protein concentration</td>
<td>0% 10%</td>
</tr>
<tr>
<td>F Temperature</td>
<td>40°C 50°C</td>
</tr>
<tr>
<td>G NaCl</td>
<td>0% 1.2%</td>
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<tr>
<td>H Emulgor type</td>
<td>New Commercial</td>
</tr>
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</table>

Table 2. The eight factors investigated in the emulgor experiment.
best factor combination, see Figure 4d. From this two-level design the direction of steepest ascent is reevaluated and the process continued. The process will eventually bring the experimenter close to an optimum, or more precisely, a stationary point as in Figure 4e. At that point the experimenter might stop. But it is often advantageous to explore the near stationary conditions in detail. To do so, we typically use a central composite design as exemplified in Figure 4f. Such designs allow us to determine the shape of the response surface near the stationary point to indicate whether it is a peaked or flat maximum or minimum, a ridge, or a saddle point, all important issues for the product’s robustness.

An example of the development of a new type of paper used for printing currency will illustrate the idea. A major problem with aging currency bills is the tendency of the ink to fade and wear off (Barrios, 1995; Denes et al., 1995). A key quality characteristic for paper used for printing currency is its ability to absorb and hold ink measured by the contact angle. In preliminary studies it was found that the surface of paper when treated in a plasma, better absorbs and holds ink. It was, however, not known precisely how the paper needed to be treated to obtain the best results.

Using an RSM approach, a half fraction of a two-level factorial design for three processing variables plus a center point was first performed. This experiment indicated some curvature in the response surface. A second experiment was then performed consisting of the complementary fraction and the data from both were analyzed showing near optimum conditions. The team then
proceeded to add six star points completing a central composite design. A second-order response-surface model was then fit to the data as shown in Figure 6. From it we see that a minimum contact angle was achieved at a pressure of about 80 and a power about 70. However, changes in pressure between 70 and 90, and in power between 60 and 80 seem to a minimal effect on the quality of the paper.

Besides showing the use of RSM for optimization in product development work, this example also illustrates the usefulness of RSM in identifying how sensitive the optimum results are to variation in processing conditions around the optimum. A pointed response surface near the optimum implies that the processing conditions must be carefully controlled. However, a rather flat response surface indicates that the process can tolerate variation without a serious drop in the quality characteristics. In other words, the process is relatively robust around the optimum.

**Robustness Experiments**

The objective of another category of experiments is to discover design parameter combinations for which the product is robust to changes in factors that are uncontrollable outside the product development laboratory. For example, when designing an automobile engine, it is important that its performance is insensitive to changes in ambient temperature and humidity. Experiments with the purpose of discovering factor combinations that are robust to variation in environmental factors are often called robustness experiments.

The original application of the robustness concept was by Gosset (1931), although not explicitly promoted as such. Later, the idea was pursued explicitly by Michaels (1964), involved in developing detergents robust to changes in water temperature, water hardness, etc. More recently the concept has been pursued and raised to prominence by Taguchi (1987), see also Kacker (1985), Box, Bisgaard and Fung (1989), Box and Jones (1992), and Bisgaard (1992b).

Ideally robustness experiments should be performed during the early design phases to prevent costly changes later. During prototyping several different prototypes ought to be evaluated for robustness, not just a single prototype, see Bisgaard and Steinberg (1997). The prototype that is most reliable and robust can then be chosen for further development. In practice, however, it is not unusual that robustness experiments are run when problems emerge later in the development process.

The following example illustrates the use of robust design. A manufacturer of fish food pellets wanted to study how robust the pellets were to variation in raw materials and processing conditions. An experiment was performed with three controllable process variables: feeder, temperature, and water percentage, and two otherwise hard to control variables: carbohydrate type (C) and degree of grinding (G). Pellet density was used as a measure of quality and the goal was to make it greater than 0.86. The experimental design and data are shown in Table 3.

By visual inspection of Table 3, we can see that the pellet quality is relatively robust to variation in carbohydrate type and degree of grinding, but vary with the processing variables. In particular, pellet recipe 3 and 8 produced

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**Response Surface of Contact Angle**

Contour plot and response surface of contact angle for SiCl4 plasma treatment. Factor time is fixed at 0 level.

Figure 5. Response surface study of plasma treatment of currency paper.

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with high (+) water level and high (+) feeder rate resulted in relatively robust or stable quality characteristics.

Conclusions

There are many benefits of the use of experimental design in product development. Most importantly, design of experiments provides an efficient and effective way for product development teams to generate information critically needed in the design process. With this information, uncertainty about future performance of the product can be reduced, and optimal and robust design solutions be found. Experimental design can greatly increase the efficiency of the large amount of experimentation and troubleshooting that inevitably will take place during the development of any product whether statistical principles are used or not. The use of statistically designed experiments, however, can greatly reduce the number of tests needed and thus decrease the cost, ensure rapid data collection, and reveal important interaction effects.

Another benefit of experimental design is that simultaneous cost reduction and quality improvement is often achieved; it is sometimes possible to select combinations of processing variables or design parameters that will not only improve the quality of the product, but also reduce the cost of making it. Even an experiment that shows that a given factor has no influence on quality is useful. Such results will allow the product developers to choose the option that costs the least. Products can also frequently be made robust to variation in uncontrollable (environmental) variables. The difference between success and failure for a product may often be determined by the way the development team deals with variables they cannot control in the field. One of the major strengths of robust design is its ability to deal with uncontrollable environmental variables such that the quality of the product is reasonably constant even when the environmental variables vary as they inevitably will in use.

Carefully designed experiments provide a systematic approach for problem solving and trouble shooting during the development process. Product developers do not as easily get confused when trying to identify variables with large effects on the quality of the end product, and in determining optimum conditions for those variables. All this sums up to better, more robust products, in shorter time, with less effort.

Acknowledgements

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References


<table>
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<th>Carb. type</th>
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<td>8</td>
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Table 3. The design and data for the fish pellet robustness experiment.

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