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An Illustration of the Taguchi-Based Design Methodology*

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This paper outlines a low-cost design exercise, which has been designed to illustrate the main elements of the Taguchi-based approach to experimental organisation and analysis. In designing the exercise, consideration was given to the needs associated with teaching the essential elements of the Taguchi approach to medium- and large-sized groups of students. This led to the development of a low-cost exercise, in which load tests are undertaken on a selected range of paper cylinders in order to establish a 'best' arrangement of the design parameters.

INTRODUCTION

THE SO-CALLED Taguchi method uses a well-defined statistical approach to the design of engineering experiments. This method, which is outlined below, allows the designer to establish the role of the various parameters in the production of what can be described as a 'good design'. Whilst the detailed operation of the method may be seen as being important, the main objective of the approach described below is to highlight its usefulness in modern engineering design. In addition to providing a vehicle for the development of an understanding of the Taguchi method, the exercise also provides an opportunity for design thinking, as well as exposing young engineers to concepts of design and process optimisation, which should clearly be an important part of the graduate engineer's design tool kit.

The exercises outlined below fully illustrates the usefulness of the Taguchi-based approach, and also identifies certain limitations in the use of the methodology that should always be considered when it is applied. In so doing the exercise can play an important role in the education of undergraduate engineering design students.

The usefulness of a Taguchi-based approach to experimental design has been well established in the reporting of many successful deployments. These range from the design and testing of entire engineering systems [1], through the design of specific engineering products [2] to the description of experiments designed to illustrate the method itself [3]. The method can thus be taught to students using previously obtained experimental results in the form of a case study like exercise.

Some experiments have been designed to allow students to perform a realistic exercise, such as the Albion Standard Taguchi Experiment [3]. Here the parameters associated with the production of an acceptable surface finish using a milling machine are analysed using the Taguchi approach. This has very clear objectives and is a good example of the method in action. It does, however, require access to potentially expensive equipment and, perhaps more importantly in the context of this paper, require that students work in small groups in a laboratory-like environment. While the above experiment would fit very well into the education of design engineers, it does not allow for the concurrent undertaking of a Taguchi-based exercise by the whole class.

Another good example of the application of a statistical approach to design problem solving is outlined by Schubert *et al.* [4] where experiments are undertaken in order to 'target' a model catapult. Here contrasts are made between theoretical development of a solution and experimental design using good engineering practice to refine solutions to meet a known and identifiable target.

The exercise outlined in this paper evolved in order to allow medium to large scale classes the opportunity to undertake concurrently a Taguchi-based design experiment. Working in small groups, the class can perform the described design and test activities, with the final design testing being undertaken in a competitive environment.

In designing this experiment, more consideration has been given to outlining the methodology associated with the Taguchi-based approach and the inherent experimental organisation involved in it, than is actually given to the analytical interpretation of the results and their refinement into an optimum solution. This ensures that first-time users of the Taguchi approach are introduced to

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the benefits that such an approach can yield. This is in keeping with the thoughts of practitioners such as Shoemaker and Kacker [5] who stress the role of such an approach in illustrating how the methodology can organise the decision and judgement making activities involved in the practical solving of robust engineering design solutions.

THE OPTIMUM PAPER CYLINDER EXERCISE

The Taguchi method uses an orthogonal array to produce a controlled series of experiments from which conclusions relating to the effects of various changes to design parameters can be drawn. This is a well-established statistical technique which cuts down the number of experiments necessary, when compared to the full factorial design procedures that are widely operated, whilst maintaining, and in many cases increasing, the level of information obtained from the set of experiments.

The Taguchi exercise which forms the basis of this paper requires that students design an 'optimum' paper cylinder. The various parameters that can be manipulated are the height, weight and diameter of the cylinder and the slope of the surface upon which the cylinder is to be tested. Testing is performed by loading each cylinder to failure. By selecting a combination of these parameters a final 'score' can be obtained for each cylinder tested, with marks being awarded for each parameter and the maximum supported load. Each parameter can vary within carefully designed limits:

Cylinder Height (H). A direct relationship is used with
Marks available = 100 × Cylinder Height (m).
Parameter limits: $0.2 < H < 1$.

Cylinder Diameter (D). A direct relationship is used with
Marks available = 666 × Cylinder Diameter (m).
Parameter limits: $0.03 < D < 0.15$.

Cylinder Weight (W). An inverse relationship is used with
Marks available = 125 − (500 × Cylinder Weight) (kg).
Parameter limits: $0.05 < W < 0.25$.

Surface Slope (A). A direct relationship is used with
Marks available = 20 × Angle of Inclination.
Parameter Limits: $0 < A < 5$.

and

Maximum Load (L). A direct relationship is used with
Marks available = 20 × Load (kg)
Parameter limits: $1 < L < 5$.

The parameter limits have been carefully set and any cylinder not meeting either the minimum or maximum criteria receive zero for that parameter. The exception to this is for the supported load, where failure to meet the minimum requirement results in the structure being designated as a complete failure. Thus, taking each parameter at its maximum limit and examining the associated marks awarded, means that a cylinder that has a height of 1 m, a diameter of 0.15 m, a weight of 0.05 kg that is tested on a 5° slope would score full marks for each parameter. However, such a cylinder would not support the minimum load and as such would be deemed worthless. It is also worth noting from the start that a maximum number of marks (100) is to be awarded for a cylinder holding a load of 5 kg, and no further marks can be obtained for this parameter. Thus, over-designed cylinders that hold more than a 5 kg load cannot gain more than full marks.

Given the above, the students are faced with a series of parameters, which may or may not interact, and are requested to produce an 'optimum' design. Each parameter needs to be considered carefully and some preliminary tests may be useful in identifying potential ranges of parameters to be used. Under a factorial design process, one would keep each parameter constant in turn and vary the others to assess the effect each has on the final design. This is a time-consuming exercise. If, for example, each parameter is to be set to three different levels, one may expect to undertake 81 experiments. The Taguchi approach suggests that this process can be performed using nine carefully selected combinations.

This is made possible by the statistical properties of specific orthogonal arrays, such as the L9 array shown in Table 1. Following from the above specification, that each parameter is to be investigated at three levels, examination of Table 1 shows that by manipulating the way in which each parameter is combined with different levels of the remaining parameters it is possible to ensure that full consideration is given to how each parameter effects to performance of the final design. It is this facility that makes the Taguchi method such a valuable and important design aid. To illustrate this, and to outline the method and its application in this exercise, a typical series of tests is given below.

A CASE STUDY

A typical set of parameter level selections, and their associated marks, is shown in Table 2. This selection is representative of a recently completed class activity and is not intended in any form to represent the 'best' such selection. Some input into the selection process is made by a series of initial tests, in which students gain experience in the material they are using, the manufacturing processes available to them and the costs associated with the manufacture of the cylinders. Thus factors such as cylinder height may be determined

Table 1. Taguchi L9 array, indicating parameter level selections for each experiment

Experiment	Factor 1	Factor 2	Factor 3	Factor 4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 2. Selected parameter levels for case study exercise

	Cylinder Height H m (Score)	Cylinder Weight W kg (Score)	Cylinder Diameter D m (Score)	Surface Slope A° (Score)
Level 1	0.55 (55)	0.05 (100)	0.09 (60)	2 (40)
Level 2	0.65 (65)	0.075 (87.5)	0.11 (73)	3 (60)
Level 3	0.75 (75)	0.1 (75)	0.13 (87)	4 (80)

by the widths of available paper, cylinder diameter by the diameter of a convenient former and the overall weight by the 'price' they are willing to pay in terms of lost marks.

At the initial stage, much of the selection is based upon instinct, and on the application of engineering common sense along the lines outlined above. More serious analysis can be applied, particularly to the stability of the structure which will be relevant to the selection of inclination levels used. However, the nature of the problem is such that theoretical analysis alone is not sufficient to produce a solution. For example the cylinder may, under differing conditions, fail as a result of toppling, buckling, bending, or any combination of these three mechanisms.

The results associated with this particular set of experiments are shown in Table 3. Marks are obtained for the highest load supported by each cylinder, and the total marks are then assessed based upon the contribution made by the supported load and the marks obtained by each parameter.

From the results shown in Table 3 that it is possible to calculate the average performance of each parameter at each level. This is the basis of the Taguchi approach, and experimental results for each factor at each level are combined to give the average responses, shown in Table 4. For example, Factor 1, the Cylinder Height, at Level 1, 0.55 m, occurs in tests 1, 2 and 3. Combining the scores for each of these experiments and taking the average gives an indication of the performance associated with the particular factor/level combination.

Table 3. Maximum load and overall score for each Taguchi experiment

Experiment	Load L kg	Load Score	Overall Experiment Score
1	4	80	335
2	5	100	375
3	5	100	396
4	4	80	373
5	5	100	353
6	1.5	30	341
7	4	80	350
8	1	20	348
9	4	80	368

Table 4. Performance indicators for each Factor–Level combination

Level	Factor 1 Height	Factor 2 Diameter	Factor 3 Weight	Factor 4 Slope
1	369	352	348	352
2	355	366	372	355
3	363	369	366	386

Taguchi analysis, which can be undertaken on proprietary computer programs, then indicates the best combination of parameter levels as represented by the values producing the highest average performance.

Examination of the average performance at each level indicated in Table 4 shows that the levels to be selected in the example being considered are:

Cylinder Height H = Level 1 = 0.55 m;
Cylinder Diameter D = Level 3 = 0.13 m;
Cylinder Weight W = Level 2 = 0.075 kg;
Surface Slope A = Level 3 = 4°.

It is apparent from the above selection that the 'best' solution is not one which was actually tested. In order to predict the failure load a simple calculation can be undertaken, which computes the predicted final performance of the selected solution. This simple method considers the best performance to be represented by:

Predicted Performance = Overall Average + Σ(Best Performance for each parameter − Overall Average).

In this instance, this predicted performance should obtain an overall score of 409 which, in turn, given the marks established already for each parameter, indicates a final load of 5 kg. On testing, the specified cylinder was found to support the predicted load and, hence, the score indicated was achieved.

AN OVERVIEW OF THE OUTLINED APPROACH

The success of the exercise shown above is typical of the level of scoring obtained. However, many different combinations of parameters have been used to reach such levels. This is brought home to students during testing where the various different solutions are seen together, and it becomes clear that more than one 'optimum' solution exists. Understanding how this can occur and how it can be related to the selection of the initial factor levels is a key element to the correct and effective utilisation of the Taguchi method.

The response graphs for the experiment used in the above example are shown in Fig. 1. These graphs illustrate the variation in the average points scored for each of the factors and, hence, can provide some very useful information regarding the design optimisation process.

Figure 1 clearly indicates that a large diameter cylinder on the greatest slope gives the best results. Less clear is the selection of cylinder weight, where the best level is apparent, but the nature of the relationship between weight and overall performance is more complicated. The best cylinder height level is clearly indicated, but again the nature of the relationship between it and the overall score is less well defined.

What Fig. 1 should tell the teams designing the cylinder is that they have set the levels, and thus can only make conclusions relating to these selections. In other words, the method used will give an optimum design based upon the parameter levels chosen. It is not guaranteed to produce the optimum, if there can ever be such a thing. This limitation is made apparent by the nature of the relationship between, for example, cylinder height and overall score where, clearly, more investigation may be needed to explore the actual maximum value.

It is also apparent from a common sense engineering approach that conclusions regarding the experimental results obtained must be contained within the parameter ranges used. It appears for example, that the greatest slope is 'best'. This may be so here, but clearly to take this assumption and convert it to a general rule would be folly, since to move towards an ever increasing angle of inclination in the testing surface may be unrewarding in the extreme should a previously stable structure become unbalanced.

CONCLUSIONS

In designing this exercise, consideration was mainly given to the need to introduce Taguchi-based design methods into undergraduate courses in a practical and enjoyable manner. It is widely agreed, by Box [6] amongst others, that the

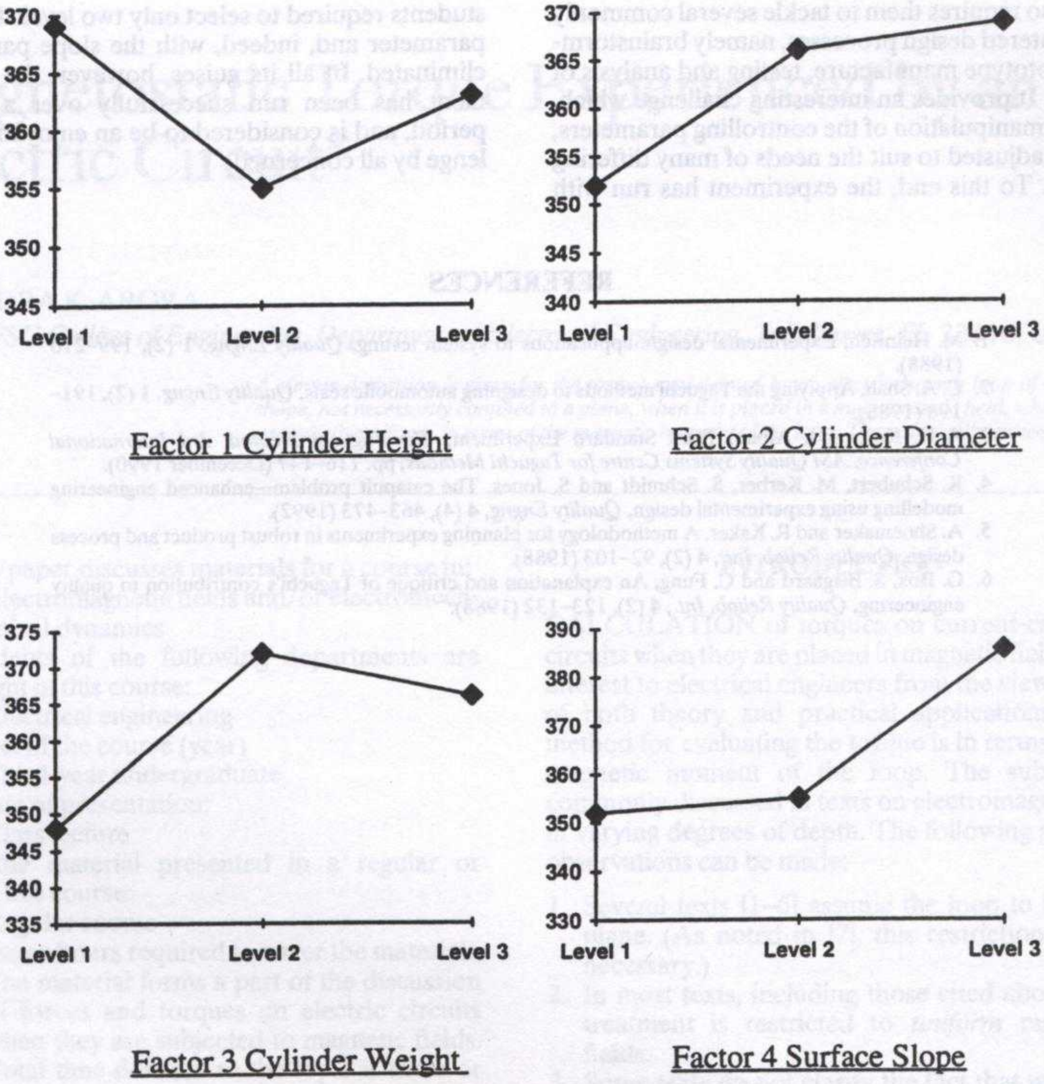

Fig. 1. Factor response graphs

advantages associated with such approaches are important enough to justify the inclusion of a basic understanding of the method into the knowledge base of all undergraduate engineers.

At the same time, however, Box also considers certain limitations and complications of the method, to a much greater depth than is attempted in this work. These limitations, which are attributed to the statistical basis of the analysis of certain parts of the experimental results, are of undoubted importance. This exercise, however, is concerned with the practical application of Taguchi and, as such, draws the users' attention to certain limitations in the conclusions drawn from the applied methodology, rather than attempting to identify how and why the statistical basis for the approach has been developed. This can be justified by the intended use of the designed experiment as an introduction and by the fact that investigators such as Box have already extensively explored the basis of the methodology elsewhere.

It is this limitation to the overall conclusions that must be stressed most strongly. What needs to be understood is the concept that, by pre-setting the parameters to certain levels, the students are examining a window in the overall field of acceptable solutions. This can be reinforced by a careful review of the final cylinder testing exercise, which is undertaken within the larger class. In the set of cylinders from which the above example was drawn, for instance, there were several similar, but slightly taller cylinders which failed due to toppling, i.e. the load caused the cylinder to unbalance rather than fail structurally. There were also several cylinders which failed due to buckling and cylinders which were more than capable of holding twice the required load, but which received poor overall marks since they could not score more than full marks for the load holding parameter.

Overall, it is proposed that the exercise outlined above is a useful way in which to introduce students to the Taguchi-based design methodology. In doing so it also requires them to tackle several commonly encountered design processes, namely brainstorming, prototype manufacture, testing and analysis of results. It provides an interesting challenge which, via the manipulation of the controlling parameters, can be adjusted to suit the needs of many differing classes. To this end, the experiment has run with students required to select only two levels for each parameter and, indeed, with the slope parameter eliminated. In all its guises, however, the experiment has been run successfully over a 3-year period, and is considered to be an enjoyable challenge by all concerned.

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