QUALITY IMPROVEMENT USING FACTORIAL DESIGN

Dr Lim Teow Ek
Associate Professor
Nanyang Technological University
Singapore 639798
E-mail: MTELIM@ntu.edu.sg
QUALITY IMPROVEMENT USING FACTORIAL DESIGN

AUTHORS
Dr Lim Teow Ek
Associate Professor
Nanyang Technological University
Singapore 639798
E-mail: MTELIM@ntu.edu.sg

ABSTRACT
Factorial design is probably the most powerful statistical technique for research into any manufacturing process for the purpose of quality improvement. This article discusses the practical aspects of using a full factorial design for the optimization of heat treatment variables to eliminate wobbling of gears. Factorial experiments were used to investigate the effects of heat treatment variables on 20, 24, and 28 teeth gears to identify the optimum settings. These settings resulted in significant improvements in flatness and concentricity of the gears which led to significant quality improvement.

INTRODUCTION
Factorial design was originally developed in the 1920’s by R.A. Fisher who sought to identify optimum processing variables. While Fisher’s work considered an experimental approach to agricultural research in England, the technique is presently being used by manufacturers as part of their unending quest to produce defect-free components. The premise of Fisher’s approach was that an experiment must be so carefully planned that even small effects due to deliberate changes in materials and methods can be discovered in the presence of major and uncontrolled environmental changes. Two of his books contain the basis of experimental designs used for industrial process research today. Among the various experimental design techniques, factorial design is probably the most powerful method for any manufacturing process.

Unlike laboratory research, closely controlled experiments of high accuracy and materials of great purity are frequently unattainable when dealing with the problems of industrial processing. Much of the literature recommends using experimental design for investigating industrial problems, primarily because it generates unambiguous results at the lowest costs and within the shortest periods of time. Other reasons include the need to learn about interactions among variables and the desire to estimate experimental error quantitatively, which conventional experiments cannot provide.

Researchers may select from such standard plans as randomized blocks, Latin squares, factorial experiments and fractional factorial experiments. The correct selection of the standard plan is only the starting point, and the success of the research relies more on a researcher’s ability to adapt the standard plan to suit the needs and peculiarities of the specific problem. Among the standard plans, factorial experimentation is most commonly used and is probably the most powerful. This technique can be adapted for optimizing the variables affecting most manufacturing processes.

A factorial experiment is one which all levels of a given factor are combined with...
all levels of every other factor in the experiment. In an industrial situation, several factors can be controlled and their effects investigated at two or more levels. The factorial design consists of taking the response at every possible combination that can be formed for each different level of the factors. In the analysis of a factorial experiment, the main effects and interaction effects (or, simply, interactions) are considered. The main effects of a given factor are always functions at the average response at the various level of the factor. A major advantage over conventional experimentation - where factors are varied one at a time - is that the interaction effect between factors within the range of the experimental settings and experimental error can be estimated by the factorial experiment.

OPTIMIZING THE PROCESS

The lengthy calculations and analysis of experimental data can be found in all textbooks on experimental design, and this article is confined to comparing the results of original settings against those of the optimized settings identified by factorial experimentation. The research considers multi-speed gear assemblies which became defective due to gear wobbling. The wobbling results from gears failing to meet flatness specifications.

To verify that heat treatment was the primary cause of gear wobbling, flatness readings of 200 20-tooth gears were taken prior to heat treatment. The samples were then subjected to standard heat treatment within the factory furnace and flatness readings were taken once more. While the samples were within flatness specifications prior to heat treatment, approximately 30% of the gears were found to be inferior subsequent to processing. It was thus concluded that the heat treatment was the cause of the gear wobbling in the assemblies. To remedy the problem, factorial experiments were used to investigate the effects of heat-treatment variables (i.e., time and temperature) on 20-, 24- and 28-tooth gears.

With the factorial experimentation completed within a two-week time frame, optimum furnace settings were identified. The original and optimal heat treatment variables are summarized in Table I. Figure 1 shows the graphs comparing flatness and concentricity readings of ten samples using the original settings against ten samples using the optimum settings. These graphs suggest that the optimum settings identified by the factorial experiment result in significant improvement in flatness and concentricity of the gears. These settings were implemented and gear wobbling defects in the gears assemblies were drastically reduced to less than 1%.

<table>
<thead>
<tr>
<th>Original Settings (Coded)</th>
<th>Optimum Settings (Coded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Gear</td>
<td>Time</td>
</tr>
<tr>
<td>20-tooth</td>
<td>100</td>
</tr>
<tr>
<td>24-tooth</td>
<td>100</td>
</tr>
<tr>
<td>28-tooth</td>
<td>110</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of gear flatness and concentricity of original and optimum
settings.

(a) Flatness of 20-tooth gear

(b) Concentricity of 20-tooth gear.

(c) Flatness of 24-tooth gear.
The optimization of heat-treatment processing demonstrates how factorial experiments can be adapted for investigations of manufacturing processes. The number of factors usually increases when the problem becomes more complex. For example, an 8 factors x 8 levels experiment can be used to study the annealing of copper tubes, and a factorial experiment using nine alloys, four sites and four observers (a 9 x 4 x 4 factorial experiment, giving 144 observations) can be used to study the corrosion resistance of aluminum alloys. For electronics and other industries more factors may be studied.

The approach used in the classical method of experimentation is to hold everything constant except the single factor under investigation. In contrast, a
factorial experiment deliberately combines all variables of all factors so that at least one trial is made for each combination. A properly planned factorial experiment will enable the researcher to quantify the effects of the various factors, the effects of interaction between the various factors (also known as joint effects), and the experimental error. This allows the researcher to identify the optimum conditions at the minimum cost for any manufacturing process.

Apart from choosing a suitable design and adapting it for the research, the researcher must consider the selection of the parameters for experimentation and the method of data collection and analysis. Other considerations might include whether historical data concerning the expected outcome of certain experimental conditions can be used and whether the experiments can be performed in stages.

The selection of the parameters (or factors) affecting the response and deciding what to do about them represents an important part of planning an industrial experiment. Good statistical knowledge alone cannot substitute for thinking about the problem, and it is a vital prerequisite of the technique that the researchers be highly knowledgeable with regards to the subject matter. Brainstorming sessions are usually organized with the objective of identifying the critical parameters affecting the problem in question.

To ensure that results are not biased by uncontrolled variables such as ambient conditions and variability among different experimenters, randomization is introduced into the experiment to the extent that is most practical. For the analysis of data, the consideration would be the choice of a reasonable statistical model to approximate the relationship between the independent process parameters and the response variable. A more complex statistical model may be required to describe relationships adequately over a relatively large experimental range. Usually, the more complex the assumed model, the greater the number of runs are necessary. Finally, clear and easy-to-understand procedures for data collection must be developed and documented.

**CONCLUSION**

Factorial design is an efficient technique for investigations into manufacturing processes. If the result of changing two or more factors is to be studied, the most efficient method of approaching the problem is generally factorial design. When there are no interactions, factorial design provides maximum efficiency in estimating effects. When interactions of an unknown nature exist, factorial design is necessary to avoid misleading conclusions. In the factorial design, the effect of a factor is estimated at several levels of the other factors, and the conclusions hold over a wide range of conditions.

**REFERENCES**

6. C. Hicks, Experiments (Holt, Rinehart and Winston, 1964)
7. Douglas C. Montgomery, Design and Analysis of Experiments, 4th ed (New
10. Davis, p.171
11. Davis, p.296
13. Davis, p.253